MODELING AND SIMULATION OF MANUFACTURING FLEXIBILITY IN CIRCUIT BOARD MANUFACTURING

by

CHRISTOPHER EDWARD COUCH

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ABSTRACT

This study examines the relationships between the types of manufacturing flexibility and the sources which cause flexibility. Flexibility types and sources were measured over an 18-month period at a printed circuit board (PCB) factory which fabricates and assembles PCBs into optical tracking and guidance systems. This data was analyzed using system-identification techniques somewhat analogous to multiple regressions, which yielded empirical models describing time-based relationships between flexibility types and sources.

Results can be summarized in three categories. First, the empirical models are reasonably accurate and provide a "roadmap" of relationships which may be useful to managers who desire to increase or decrease certain types of flexibility. Second, the models offer insight into the flexibility framework which was assumed at the beginning of the research. This framework is important because it is used to define the types and sources of flexibility. Finally, the models and their implications suggest useful ways to continue research into strategic management of manufacturing flexibility.

Thesis Supervisor: Dr. Charles H. Fine
Title: Associate Professor of Management Science

Thesis Supervisor: Dr. Stanley B. Gershwin
Title: Senior Research Scientist
Thanks to Hughes for supporting this research when I should have been designing test stations; thanks to Stan for indulging me in two-hour discussions over apricot tea; thanks to Charlie for letting me migrate to Sloan for a while; thanks to Mom and Dad and God for support and love – I’m finally out of here!
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Introduction

Almost everyone agrees manufacturing flexibility is important. Being flexible makes intuitive sense: the demand for different types and amounts of products, varying delivery time constraints (i.e. those placed upon suppliers to a JIT factory), and the need for development of new products all require a production system which is flexible enough to meet these demands and stay profitable. Three questions immediately present themselves. First, what are the types of flexibility and how can they be appropriately measured? Second, what are the things that may cause these flexibilities to wax or wane, and how can these sources be measured? Finally, given the ability to quantify flexibility types and sources, how can we discover the relationships between them?

In response to the first and second questions, academia has produced a dizzying array of often conflicting answers. Academics and practitioners alike have trouble agreeing on the types of flexibility. Some people have simplified the concept of flexibility so far that we are left with definitions like “flexibility is the ability to change.” Others have written tomes containing dozens of definitions of flexibility; in these cases we are forced to deal with flexibility names such as “the ability of this tool to cut different gauges of wire.” These blatant examples illustrate the range of perspectives on flexibility, and how poorly flexibility can be defined in both the literature and managers’ minds. When too generally defined, it is impossible to quantify the value of manufacturing flexibility, if indeed that value is positive. When too specifically defined, flexibility measurements run the risk of
not being generally applicable. This can eliminate the possibility of making operating or strategic decisions based on sound analysis and comparison. Sethi and Sethi touch on this point in (1), and it is addressed with a hierarchical approach by Upton in (2) and Slack in (3).

To make matters more confusing, even those who agree on the scope of flexibility have difficulty finding consensus on taxonomy. Take, for example, the concept of varying production volume. In simple terms, this means the number of products a factory makes during one time period is different than the number of products it makes in the next time period. A factory which can vary this number freely is called output flexible by one author [(4) and (5)]. Another calls the same concept loading flexibility [(6) and (7)], and yet another calls it volume flexibility (8). This nonstandard vocabulary is understandable given the varied disciplinary backgrounds of the authors; these backgrounds range from Operations Research [(9) and (10)] to Thermodynamics (11) to Mechanical Engineering (12). Nevertheless, it is confusing. (For some interesting alternative viewpoints on flexibility, see Upton and Barash (13), Taylor (14), de Groote (15), and Kulatilaka (16).)

The first task, therefore, is to decide on a relevant flexibility framework. A good framework will provide useful definitions of flexibility types. These definitions will be specific enough that concrete flexibility metrics can be developed. With these metrics, management can compare operating and strategic choices in terms of flexibility. A good framework will also contain operational or strategic implications which reveal tradeoffs between flexibility types, quality, efficiency, and strategy (this is reminiscent of Chryssolouris (17)). Management's intuition about these tradeoffs should be fostered by the framework and associated metrics. In addition, the framework should at least suggest the sources of flexibility. These source definitions must likewise be quantifiable and useful.
This study uses a framework developed by Suárez and Suárez et al. in (8) and (18). The framework meets all the criterion for a “good” framework in that it provides useful definitions of both flexibility types and flexibility sources. Using these definitions, the next task is to carefully articulate the metrics for flexibility sources and types. The Suárez framework is defined crisply enough that these metrics are fairly obvious. Only after these metrics are articulated can they be applied to a real factory, and used to generate data.

The next step is to answer the third question: how can we discover the relationships between flexibility sources and types? In an earlier study (8) this was done by applying the metrics to many factories at one instant in time, and performing multivariable regressions on the data to reveal correlations. Although useful in many ways, this method has three shortcomings. First, the correlations are based on a single, multidimensional data point from each factory. This point has the same number of dimensions as the number of metrics applied to the factory. The correlations describe trends across factories at the expense of detail about each factory. These details may or may not resemble the cross-factory trends: either way, the analysis cannot make a distinction.

Second, the data do not describe behavior of the factories over time. It is merely a “snapshot” of flexibility sources and types at a single instant in time. While this provides useful information about possible source/type relationships, the relationships may be transient. In other words, one flexibility source may correlate strongly with some flexibility type this month, but not so strongly next month. Of course it can be argued that in the Suárez study there are snapshots of several factories, so if the source/type relationships do change with time, many possible configurations are observed. However, even if this is true we are still left with average relationships giving the best data fit for all observed stages of the source/type relationships.
Third, multivariable regressions describe correlations between *possible* causes and effects. While such correlations are useful, they do not take into account the possibility that factory flexibility is a dynamic system. A dynamic system is one which has internal states. These states affect themselves and the outputs from the system at later times. For example, a mass hanging on the end of a spring is a dynamic system in the sense that, given an initial pluck, it will vibrate for some time even if it is not plucked again. If we apply the metrics "system was plucked" and "system is moving" to the system, we will find that these metrics correlate very strongly. However, the oscillatory motion of the system can hardly be described by this correlation alone.

This study attempts to improve on the multivariable regression approach by using some mathematical techniques borrowed from mechanical engineering. These techniques, called system identification, allow one to estimate internal states of a system given input/output data. In this case, inputs are flexibility sources and outputs are flexibility types. System identification also provides estimations of parameters describing the effects of internal states on the outputs. With these estimates of states and parameters, we form a model which approximates the behavior of the system. Flexibility is then be predicted within the valid ranges of the model. Armed with these models, manufacturing managers can isolate the most important sources for each type of flexibility and make changes (investments, etc.) according to their flexibility needs.

This thesis is organized in the following manner. The next chapter describes the industry and factory from which data was taken within the context of the framework. Chapter 3 details the Suárez framework and associated hypotheses, describes the flexibility metrics developed for this thesis, and summarizes the system identification techniques used in the analysis. Chapter 4 presents the results: important source/type relationships, models, and
error analysis. Chapter 5 compares results to hypotheses. In addition, Chapter 5 expands on the results by using the models to simulate and predict factory flexibility performance for some selected cases of interest. Chapter 6 discusses the implications of the results. Its primary focus is on the flexibility framework and suggestions for future research. Finally, the appendices present detailed descriptions of the production areas, the questionnaires used to collect data, a development of the system identification techniques, and the computer code written to perform system identification.
The Industry

Throughout much of history, warfare was a daytime activity. In many societies it was a standard "code of war" that armies slept at night and fought during the day. However, during recent decades new strategies and technologies have changed that code; the modern army must be prepared to fight during day, night, or adverse weather conditions. To meet this need, armies must have the ability to "see" through darkness, sandstorms, snow, rain, and fog. Infrared optical systems provide this ability.

The infrared optical system industry is inherently tied to the defense industry as a whole. The United States military is the primary customer for US-based infrared system manufacturers. In recent years overall US military spending has declined; Figure 2.1 shows US defense outlays as a percentage of the Federal budget. To make matters worse for defense product manufacturers, current contracts are becoming increasingly difficult to renew. This is a result of projected cuts in US defense outlays. Contracts are awarded by branches of the US military (Army, Navy, Air Force), and as their funding decreases so does their generosity.
Figure 2.1: US defense outlays as a percentage of Federal budget (19).

One possible favorable result of US defense spending cuts is the “conditioning” of the US defense industry. In the past, cost-plus contracts were the norm; these contracts basically gave defense manufacturers a blank check for all development and production expenses. In addition, manufacturers were often allowed to take development projects into production. This is no longer the case. In a 1992 document (20), the Pentagon outlines its new attitude about defense manufacturing. The Pentagon essentially wants manufacturers to develop expensive, sophisticated products but not to expect to go into production. However, it wants manufacturers to retain the ability to “switch on” production in the event that the military needs new hardware. This is a tall order. It requires levels of flexibility previously unimagined by defense manufacturers, levels which may be difficult to achieve. But the customer requirement exists, and there is money to be made by manufacturers who can meet this demand (this discussion is reminiscent of R.H. Hayes and S.C. Wheelwright (21)).
Hughes Aircraft and EDSG

Hughes Aircraft's Electro-Optical and Data Systems Group (EDSG) is a 997-person group which produces infrared systems for modern militaries, such as the Hughes Night Vision System (HNVS). A listing of EDSG products is given in Table 2.1. Like HNVS, most products are variations on a theme: they consist of an infrared detector and associated electronics. A detector is a sensitive array of electronics which converts infrared energy into electrical signals. These signals can be converted into TV images or used by computers to target, track, or navigate. EDSG products are differentiated by the complexity of the detector, the pointing mechanism surrounding the detector, and the inclusion of any additional systems such as laser rangefinders or day TV (day TV refers to standard TV technology, which creates images using visible light). All products can be characterized in terms of detectors, printed circuit boards (PCBs) and mechanical subassemblies.

<table>
<thead>
<tr>
<th>M1–gunner sight for tanks</th>
<th>HNVS–Hughes Night Vision System</th>
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<tr>
<td>Subunits:</td>
<td>TOW–guidance for TOW missile</td>
</tr>
<tr>
<td>CPCU/MEU (power and electronics)</td>
<td>AAS38–navigation pod for F18 fighter</td>
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<tr>
<td>LRF (laser range finder)</td>
<td>GPS/LOS–gunner sight for tanks</td>
</tr>
<tr>
<td>TRU (thermal imaging unit)</td>
<td>TWS–thermal weapon sight</td>
</tr>
<tr>
<td>EN6–guidance for cruise missile</td>
<td>HIRE–thermal sight</td>
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</table>
Manufacturing at EDSG consists of two main activities: PCB production, and integration of optical, mechanical, and electrical systems. Almost all mechanical and optical components, as well as certain electrical components like wiring harnesses and power supplies, are made outside of EDSG. EDSG’s true manufacturing expertise lays in integration of sophisticated, high-precision subsystems from the mechanical, optical, and electrical realms. Most PCBs are made in EDSG, but recently these operations have come under scrutiny and there is speculation that PCB production will cease in the near future; if this happens all boards will be outsourced.

Production History

Most EDSG products share a similar production history. Typically the production programs begin as prototype or proof-of-principle exercises which demonstrate EDSG’s ability to manufacture the desired product for the military. In this phase of production most subassemblies are one- or two-of-a-kind, and manufacturing is done at the laboratory level by engineers.

If prototyping is successful, the military awards production contracts. Once products become full-fledged production programs, printed circuit board manufacturing is typically located in common assembly. This is a 15,510 square meter area which fabricates and tests PCBs. In addition, integration of PCBs into mechanical assemblies is performed in a product-specific area adjacent to common assembly. In the integration areas, circuit boards (many of them common between products) are packaged into the mechanical assemblies of different end products. For example, infrared detectors and associated circuit boards could be integrated into turrets, which are mounted on ground vehicles, or pods, which are slung under aircraft wings. Table A.1 in Appendix A lists
the repertoire of major fabrication, integration, and test operations performed in common assembly.

It is important to note that most operations revolve around testing. This is mainly a result of stringent military product requirements, and characterizes operations in EDSG. Walking through the factory one quickly notices that test stations comprise nearly all production equipment. There are many assembly workspaces with small hand tools, lamps, etc., but EDSG production equipment means, for the most part, test stations. Test stations are by far the most costly production equipment in terms of dollars and time. Small "black box" test stations can cost over $1M, and a single environmental test can take hours. Contrast this to the cost of a screwdriver and the time it takes to fasten a PCB to a chassis with a few screws.

Historically, common assembly and the adjacent integration areas operated essentially as line flow operations. Since Fall 1991 all production areas have undergone major changes. A pull system utilizing kanban cards has been implemented. Statistical Process Control has been widely applied, and current SPC applications span the range from mature, successful projects to those which accomplish little more than data collection. However, the most drastic change has been the reorganization of common assembly and integration lines into manufacturing villages (22).

EDSG Villages

A village is a product-specific group of machines, tools, stores, test equipment, and personnel located in one common area. Villages are sectioned off from the rest of the common assembly floor space by moveable partitions. As of June 1992 there are 11 villages counting common assembly. The HNVS village is representative of the other
villages in terms of products and operations; this village is described in detail by the
figure and tables in Appendix A.

Figure A.1 shows the physical makeup of the village: machines, tools, stores, test
equipment, and floor space. In addition, it roughly outlines material flow. Table A.2 lists
the village personnel. Finally, Table A.3 lists the processes and capabilities performed or
utilized by the village. This table defines the functional boundaries of the village.

The village concept marks a radical departure from previous operations. Each village is
responsible for all production operations from direct receipt of parts/subassemblies, to
packaging and delivery to the shipper. Even if a village needs to utilize a service, skill, or
machine not contained in the village (for example, certain environmental tests), there is
close coordination between the village and the provider of the outside operation.

Next, the villages must be described in terms of the research. The following section
discusses pertinent village characteristics, and is organized into 7 sections denoted by
italicized headings. These headings are discussed in Chapter 3. At this point we assume
these descriptions are valid for all villages; departures from general trends will be
addressed later.

*Production technology:* Table A.3 lists the fabrication and integration processes
performed in a typical village. Note that very few of the processes have any degree of
automation. Only PCB component kitting and placement, wave solder, and testing are
true exceptions; these three processes are almost 100% automated. However, even
component kitting and placement are occasionally performed manually due to lack of
automated process capacity.
Component kitting and placement is highly flexible; kitting supply reels and programs can be quickly and cheaply changed, and the board placement robots can be reprogrammed at a greater expense. The wave solder unit is not very flexible in its operating parameters (i.e. solder temperature and conveyor speed) but is quite flexible in the types of boards it can process.

EDSG villages historically have not been responsible for maintaining and upgrading production technology. This service has been provided primarily by an Industrial Engineering support group which is shared among all villages. In addition, other common support groups exist: hazardous waste disposal, machine repair, etc.

*Production management techniques:* When EDSG created the villages, the old supervisor and worker roles were basically superimposed on the new factory geography. Since the creation of the villages, however, EDSG has been moving towards implementing a self-directed teemed workforce. To date, the changes include commencing each shift with a team meeting, during which time daily priorities are set, operations are improved or proposed, and problems are addressed. In addition, supervisors are beginning to use visual team management techniques like whiteboard (dry-erase board) scheduling.

EDSG management is truly committed to the teemed workforce concept. Team management training is provided for all supervisors, and will eventually be provided for all workers. Most importantly, EDSG is committed to minimizing layers of management between the teams and top division management.

All product lines now attempt to use lean management techniques such as kanban (or "pull" systems), JIT, and other TQM tools. Management is committed to full
implementation of healthy lean management practices, but these efforts are recent (since Summer 1991) and have not had sufficient time to mature. For example, batch sizes are still experimented with, and when production problems arise old techniques are sometimes used for "fire-fighting." The influence of the old management techniques is significantly affecting the maturity of lean techniques.

In addition, it is meaningful to try and gauge the appropriateness of imposing strict lean techniques in this industry. Productions volumes are small enough that management tools typically used in conjunction with lean manufacturing, like SPC, have little meaning. Also, EDSG's suppliers are not equipped with the skills required to work within a JIT system. These suppliers manufacture mid- to low-volume components which must meet stringent military specifications. Finally, EDSG's customers (namely, the US and other allied militaries) do not typically demand timely product deliveries. For this reason, delivery time flexibility is not addressed in this thesis. JIT may offer EDSG benefits such as reduced inventory costs, but it is doubtful that even these benefits can be obtained since inventory reduction techniques are difficult or impossible to implement in such a low-volume environment.

**Supplier/distributor relationships:** Villages currently receive parts and subassemblies from two sources: internal and external suppliers. The primary internal supplier is common assembly. Since common assembly is close to the end-product villages, PCBs are easily pulled into these villages when dictated by kanbans. External suppliers deliver to a receiving area. This area is responsible for some testing of received units, as well as kitting units into the quantities necessary for use by village assembly personnel. From receiving the parts either go to the production floor or to parts stores.
EDSG hopes to eventually achieve direct delivery of all parts and subassemblies to the villages. Preexisting supplier contracts committed EDSG to bulk-quantity purchases and gave EDSG little or no control over quality, kit sizes, and delivery schedules. As these contracts are gradually phased out, EDSG hopes to achieve its goal of true JIT, inspectionless, pre-kitted delivery of parts to the individual manufacturing villages. Until then receiving, inspection, and parts stores still exist.

EDSG has, over the past year or so, required the suppliers of at least 3 newer product lines to use SPC. This step has been taken in response to customer demands. In addition, EDSG is slowly phasing in SPC requirements for suppliers of older programs.

*Worker training/skills:* The village teams consist almost entirely of workers who were part of the old production system. In addition, village leaders consist primarily of product line managers from the old system. In preparation for EDSG's transition to lean manufacturing, most of these personnel attended seminars given by external consultants. These seminars focused on topics like "employee empowerment" and "working together as a team." Management chose these topics as introductions to new manufacturing practices because "people issues" were identified as critical for a successful transition to lean manufacturing.

During 1991 EDSG made a significant investment in providing modern manufacturing literature and benchmarking information to its employees. However, only certain managers and personnel had exposure to these materials. Furthermore, these personnel received almost no formal training in the concepts and details of pull systems, teamed workforces, and other Total Quality Management techniques. Many personnel sat through the seminars discussed above, but these seminars cannot substitute for rigorous introductions to the new manufacturing techniques EDSG wishes to implement.
EDSG is working hard to produce a formal team framework which will set as policy the company's expectations for village team member performance. In addition, the company intends to formally train all personnel in continuous measurable improvement (cmi) techniques. These techniques include basic Taguchi quality tools as well as company-established standards for documenting and reporting improvements.

*Labor policies:* Hughes employs union production personnel. Historically the union contracts contained large numbers of job classes which were rigorously defined and followed. Only during the last round of negotiations in November 1991 did management and the union come to an agreement; both sides now recognize the need to simplify and generalize union job descriptions, and the last round of negotiations was uniquely facilitated by a third party. Progress is being made — EDSG has downsized from 13,500 personnel in 1990 to 4000 in 1992, and both the union and management are eager to work together to prevent further losses.

Human Resource representatives are leading the charge at simplifying and generalizing factory job descriptions. Great progress has been made, and general cross-village job descriptions should be available within a few months.

While job descriptions become more flexible, tenures or "bumping rights" are still strictly controlled by union rules. This can be detrimental; in the wake of recent layoffs some union personnel were "bumped" into positions for which they had no experience. Such bumping has a serious impact on productivity, since these workers must be retrained.

*Product development process:* There is currently almost no village participation in the product development process. One person is examining the possibility of having village
leaders participate in the concurrent engineering loop within EDSG (i.e. participating in Design for Manufacturability seminars), but so far participation has only consisted of a few production workers. In fact, not everyone within EDSG agrees village representatives should participate in concurrent engineering activities.

Accounting and information systems: EDSG is in the process of phasing out an expensive, "home grown" centralized MRP system. This system requires $5M-$7M per year for operations and upkeep. In addition, the system cannot be modified enough to meet the needs of a lean production system. It was designed to be a decision making tool which produces huge amounts of data; new manufacturing practices in EDSG require a decision support tool capable of efficiently providing specific information.

The replacement system is a distributed MRP2 called TRITON. TRITON runs on IBM PCs, has a graphical interface, and is quite flexible in the kinds of data which it can extract. Data will be stored on a shared HP 9000.

Accounting is also in the process of improving their methods and information systems. They have recognized the need to identify costs concisely and accurately, and are currently searching for ideas and consensus on how to meet this need. Specifically, they are investigating activity-based cost systems.

A Note on Data Collection Methods

Two methods were used to collect data. The first was a set of questionnaires. These questionnaires were distributed to over 100 personnel in EDSG during June 1992. These questionnaires asked for detailed data about EDSG's operations over the 18 months prior to August 1992.
Distribution was designed to direct particular questions to individuals with the most ready access to the requested data. Some questions regarding products and production areas were identical from village to village; other questions pertained to overall operations within EDSG. A collection of all questions is presented in Appendix B. Beside each question appears the job description of the person who received the question. Note that no one individual was asked each question.

Response to the questionnaires was mixed. Some people answered with alacrity, while others felt the study was a low-priority item in their schedules. However, all questionnaires were returned within one month.

The second method of data collection was time spent in the factory, and researching internal records. Between June and August of 1992 I spent approximately 300 hours in the EDSG factory. Production area layouts, test station data, and worker empowerment are examples of data obtained by direct inspection on the factory floor. Time on the factory floor was crucial to fully comprehending production flows and processes.
The flexibility framework used in this study is developed by Suárez et al. in (8). This work offers a thorough discussion on the development and reasoning behind the framework. This chapter merely presents the details of the framework and spends the bulk of its content detailing original metrics and hypotheses.

(8) proposes there are 4 types of flexibility and 7 sources which affect them. These are listed in Table 3.1.

Table 3.1: Sources and types of flexibility.

<table>
<thead>
<tr>
<th>Flexibility Types</th>
<th>Flexibility Sources</th>
</tr>
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<tbody>
<tr>
<td>volume flexibility</td>
<td>production technology</td>
</tr>
<tr>
<td>mix flexibility</td>
<td>production management techniques</td>
</tr>
<tr>
<td>new product flexibility</td>
<td>supplier relationships</td>
</tr>
<tr>
<td>delivery time flexibility</td>
<td>worker training and skills</td>
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<td></td>
<td>labor policies</td>
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<td></td>
<td>product development</td>
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<td>information and accounting systems</td>
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</table>
The following section gives a brief description of each entry in Table 3.1, and describes the metrics used to measure them. Next to each item is a number beginning with either “y” or “u.” These numbers are indices which will be used later in discussing system dynamics. “y” denotes flexibility types, and “u” denotes flexibility sources.

Flexibility Types

(y1) Volume flexibility: the ability to vary the amount of product produced in a given time period. Volume flexibility should not come at the expense of quality or cost, so these factors are included in the metric. The metric is:

\[
VF = \frac{3 \text{ month volume range}}{(\text{reject rate})(\text{standard time} + 1.5(\text{overtime}))}
\]

where three month volume range is the highest monthly production volume minus the lowest monthly production volume in a three month period. The three month period is selected to match the time scale of volume changes in the factory. Reject rate is the fraction of products that fail final test on the first attempt, standard time is the total non-overtime labor hours per product per month, and overtime is the total overtime labor hours per product per month. Overtime is weighted by 1.5 to reflect the fact that overtime wages are 1.5 times standard wages. The reject rate, standard time, and overtime numbers are averaged over the three month period. The metric is calculated monthly as a moving average.
(y2–y5) **Mix flexibility:** the ability to vary the types of products produced in a given time period. In an attempt to capture several aspects of product mix, we use multiple metrics. They are:

- *(y2)* **number of product categories.** Categories are defined by end use. An example is a product called HNVS, which has two versions: one which attaches to a tank, and the other to an F18 aircraft. Thus the HNVS production line qualifies as having two product categories.

- *(y3)* **highest technology level of PCBs.** Technology levels are defined from 1-10, with 10 being the most sophisticated technology. PCB (printed circuit board) engineers created this ranking system. The technology levels are based on 10 boards which are representative of all the PCBs EDSG manufactures. “Highest technology level of PCBs” is the technology level of the most sophisticated circuit board used by a production area.

- *(y4)* **weighted technology level of PCBs.** This quantity is determined by finding the average PCB technology level for each product. An average level is then calculated for the entire production area by weighting these individual product averages by the quantity produced of each product.

- *(y5)* **number of DCIs.** DCI means “deliverable control item,” which is EDSG’s term for final assemblies.
“Number of DCIs” is the number of different final assembly types produced in a month.

(γ6) New product flexibility: the ability to begin production of new products. This is measured by the cycle time of the first unit made for each product. Cycle time is defined as the time (in months) elapsed between release of the WAD (Work Authorization Document), which allows factory retooling to begin, and the date the first unit ships to the customer.

Delivery time flexibility: the ability to meet changing customer delivery schedules. Due to the nature of EDSG’s contracts and customers, delivery time flexibility is probably not important. Thus, it is reasonable to suspect that we will not observe utilization of this flexibility type. For this reason delivery time flexibility is ignored.

Flexibility Sources

(u1–u10) Production technology: the hardware and software technology utilized in production. The vast majority of operations performed in EDSG are assembly and test operations. The vast majority of assembly is performed by hand. Thus, the only real equipment (besides hand tools) consists of test stations. Test station technology is measured by multiple quantities:

•(u1–u3) Test station automation. This is divided into three categories: test station loading, operation, and unloading. Each category receives a 1-3 ranking: 1=manual, 2=semi-automatic (some worker assistance required), 3=automatic. All test stations are rated in the three categories, then
average rates for the production area test stations are calculated.

•(u4) **test station age.** The average age for all test stations in a production area. Age is ranked from 1-4, with 1 being the oldest. 1=over 9 years old, 2=6-9 years old, 3=3-6 years old, 4=0-3 years old.

•(u5–u8) **test station technology level.** A 1-4 ranking based on software, hardware, and user interface characteristics. 4 is the highest technology. See the questionnaire in Appendix C for a detailed listing of these characteristics. We calculate an average for each production area.

•(u9) **generic test stations.** A 0 or 1 ranking. 0 means the test station can only test one product, and 1 means the station can test more than one product. We calculate an average for each production area.

•(u10) **TDP difficulty.** TDP means “Test Data Package.” This is the document given to the test station designers. It contains all the specifications for test stations associated with a specific product. Test station designers created a 1-6 ranking system, with 6 being the most difficult. A difficult TDP requires sophisticated, higher technology test stations.
Note that all these test station metrics are averaged for each production area. There is not enough data to factor in each station as an independent flexibility source, so the average values are used.

(*ul 1–20) Production management techniques: the various methods used to manage the factory. These methods include things like machine maintenance, inventory policy, management structure, and worker autonomy. These four items are measured as follows:

• *(u11) average runtime. The average runtime, in minutes, of test stations in each production area.

• *(u12) average setup time. The average setup time of test stations in each production area. Setup time is calculated as a percentage of runtime.

• *(u13) average downtime. The average downtime of test stations in each production area. Calculated as a percentage of runtime.

• *(u14) total inventory. Total inventory, in dollars, in each production area. Total inventory includes WIP (Work-in-Progress), rework, returns from customers, parts stores, and finished goods.

• *(u15) number of management levels. The number of levels from factory worker supervisor to project manager.
•(u16–u20) worker empowerment. Five aspects of worker empowerment and autonomy are ranked from 1-5 by production area workers. We average these responses. For the exact wording of the questions, see the questionnaire in Appendix C.

(u21-25) Supplier relationships: the formal and informal (contractual and noncontractual) means which EDSG uses to interact with part suppliers. Again, we use a multidimensional metric:

•(u21) supplier on-site hours. This is the number of hours each month that suppliers of a certain production area spend at EDSG. The idea is that more supplier on-site hours result in better-developed parts, quality methods, and delivery strategies.

•(u22) EDSG off-site hours. This is the number of hours each month that EDSG personnel spend at supplier sites. The idea is that more EDSG off-site hours result in better-developed parts, quality methods, and delivery strategies.

•(u23) percent of subassemblies subcontracted. Subcontracted subassemblies are delivered pre-assembled from suppliers. Non-subcontracted subassemblies are built within EDSG.
• (u24) **percent of suppliers using SPC.** Military electrical components must meet rigorous quality standards. Typically, supplier components have a 10% reject rate when tested at EDSG. SPC (Statistical Process Control) can help decrease reject rates.

• (u25) **number of suppliers.** The number of different external sources which supply parts to a production area.

(u26–u27) **Worker training/skills:** the amount and type of training offered to workers. Two types of training are measured: (u26) **number of hours of team training,** offered to worker groups, and (u27) **number of hours of individual training,** offered to individual workers. Both metrics are cumulative over the time period we examine, and are measured monthly.

(u28–u30) **Labor policies:** the contracts and policies regarding workers and their job descriptions. EDSG employs workers from two unions: EST (Electronic and Space Technicians), and IEEJ (Industrial Electronics Electrician Journeymen). The current union contracts are valid from 2 November 1991 to 5 November 1994. We measure two aspects of these contracts, the total number of job categories in EDSG, called (u28) **number of jobs overall,** and the actual number of job categories in each production area, called (u29) **number of jobs in village.** These number are in flux during the data collection period due to contract renegotiations. In addition, we measure the monthly ratio of overtime hours to standard hours. Hours are the total hours for all production area workers. This metric is called (u30) **OT/ST.**
(u31–u32) **Product development:** the product development process as reflected by the complexity of products, and difficulty of assembly. The metrics are:

- **(u31) technology content of DCIs.** This is essentially the amount of technology crammed into final products. It is calculated by multiplying the average technology level of each DCI by the DCI density (kg/cm³). We use an average value for all DCIs in a production area. This average is weighted by the number of each DCI produced.

- **(u32) work content of DCIs.** This is the amount of labor in each DCI, weighted by the DCI technology level. It is calculated by multiplying the average technology level of each DCI by touch hours. Touch hours are the number of hours factory workers spend performing operations on the DCI. We use an average value for all DCIs in a production area. This average is weighted by the number of each DCI produced.

(u33–u34) **Information/accounting systems:** the systems used to handle inventory, scheduling, financial, and other factory data. Unfortunately, most contracts require separate information systems, which are often “home-grown” and unique. It is difficult to construct meaningful metrics which can fairly be applied to all such systems. However, all production areas utilize MRP (Materials Requirement Planning). In addition, it is anticipated that during the data collection period, production areas will switch to an MRP2 system. We hope to isolate this switch as a factor which influences flexibility. Thus, the metrics are:
• **MRP in use.** This metric takes a value of 1 (yes) or 0 (no).

• **MRP2 in use.** This metric takes a value of 1 (yes) or 0 (no).

It is important to note that all metrics are calculated monthly during the data collection period (18 months).

**Hypotheses**

The next step is to develop hypotheses using the Suárez framework. These hypotheses concern the relationships between metrics and flexibility types. Hypotheses must describe: 1) the direction of relationships (i.e., if metric goes down flexibility goes up); and 2) the magnitude of effects.

The remainder of this chapter is organized into three sections, one for each flexibility type investigated in the study (the reasons for excluding delivery time flexibility are discussed in Chapter 2). Within each section, all source factors and metrics are listed along with hypothesized effects on the flexibility type. These effects include the expected direction of influence (positive or negative), as well as magnitudes (small, large, etc.). Brief explanations follow each hypothesis set.

In some cases hypotheses are supported by correlations run on preliminary data. These results are shown where appropriate.
**Volume Flexibility Hypotheses**

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production Technol</strong></td>
<td>automation level</td>
<td>-</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>equipment age</td>
<td>+</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>TS technology level</td>
<td>-</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>generic equipment</td>
<td>+</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>TDP difficulty</td>
<td>-</td>
<td>small</td>
</tr>
</tbody>
</table>

To formulate these hypotheses, we need to know if newer test stations are faster or slower, since faster test stations can produce at higher rates. Such increases in throughput can be exploited to achieve volume flexibility. We find out by correlating test station age with [test time, downtime, and setup time], or in other words age and throughput. From the following correlation matrix in Figure 3.1, we see that newer test stations tend to have lower throughputs; since newer stations also tend to utilize higher technology, we hypothesize that production technology has a negative effect on volume flexibility. Also, the time spent at test stations (called “touch time”) is a small percentage of cycle time (see Table 3.2) so faster stations shouldn’t have a large effect on volume flexibility. Thus we hypothesize small magnitudes.
<table>
<thead>
<tr>
<th>Tput</th>
<th>TS age</th>
<th>Setup/run</th>
<th>Down/run</th>
<th>Runtime</th>
<th>Automat</th>
<th>TS tech level</th>
<th>generic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.4952</td>
<td>.1515</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS age</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Setup/run</td>
<td>.9003</td>
<td>.2282</td>
<td>.7388</td>
<td>-1.518</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Down/run</td>
<td>-.2944</td>
<td>-.7819</td>
<td>.2377</td>
<td>-.0264</td>
<td>.1025</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Runtime</td>
<td>-.7939</td>
<td>-.9543</td>
<td>-.3258</td>
<td>.0778</td>
<td>.4633</td>
<td>.7583</td>
<td>1</td>
</tr>
<tr>
<td>Automat</td>
<td>-.0648</td>
<td>-.7819</td>
<td>.2377</td>
<td>-.0264</td>
<td>.1025</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>TS tech level</td>
<td>-.641</td>
<td>-.9543</td>
<td>-.3258</td>
<td>.0778</td>
<td>.4633</td>
<td>.7583</td>
<td>1</td>
</tr>
<tr>
<td>generic</td>
<td>.3662</td>
<td>.4002</td>
<td>-.773</td>
<td>-.2788</td>
<td>.0117</td>
<td>-.0003</td>
<td>1</td>
</tr>
<tr>
<td>TDP</td>
<td>-.6933</td>
<td>-.6527</td>
<td>.558</td>
<td>-.2297</td>
<td>.7098</td>
<td>.5262</td>
<td>.8355</td>
</tr>
</tbody>
</table>

**Figure 3.1:** Correlations of test station metrics.

**Table 3.2:** Time at test stations (touch time) as a fraction of total production cycle time, calculated for the six fiscal quarters of data collection. Reductions in touch time will have little impact on total cycle time, and thus little impact on throughput.

<table>
<thead>
<tr>
<th>Village/Quarter</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
<th>Q6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPCU DC11</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0004</td>
<td>0.0005</td>
</tr>
<tr>
<td>CPCU DC12</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.0003</td>
<td>0.0004</td>
</tr>
<tr>
<td>EN6 DC11</td>
<td>0.0010</td>
<td>0.0013</td>
<td>0.0019</td>
<td>0.0036</td>
<td>0.0090</td>
<td>0.0045</td>
</tr>
<tr>
<td>HNVS DC11</td>
<td>0.0021</td>
<td>0.0024</td>
<td>0.0028</td>
<td>0.0039</td>
<td>0.0038</td>
<td>0.0080</td>
</tr>
<tr>
<td>HNVS DC12</td>
<td>0.0021</td>
<td>0.0024</td>
<td>0.0028</td>
<td>0.0039</td>
<td>0.0038</td>
<td>0.0080</td>
</tr>
<tr>
<td>LRF DC11</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>TRU DC11</td>
<td>0.0001</td>
<td>0.0001</td>
<td>NA</td>
<td>NA</td>
<td>0.0002</td>
<td>0.0003</td>
</tr>
<tr>
<td>TOW DC11</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>TOW DC12</td>
<td>0.0110</td>
<td>0.0220</td>
<td>0.0323</td>
<td>0.1969</td>
<td>0.3376</td>
<td>0.6154</td>
</tr>
<tr>
<td>TOW DC13</td>
<td>0.0075</td>
<td>0.0149</td>
<td>0.0338</td>
<td>0.2063</td>
<td>0.2767</td>
<td>0.4457</td>
</tr>
<tr>
<td>TOW DC14</td>
<td>0.0134</td>
<td>0.0268</td>
<td>0.0343</td>
<td>0.2092</td>
<td>0.4105</td>
<td>0.6614</td>
</tr>
<tr>
<td>HIRE DC11</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Some points of interest from Figure 3.1 and Table 3.2:

- Touch/cycle time is small, thus faster TS should have a small effect on volume flexibility
- Expected magnitude of automation level effects is almost 0
- Sign of automation level, equipment age, and TS technology effects is not what I expected
- New TS display higher technology levels
- New TS are more highly automated
- New TS have harder TDPs
- Generic TS have less downtime
- Harder TDPs mean longer runtimes
- High technology levels and automation appear together
- High technology and difficult TDPs go together

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Mgmt</td>
<td>setup time</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>downtime</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>inventory levels</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td># management levels</td>
<td>-</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>worker empowerment</td>
<td>-</td>
<td>med</td>
</tr>
</tbody>
</table>

The response to all these metrics might be dominated by the "learning curve" effect. For example, when a new product is introduced to a village it may take time for inventory levels and throughput rates on test stations to "settle" since the workers, teams, and managers are adjusting and learning. Note that production management techniques are expected to have the largest effect on volume flexibility during demand peaks and/or near
capacity. Away from these operating conditions, effects should be small. This is due to the fact that at low production volumes, setups and downtimes do not place any constraints on throughput—machine operations are being constrained due to lack of demand.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier Relations</td>
<td>supplier on-site hours</td>
<td>+</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>HAC off-site hours</td>
<td>+</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>% S/A subcontracted</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>% suppliers using SPC</td>
<td>+</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td># suppliers</td>
<td>+</td>
<td>med</td>
</tr>
</tbody>
</table>

These metrics are grouped in the comment column as "contact" metrics or "extent" metrics. "Contact" refers to the quality or intimacy of supplier relationships, while "extent" refers to the quantity of relationships. "Contact" should allow fluctuation in batch sizes since supplier relations should be close and friendly. At or near capacity, "extensive" relationships means there may be other suppliers to take up slack when primary suppliers can't meet demand. Thus, all metrics are hypothesized to have a positive effect on volume flexibility.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Policies</td>
<td># overall job categories</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td># village jobs</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>overtime/straight time</td>
<td>-</td>
<td>large</td>
</tr>
</tbody>
</table>
Increasing the number of union job categories is equivalent to increasing the specialization of each job. Higher job specialization should translate into higher attainable production rates, although higher specialization means it may be cost-ineffective to run at lower volumes (even though it is possible to do so). Thus the number of jobs is hypothesized to have a positive effect on volume flexibility. Premium/straight time is basically a measure of how overloaded the workforce is, since the presence of second or third shift workers would mitigate the need for overtime on any one shift. As this ratio gets larger the workforce is more overloaded with tasks, leaving less room to increase production volume. OT/ST is hypothesized to have a negative effect on volume flexibility.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skills &amp; Training</td>
<td>hours training/worker</td>
<td>+</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>hours training/team</td>
<td>+</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>educational level</td>
<td>+</td>
<td>large</td>
</tr>
</tbody>
</table>

Consider the types of training offered to EDSG hourlies: SPC, team skills, empowerment, etc. Theoretically this training should make employees more productive, but the effects of things like “team skills” on production rates is probably slight. SPC techniques should noticeably help, especially on low yield products like EN6, but EDSG simply does not produce enough of any item in a short enough period of time to warrant true SPC. Educational level should have some "threshold" where further education isn't much help — a college education won't provide many advantages for an hourly board assembler, but knowing how to read well is essential. Some workers simply match pictures on assembly packages instead of reading directions (for example, LRF village) and this has serious consequences. Unfortunately, educational data is almost impossible to obtain.
<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Devel</td>
<td>technological content</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>work content</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>component density</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Technological content and component density should have similar negative effects on volume flexibility. Both concern "amount of stuff" crammed into specific products. The more "stuff" one has, and the smaller and more complex the "stuff" is, the more difficult it is to assemble and test the product, thus constraining volume flexibility by requiring high skills and expensive test stations. Work content, when weighted by the complexity of what's being assembled, reflects the complexity of the product --- small, complicated parts simply take longer to assemble and test (as for tech. content and component density). In some ways, work content is "predicted" by those other two measurements. This is supported by the correlations in Figure 3.2. This will give an idea of "goodness" of tech content and component density metrics. Note that strong production technology can compensate for complex products; in other words, assembly and test of complex products is easier with good test stations. Thus, effects of product development should be small, especially on programs with newer stations.

<table>
<thead>
<tr>
<th>PCB tech level</th>
<th>TS runtime</th>
<th>PCB work content</th>
<th>PCB tech content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.6592</td>
<td>.8968</td>
<td>.262</td>
</tr>
<tr>
<td>TS runtime</td>
<td>1</td>
<td>.8524</td>
<td>-.2367</td>
</tr>
<tr>
<td>PCB work content</td>
<td>.8968</td>
<td>1</td>
<td>.0887</td>
</tr>
<tr>
<td>PCB tech content</td>
<td>.262</td>
<td>-.2367</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 3.2:** Product development correlations.
Some points of interest from Figure 3.2:

- Products containing high technology have high work content.
- Products containing high technology have longer runtimes.
- There is a weak correlation between products containing high technology and those with high technology density.
- Products with long runtimes have high work content.
- Products with high technology density have almost no correlation to products with high work content.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Info Systems</td>
<td>MRP in use</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>MRP2 in use</td>
<td>+</td>
<td>med</td>
</tr>
</tbody>
</table>

Learning curve involved stronger effect than MRP

Better planning should allow planners to construct a wider variety of schedules, thus increasing volume flexibility. MRP2 should facilitate better planning.
Mix Flexibility Hypotheses

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Technol</td>
<td>automation level</td>
<td>-</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>equipment age</td>
<td>-</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>technology level</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>generic equipment</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>TDP difficulty</td>
<td>-</td>
<td>med</td>
</tr>
</tbody>
</table>

According to Figure 3.1, highly automated test stations are not necessarily dedicated to certain products (automation vs. generic). In addition, new test station technology does not necessarily include generic stations with flexible programs and hardware, which are easily configured for changeovers (age vs. generic). Automation level and equipment age are thus hypothesized to have small but negative effects on mix flexibility.

Technology level of the test stations takes into account BIT (Built In Test), auto calibration, VXI interfaces, and menu interfaces which all increase "adaptability" of the stations to different products. Generic stations are adaptable to different products by definition. Thus, both these metrics are hypothesized to have positive effects on mix flexibility. However, the highest technology programs (like EN6) are usually required by contract to use highly specialized test equipment which is difficult to produce. These programs have difficult TDPs, so the predicted effect of TDP difficulty is negative.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Mag</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Mgmnt</td>
<td>setup time</td>
<td>-</td>
<td>med</td>
</tr>
</tbody>
</table>
downtime + small small magnitude at best
inventory levels - med
# management levels - med learning curve involved
worker empowerment + med learning curve involved

Test stations with short setup times have quicker changeovers, so mix flexibility should increase as setup times decrease. From Figure 3.1 we see that downtime correlates negatively with generic test station designs. Since generic designs facilitate mix flexibility, we hypothesize that downtime has a negative relationship with mix flexibility.

As inventory levels go up, there is more "inertia" in the production pipeline; it becomes difficult to introduce new products. Inventory should be negatively related to mix flexibility. As the number of management levels goes down and worker empowerment increases, workers should become accustomed to tackling tasks like learning how to make unfamiliar products. Thus, the number of management levels is hypothesized to be negatively related to mix flexibility, and worker empowerment is hypothesized to be positively related to mix flexibility.

As a point of interest, we note that there is no correlation between worker empowerment and number of management levels (R = -0.05). Perhaps this suggests that in villages with high empowerment, the attitude and technique of managers is much more important than the number of management layers.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier Relations</td>
<td>supplier on-site hours  + large</td>
<td>&quot;contact&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HAC off-site hours      + large</td>
<td>&quot;contact&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% S/A subcontracted     + med</td>
<td>&quot;extent&quot;</td>
<td></td>
</tr>
</tbody>
</table>
% suppliers using SPC + large "contact"
# suppliers + med "extent"

"Contact" facilitates good relationships, which allows small and varying lot sizes to be negotiated. This allows for small EOQ and easy changeovers. Mix flexibility should be positively affected. "Extent" provides more suppliers to choose from, and consequently a wider range of components for different products. Mix flexibility should be positively affected.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Policies</td>
<td># overall job categories</td>
<td>- med</td>
<td>learning curve</td>
</tr>
<tr>
<td></td>
<td># village jobs</td>
<td>- med</td>
<td>learning curve</td>
</tr>
<tr>
<td></td>
<td>premium/straight time</td>
<td>0 tiny</td>
<td>at best</td>
</tr>
</tbody>
</table>

As the number of jobs increases, worker specialization increases. This hinders the ability of workers to switch between tasks associated with different products. Mix flexibility should decrease as number of jobs increases. Premium/straight time is basically a measure of how overloaded the workforce is, since the presence of second or third shift workers would mitigate the need for overtime on any one shift. It is not clear that being overloaded has anything to do with the ability to switch tasks.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skills &amp; Training</td>
<td>hours training/worker</td>
<td>+ med</td>
<td>learning curve</td>
</tr>
<tr>
<td></td>
<td>hours training/team</td>
<td>+ med</td>
<td>learning curve</td>
</tr>
<tr>
<td></td>
<td>educational level</td>
<td>+ large</td>
<td>threshold</td>
</tr>
</tbody>
</table>
The team training the EDSG workers receive may be useful in facilitating frequent redefinition of general job categories. This ability to be flexible in worker tasks enhances mix flexibility. Educational level should have some "threshold" where further education isn't much help — a college education won't provide many advantages for an hourly board assembler, but knowing how to read well is essential to being task-flexible.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Devel</td>
<td>technological content</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>work content</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>component density</td>
<td>-</td>
<td>large</td>
</tr>
</tbody>
</table>

It is difficult to design test fixtures and software for products with high technological content and component density. This fact results in dedicated test stations which cannot be shared easily among products. We hypothesize that technological content negatively affects mix flexibility. Work content, when weighted by the complexity of what's being assembled, reflects the complexity of the product — small, complicated parts simply require more effort to assemble and test. This can be seen in Figure 3.3. Suárez (18) utilizes a “reusability” metric for mix flexibility to try and capture the effects of having high commonality of parts between products. However, this type of metric is not appropriate for this study since common components are almost never used within EDSG. This is typical for defense contract work.
<table>
<thead>
<tr>
<th>TS tech level</th>
<th>runtime</th>
<th>work content</th>
<th>PCB tech content</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS tech level</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>runtime</td>
<td>.6592</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>work content</td>
<td>.8968</td>
<td>.8524</td>
<td>1</td>
</tr>
<tr>
<td>PCB tech content</td>
<td>.262</td>
<td>-.2367</td>
<td>.0887</td>
</tr>
</tbody>
</table>

Figure 3.3: Product development metric correlations.

Some points of interest from Figure 3.3:

• Products containing high technology have high work content
• Products containing high technology have longer runtimes
• There is a weak correlation between products containing high technology and those with high technology density
• Products with long runtimes have high work content
• Products with high technology density have no correlation to products with high work content

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Info Systems</td>
<td>MRP I in use + med</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MRP II in use + med</td>
<td></td>
<td>larger mag than MRP I</td>
</tr>
</tbody>
</table>

More accurate scheduling should allow more latitude in mix decisions.
New Product Flexibility Hypotheses

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Technol</td>
<td>automation level</td>
<td>-</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>equipment age</td>
<td>-</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>technology level</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>generic equipment</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>TDP difficulty</td>
<td>-</td>
<td>med</td>
</tr>
</tbody>
</table>

According to Figure 3.1, highly automated test stations are not necessarily dedicated to certain products (automation vs. generic). In addition, new test station technology does not necessarily include generic stations with flexible programs and hardware, which are easily configured for changeovers (age vs. generic). Automation level and equipment age are thus hypothesized to have small but negative effects on mix flexibility.

Test station technology metrics take into account BIT (Built In Test), auto calibration, VXI interfaces, and menu interfaces which all increase "adaptability" of the stations to different products. Generic stations are adaptable to different products by definition. Thus, both these metrics are hypothesized to have positive effects on mix flexibility. However, the highest technology programs (like EN6) are usually required by contract to use highly specialized test equipment which is difficult to produce. These programs have difficult TDPs, so the predicted effect of TDP difficulty is negative.
<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production Mgmt</strong></td>
<td>setup time</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>downtime</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>inventory levels</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td># management levels</td>
<td>-</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>worker empowerment</td>
<td>+</td>
<td>med</td>
</tr>
</tbody>
</table>

Test stations with short setup times have easier changeovers, so new product flexibility should increase as setup times decrease. From Figure 3.1 we see that downtime correlates negatively with generic test station designs. Since generic designs also facilitate changeovers, we hypothesize that downtime has a negative relationship with new product flexibility.

As inventory levels go up, there is more "inertia" in the production pipeline; it becomes difficult to introduce new products. Inventory should be negatively related to new product flexibility. As the number of management levels goes down and worker empowerment increases, workers should become accustomed to tackling tasks like learning how to make unfamiliar products. Thus, the number of management levels is hypothesized to be negatively related to new product flexibility, and worker empowerment is hypothesized to be positively related to this flexibility.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supplier Relations</strong></td>
<td>supplier on-site hours</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>HAC off-site hours</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>% S/A subcontracted</td>
<td>+</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>% suppliers using SPC</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td># suppliers</td>
<td>+</td>
<td>large</td>
</tr>
</tbody>
</table>
“Contact” facilitates good relationships, which allows small and varying lot sizes to be negotiated. This allows for small EOQ and easy changeovers. New product flexibility should be positively affected. “Extent” provides more suppliers to choose from, and consequently a wider range of components for different products. New product flexibility should be positively affected.

<table>
<thead>
<tr>
<th>Source Factor</th>
<th>Metrics &amp; Expected Sign</th>
<th>Magnitude</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Policies</td>
<td># overall job categories</td>
<td>med</td>
<td>learning curve</td>
</tr>
<tr>
<td></td>
<td># village jobs</td>
<td>med</td>
<td>learning curve</td>
</tr>
<tr>
<td></td>
<td>premium/straight time</td>
<td>0</td>
<td>tiny at best</td>
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As the number of jobs increases, worker specialization increases. This hinders the ability of workers to switch between new tasks associated with new products. New product flexibility should decrease as number of jobs increases. Premium/straight time is basically a measure of how overloaded the workforce is, since the presence of second or third shift workers would mitigate the need for overtime on any one shift. It is not clear that being overloaded has anything to do with the ability to learn new tasks.

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<tr>
<td></td>
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<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>educational level</td>
<td>+</td>
<td>large</td>
</tr>
</tbody>
</table>

The team training the EDSG workers receive may be useful in facilitating frequent redefinition of general job categories. This ability to be flexible in worker tasks should enhance new product flexibility, since workers can more easily adapt to new tasks.
associated with new products. Educational level should have some "threshold" where further education isn't much help — a college education won't provide many advantages for an hourly board assembler, but knowing how to read well is essential to being task-flexible.

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<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>work content</td>
<td>-</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>component density</td>
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<td>large</td>
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It is difficult to design test fixtures and software for products with high technological content and component density. This fact results in dedicated test stations which cannot be shared easily among new and different products. We hypothesize that technological content negatively affects new product flexibility. Work content, when weighted by the complexity of what's being assembled, reflects the complexity of the product — small, complicated parts simply require more effort to assemble and test. This can be seen in Figure 3.3 in the previous section.

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<tbody>
<tr>
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<td>MRP I in use</td>
<td>+</td>
<td>med</td>
</tr>
<tr>
<td></td>
<td>MRP II in use</td>
<td>+</td>
<td>med</td>
</tr>
</tbody>
</table>

More accurate scheduling should make it easier to introduce new products.
A Note on The Hypotheses

There is quite a bit of similarity between the mix flexibility and new product flexibility hypotheses. In fact, the expected signs of effects are identical for all source factor metrics.

Perhaps mix flexibility is similar to new product flexibility but on a much shorter time scale. The difference comes down to the difference between changeovers (mix flexibility) and full-scale retooling/retraining (new product flexibility). Changeovers by definition mean retooling for a product which has been produced before. Learning curve effects will be smaller and shorter in duration than for true retooling.

The Next Steps

With a flexibility framework, metrics, and data in hand, the next step is analysis. Analysis consists of two steps. First, relevant data must be extracted from the complete data set. The data set can be thought of as a matrix: each row corresponds to data from one metric for a flexibility source or type. These rows are time series since metrics are calculated monthly for 18 months. The system identification technique requires these rows to be linearly independent, or in other words, the matrix must have full rank.

The total data matrix does not have full rank. Therefore, we must extract as many independent rows as possible. This is accomplished by using the Juricic algorithm described in Appendix D.

Second, this partial data matrix must be analyzed using system identification techniques.
This is performed using the Goodwin algorithm code presented in Appendix D. The mathematical foundations of this code are developed in Appendix C.
Results can be grouped into three categories. First, the Juricic algorithm identifies input and output data matrices for each village. These data matrices are subsets of the entire data matrix. Second, these data matrices are fed to the system identification algorithms, which return flexibility model parameters. Error analysis yields a third set of results, but this is discussed in Chapter 5 with the simulations.

Juricic Algorithm Results

The entire raw data matrix for each village, complete with fully dependent timeseries, is fed into the Juricic algorithm. Before running the algorithm the ranks of the raw data matrices are determined using the stock MATLAB routine “rank” (25). These ranks are used to limit the number of iterations of the algorithm.

Table 4.1 shows the ranks of all raw data matrices under the “Rank” column. Output sets from the Juricic algorithm are listed under “Use Rows.” Sets in this column are ordered as follows: the first entry is the row index chosen to seed the algorithm. The other entries are given in order of decreasing linear independence with the seed row.
Table 4.1: Village input/output data matrix ranks and results from Juricic algorithm.

<table>
<thead>
<tr>
<th>Village Input (u) or Output (y)</th>
<th>Rank</th>
<th>Use Rows</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPCu</td>
<td>8</td>
<td>14, 22, 27, 25, 28, 32, 30, 31</td>
</tr>
<tr>
<td>CPCy</td>
<td>4</td>
<td>1, 6, 3, 4</td>
</tr>
<tr>
<td>EN6u</td>
<td>7</td>
<td>14, 32, 28, 22, 27, 29, 30</td>
</tr>
<tr>
<td>EN6y</td>
<td>3</td>
<td>1, 6, 3</td>
</tr>
<tr>
<td>HIREu</td>
<td>6</td>
<td>UNRESOLVABLE</td>
</tr>
<tr>
<td>HIREy</td>
<td>0</td>
<td>UNRESOLVABLE</td>
</tr>
<tr>
<td>HNVSu</td>
<td>8</td>
<td>14, 32, 28, 27, 22, 31, 13, 30</td>
</tr>
<tr>
<td>HNVSy</td>
<td>3</td>
<td>1, 6, 4</td>
</tr>
<tr>
<td>LRFu</td>
<td>8</td>
<td>14, 22, 25, 28, 27, 26, 32, 30</td>
</tr>
<tr>
<td>LRFy</td>
<td>4</td>
<td>1, 6, 3, 5</td>
</tr>
<tr>
<td>TOWu</td>
<td>7</td>
<td>14, 32, 11, 28, 15, 30, 31</td>
</tr>
<tr>
<td>TOWy</td>
<td>3</td>
<td>1, 6, 4</td>
</tr>
<tr>
<td>TRUu</td>
<td>7</td>
<td>14, 22, 25, 27, 28, 30, 32</td>
</tr>
<tr>
<td>TRUy</td>
<td>4</td>
<td>1, 6, 5, 3</td>
</tr>
</tbody>
</table>

Results are extremely robust; when *any* of the entries under "Use Rows" is used to seed the algorithm, set membership is unchanged. Furthermore, set ordering is usually preserved within 1 entry (excluding the seed index).

Unfortunately the output data matrix for the HIRE village is totally rank-deficient. In the table above, the HIRE matrices are labeled as unresolvable since the system identification algorithms will be unable to find input/output relationships.

It is interesting to note at this point that four inputs are identified as common to all villages: 14 (total village inventory), 28 (number of overall jobs in union), 32 (work
content of DCIs), and 30 (overtime hours/standard hours). Two outputs are common to all villages: 1 (volume flexibility) and 6 (first unit cycle time).

Two additional inputs are common to most villages: 22 (EDSG@supplier hours/month) and 27 (cumulative team training hours). Finally, two additional outputs are common to most villages: 4 (weighted technology level of PCBs) and 3 (highest technology level of PCBs).

Goodwin Algorithm Results

Assuming all dynamics are first order (we are forced to make this assumption due to lack of data) and assuming there are no delays, the Goodwin Algorithm returns parameters which estimate the flexibility system dynamics. Unfortunately these parameters are uninteresting; the systems display no dynamic behavior. This can be seen in a Bode plot constructed from Goodwin-generated parameters for the CPCU village in Figures 4.1a–4.1d. These figures show input/output dynamics (or lack thereof) for the 4 Juricic-generated outputs and 8 inputs.

These Bode plots typify the other villages. No dynamics were found in any case, so other plots are not presented.

In mathematical terms, we are creating models of the form:

\[
\frac{y}{u} = G(s) = \begin{bmatrix}
g_1(s) & \ldots & g_{10}(s) \\
\vdots & \ddots & \vdots \\
g_1(s) & \ldots & g_{10}(s)
\end{bmatrix}
\]
where

\[ g_u = \frac{b_{0u}}{a_{0u}s + a_{0y}} \]

\( G(s) \) is a multi-input/multi-output (MIMO) transfer function matrix, with elements \( g_{ij}(s) \).

In all our models we find \( a_{1ij} = 0.000 \).
Figure 4.1a: CPCU village Bode plot, $y_1$ (volume flexibility) vs. all Juricic inputs. There is a slight curve up at higher frequencies which is reminiscent of an approach to a second-order resonant frequency; however, we are using first-order models. The curve is due to sampling frequency effects. This effect is also seen in Figures 4.1b – 4.1d.
Figure 4.1b: CPCU village Bode plot y3 (highest technology level of PCBs) vs. all Juricic freats.
Figure 4.1c: CPCU village Bode plot, y4 (weighted technology output level) vs. all Juricic inputs.
Figure 4.1d: CPCU village Bode plot, y6 (WAD-to-first unit cycle time) vs. all Juricic inputs. Sampling effects are quite pronounced in this plot.
Despite the lack of dynamics, the Goodwin algorithm returns model parameters which are more or less analogous to multivariable regression coefficients. The only real difference is that the algorithm minimizes a loss function rather than least squares. Nevertheless, the parameters can safely be conceptualized as first-order coefficients.

Tables 4.2 – 4.7 list these coefficients for the 6 resolvable villages. Individual village coefficients are generated by using data from all 18 time steps. This table also uses three-quarters of all data points, or 81 out of 108 time steps (18 time steps per 6 villages), to create one aggregate model. Note that this requires stringing all the villages' timeseries together, end-to-end. We can do this because we have already demonstrated a lack of dynamics within villages; mixing the order of timesteps does not sacrifice any system information.

Coefficients are grouped by flexibility output rather than village. This is to allow for easy comparison of results across villages. Where there are blank entries, the Juricic algorithm does not indicate this input should be used. Lightly shaded rows that begin with "NA" means the Juricic algorithm does not indicate this output should be used.

Any row beginning with "rank-def" lacks significant richness of data to give meaningful parameters. Such rows are not strictly rank-deficient, but parameters returned by the Goodwin algorithm are zero to three decimal places. Finally, note that the 81-point model uses all inputs. This is because over 81 steps all raw data matrices are full rank. However, many parameters are returned as zero (at least to three decimal places).
<table>
<thead>
<tr>
<th>VILLUM #</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>26</th>
<th>27</th>
<th>30</th>
<th>31</th>
<th>32</th>
<th>33</th>
<th>34</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Table 4.3:** Model Parameter Summary for Y2 (number of product categories)
<table>
<thead>
<tr>
<th></th>
<th>000'0</th>
<th>000'0</th>
<th>000'0</th>
<th>000'0</th>
<th>0130</th>
<th>0'303</th>
<th>0'037</th>
<th>0'0118</th>
<th>0'125</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
<th>0'118</th>
</tr>
</thead>
<tbody>
<tr>
<td>0'000</td>
<td>TOW</td>
<td>TOW</td>
<td>TOW</td>
<td>TOW</td>
<td>TOW</td>
<td>TOW</td>
<td>TOW</td>
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<td>TOW</td>
<td>TOW</td>
</tr>
<tr>
<td>0'000</td>
<td>LRF</td>
<td>LRF</td>
<td>LRF</td>
<td>LRF</td>
<td>LRF</td>
<td>LRF</td>
<td>LRF</td>
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<tr>
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<td>HNV</td>
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<td>HNV</td>
<td>HNV</td>
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<td>HNV</td>
</tr>
<tr>
<td>0'000</td>
<td>ENG</td>
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<td>ENG</td>
<td>ENG</td>
<td>ENG</td>
<td>ENG</td>
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<td>ENG</td>
<td>ENG</td>
<td>ENG</td>
<td>ENG</td>
</tr>
<tr>
<td>0'000</td>
<td>CPCU</td>
<td>CPCU</td>
<td>CPCU</td>
<td>CPCU</td>
<td>CPCU</td>
<td>CPCU</td>
<td>CPCU</td>
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</tbody>
</table>

| 0'000 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 | 0'037 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0'037 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 | 0'082 |
| 0'082 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 | 0'142 |
| 0'142 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 | 0'228 |
| 0'228 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 | 0'339 |

**TABLE 4.7:** Model Parameter Summary for y6 (WAD-to-first unit cycle time).
Table 4.8 summarizes the 81-point aggregate model parameters in one additional way; it lists the top 5 most important source factors for each flexibility type. This table becomes especially interesting when it is used to compare important source factors across flexibility types. This will be discussed in greater detail in Chapter 6.

**Table 4.8:** Top 5 most important source factors for each flexibility type in the 81-point aggregate model. $y =$flexibility type, $u =$flexibility source.

<table>
<thead>
<tr>
<th>Rank</th>
<th>$y_1$</th>
<th>$y_2$</th>
<th>$y_3$</th>
<th>$y_4$</th>
<th>$y_5$</th>
<th>$y_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>u30</td>
<td>u19</td>
<td>u19</td>
<td>u30</td>
<td>u30</td>
<td>u30</td>
</tr>
<tr>
<td>2</td>
<td>u13</td>
<td>u24</td>
<td>u24</td>
<td>u13</td>
<td>u13</td>
<td>u13</td>
</tr>
<tr>
<td>3</td>
<td>u19</td>
<td>u22</td>
<td>u23</td>
<td>u19</td>
<td>u19</td>
<td>u19</td>
</tr>
<tr>
<td>4</td>
<td>u31</td>
<td>u23</td>
<td>u21</td>
<td>u15</td>
<td>u31</td>
<td>u29</td>
</tr>
<tr>
<td>5</td>
<td>u15</td>
<td>u11</td>
<td>u11</td>
<td>u31</td>
<td>u15</td>
<td>u21</td>
</tr>
</tbody>
</table>

**ARX and IV4 Algorithm Results**

As a check, two additional system identification algorithms are used from the MATLAB System Identification Toolbox. Note that the nature of these algorithms does not require input and output data matrices to be full-rank; for this reason, if they return system parameters of 0 for linearly dependent data matrix rows, we can feel confident that the Juricic and Goodwin algorithms are providing reasonable answers.
There is nearly perfect agreement in results from the three algorithms, so results from ARX and IV4 are not presented. Any differences can probably be attributed to the fact that Goodwin minimizes a loss function, while ARX and IV4 minimize least-square error functions.
In this chapter we compare the results from Chapter 4 with the hypotheses from Chapter 3. Next the flexibility models are used to simulate factory performance. These simulations are compared to real data, and their accuracy is quantified.

Results Versus Hypotheses

Overall the hypotheses hold up quite strongly against the results. There are a few cases, however, where the hypothesized relationships simply do not exist, or contradict the results altogether. These exceptional cases are the most educational.

Table 5.1 lists the flexibility sources versus flexibility types. The table entries are either “X”s or “o”s. An “X” means the hypothesized relationships between that flexibility type and the source factor metrics are mostly wrong; an “o” means they are mostly correct. The last row and column tabulate the occurrences of “X”s.

It can quickly be seen that the hypotheses regarding production technology and information systems are mostly wrong for all flexibility types. In the case of information systems, this can be easily explained: the metrics applied to information systems did not change over the data collection period. In addition, the metrics did not change from village to village. At the beginning of this study it was assumed that the factory would switch from an MRP system to an MRP2 system; however, this switch did not take place.
before the end of data collection. Since these metrics are constant, the analysis says they have no effect on changes in flexibility. Thus the hypotheses are deemed “wrong.”

The case of production technology is a bit different. Consider test station age, one of the metrics of production technology. Test station age is quantified in steps of 3 years. This means, according to the metric, that the stations don’t “age” during the data collection period, which lasts only 18 months. At first glance it may seem that this metric does not have fine enough resolution to capture aging during the study. However, the metric was constructed according to a factory reality: most equipment is nearly a decade old, and the time scale for equipment change is on the order of 3-5 years. Thus, the metric should be able to capture real equipment changes. Similar arguments can be made for the other production technology metrics.

Like information systems, the results show that production technology has little or no effect on flexibility. However, unlike information systems the production technology metrics probably capture all real changes. Thus, the problem is likely not with the metric, but with the fact that the data does not span a long enough period to see the metrics change. If the metrics are capturing all real equipment changes, then the hypotheses are indeed wrong; production technology has little effect on any flexibility for the time scales examined.
Table 5.1: Good and bad hypotheses. “o” = mostly good, “X” = mostly bad.

<table>
<thead>
<tr>
<th>prod tec</th>
<th>prod mg</th>
<th>supplier</th>
<th>training</th>
<th>labor</th>
<th>prod dvl</th>
<th>info sys</th>
</tr>
</thead>
<tbody>
<tr>
<td>vol flex</td>
<td>X</td>
<td>o</td>
<td>o</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>mix flex</td>
<td>X</td>
<td>X</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>X</td>
</tr>
<tr>
<td>np flex</td>
<td>X</td>
<td>o</td>
<td>X</td>
<td>X</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

In the following section, discussions of the other “X”s are broken down into bulleted items.

• *Production management and mix flexibility:* The relationship between downtime (a production management metric) and mix flexibility is hypothesized to be strongly positive. The results show little or no relationship in most cases, and a strong negative relationship in one case (the HNVS village). This is especially true for the weighted technology level of the PCBs (a mix flexibility metric). This means that, according to the results, as downtime goes down mix flexibility goes up. One interpretation of this result might be that test stations with less downtime are more often available, and can thus produce a wider mix of products.

• *Supplier relationships and new product flexibility:* The hypotheses from this category show the worst agreement with the results. Particularly, the relationships between two supplier metrics, percent of subassemblies subcontracted and number of suppliers, and new product flexibility are hypothesized to be strongly positive. The results show almost no correlation.
The percent of subcontracted parts and number of suppliers characterizes the “extent” of supplier relationships, versus the other metrics (like supplier hours on-site at EDSG) which characterize the “quality” of relationships. Since all metrics had little or no correlation with new product flexibility, one interpretation might be that “extent” is no more important than “quality.” This is contrary to the hypotheses.

• *Worker training and new product flexibility:* This relationship is hypothesized to be weak for all metrics, and the results support this hypothesis. This is surprising given the richness of the training data. However, while both the hypotheses and the results support weak relationships, the results show a negative correlation between hours of training (both team and individual) and all metrics for new product flexibility. This is contrary to the hypotheses. One possible interpretation might be that the type of training offered to the workers does not make them more “task-flexible.” This interpretation fits nicely with the observation that most training given during the data collection period was “people” training (i.e., how to work in teams, etc.) rather than “task” training.

• *Labor policies and volume flexibility:* Premium/standard time (a labor policy metric) is hypothesized to have a large negative effect on volume flexibility. However, a large positive correlation is observed. The reasoning behind the hypothesis is that a workforce putting in lots of overtime cannot easily increase its production volume; the workforce is already working as hard as it can. This assumes overtime is the *result* of increasing production volume. Since this is not observed, another interpretation might be that overtime is used as the *means* of achieving volume flexibility in EDSG.

• *Product development, volume flexibility, and mix flexibility:* Technological content (a product development metric) is hypothesized to have a strong negative effect on volume
flexibility. This hypothesis is based on the following reasoning. Technological content is a measure of how much technological "stuff" is crammed into specific products. Products with high technological content are difficult to assemble and test, thus requiring high worker skills and complicated test stations. This requirement was thought to be a constraint on volume flexibility, since such test stations and worker skills are difficult and expensive to acquire.

The hypothesized relationship is not observed. In fact, a strong positive correlation is found between technological content and volume flexibility. This suggests that test station expense and worker training are not considered barriers by EDSG. EDSG will acquire whatever is necessary to build the product. This is believable, since in the world of defense contracts the customer typically incurs all such expenses.

From this discussion it is clear that hypotheses about certain flexibility sources and types fare worse than the others. For flexibility sources, production technology hypotheses fare the worst in general (ignoring information systems, which may use inappropriate metrics), taking three "X"s. For flexibility types, hypotheses regarding volume flexibility and new product flexibility fare the worst, taking four "X"s each. Since the hypotheses are essentially an intuitive guess, this may be a point of caution for manufacturing managers who wish to increase volume or new product flexibility. Their causes may not be intuitively obvious.

Finally, the most disappointing hypothesis is implicitly stated throughout this thesis. This hypothesis says that flexibility as measured is a dynamic system. According to the results, this is blatantly wrong. Nevertheless, this is an important result whose implications are discussed in Chapter 6. And despite the lack of dynamics, the flexibility
models still have some predictive value. This value is exploited through simulations in the following section.

Simulations

The idea behind the simulations is to build flexibility models using some part of the total input/output datamatrix, then put the remaining inputs into the model to generate predicted outputs. These predictions can be compared against the corresponding real output data.

Two approaches are used. First, models are built for individual villages. These models are used to predict behavior for other villages. Since there are only 18 time steps for each village, there is not enough data to build a village model and simulate the same village. Second, a model is built using three-quarters of the total datamatrix (81 out of 108 time steps). The remaining 27 time steps are put into the model, and predicted outputs are compared to real outputs.

The first approach yields terrible results. The best case is simulating the HNVS village using a CPCU flexibility model. The predicted output curves are not recognizable when compared with the real HNVS output data. In addition, the scale is off by a factor of approximately 100.

These results seem discouraging at first, but the models for individual villages are not built using all the inputs and outputs. In fact, the Juricic algorithm typically limits the number of inputs to about 7 (out of 34), and the number of outputs to about 4 (out of 6). No two villages should use the same input/output set according to Juricic. It is therefore no surprise that a CPCU model, which uses a certain set of inputs and outputs, miserably
simulates the HNVS village, which should be modeled using a different set. This limitation could be overcome if enough data were collected that each village model could utilize all the inputs and outputs. Specifically, raw village datamatrices need to be full rank.

The second approach effectively achieves this. Since there are no input/output dynamics (see Chapter 4), we can ignore the sequence of the time steps and “pool” the data from all villages. This yields a total of 108 time steps. This complete datamatrix is, fortunately, full rank. Even more fortunately, it still has full rank if we take any 81 time steps. This means we can build a model using all inputs and outputs, and have enough data left over to check any simulations we care to perform.

Figures 5.1a – 5.1f show the results from this second approach. Each figure shows the simulated and real output data for a particular flexibility type. Dotted lines represent simulation results, and solid lines represent real output data. Simulations begin at t=81 since real output data for t<81 is used to construct the models.
**Figure 5.1a:** Volume flexibility versus time. Simulation starts at $t=81$ months. Dotted=simulation, solid=actual.

Note: The flexibility model for volume flexibility ($y_1$) is constrained. Since the metric for volume flexibility is only defined for values greater than zero, whenever the simulation returns a negative value this value is set to zero.

**Figure 5.1b:** Number of product categories versus time. Simulation starts at $t=81$ months. Dotted=simulation, solid=actual.
Figure 5.1c: Highest technology level of PCBs versus time. Simulation starts at $t=81$ months. Dotted=simulation, solid=actual.

Figure 5.1d: Weighted technology output level of PCBs versus time. Simulation starts at $t=81$ months. Dotted=simulation, solid=actual.
Figure 5.1e: Number of DCIs versus time. Simulation starts at t=81 months. Dotted=simulation, solid=actual.

Figure 5.1f: First unit cycle time versus time. Simulation starts at t=81 months. Dotted=simulation, solid=actual.
Additionally, a few other 81-point simulation approaches yield mixed results. These results are summarized in Table 5.2. These models are constructed using 81 time steps of selected inputs and outputs in an attempt to find subsets which may *approximately* describe flexibility behavior.

**Table 5.2:** Input/output subset models. Results summarize all villages.

<table>
<thead>
<tr>
<th>Subset Explanation</th>
<th>y Used</th>
<th>u Used</th>
<th>Scale Results</th>
<th>Output Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Juricic y and u common to</td>
<td>1, 6</td>
<td>14, 28, 32, 30</td>
<td>off by 10x</td>
<td>unrecognizable</td>
</tr>
<tr>
<td>all villages</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juricic y and u common to</td>
<td>1</td>
<td>14, 22, 27, 28, 32, 30</td>
<td>off by 10x</td>
<td>unrecognizable</td>
</tr>
<tr>
<td>most villages</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>“</td>
<td>off by 1x</td>
<td>poor</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>“</td>
<td>off by 1x</td>
<td>poor</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>“</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

In Table 5.2, the “Subset Explanation” column lists the general categories of inputs and outputs used to create the 81-point models. “y Used” and “u Used” list the actual input and output subsets used to construct the models. “Scale Results” lists the approximate factor by which the subset model simulations differ from real output data. Finally, “Output Curves” describes the fit between the shapes of simulated output curves and real output curves. It is clear that this subset model approach does not provide accurate output simulations, with the exception of weighted technology level of PCBs (y4).
Error

There is a large number of potential sources of error in this research. There is certainly error in the data collection process, caused by poorly worded questions and inaccurate responses. There is also some error associated with the system identification mathematics. In the cases where we model villages using entire datasets we have no way to find this error except to attempt to calculate error contributions from the above sources. However, in the cases where we build models using partial datasets (for example, the 81-point models) we have real data left over. This data, when compared to predicted output data, offers an easy “acid test” on the model accuracy.

The most important partial dataset models are the 81-point models whose simulation results are shown in Figures 5.1a–5.1f. Errors for these simulations are summarized in Table 5.3. This table shows three types of error: absolute error (Abs e), sum of squares error (SS e), and root sum of squares error (RSS e). In addition, the root sum of squares errors are ranked from 1 (least error) to 6 (most error).
Table 5.3: Errors for simulated outputs in Figures 5.1a–5.1f.

<table>
<thead>
<tr>
<th></th>
<th>y1</th>
<th>y2</th>
<th>y3</th>
<th>y4</th>
<th>y5</th>
<th>y6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs e</td>
<td>253</td>
<td>16.8</td>
<td>68.0</td>
<td>26.3</td>
<td>25.4</td>
<td>170</td>
</tr>
<tr>
<td>SS e</td>
<td>10700</td>
<td>15.7</td>
<td>257</td>
<td>29.2</td>
<td>35.0</td>
<td>1390</td>
</tr>
<tr>
<td>RSS e</td>
<td>103</td>
<td>3.96</td>
<td>16.0</td>
<td>5.41</td>
<td>5.92</td>
<td>37.3</td>
</tr>
<tr>
<td>Rank</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

As can be guessed by inspection of Figures 5.1a – 5.1f, three mix flexibility metrics are the most accurately predicted of all flexibility metrics. These mix flexibility metrics are number of product categories (y2), weighed technology output of PCBs (y4), and number of DCIs (y5).

One other observation about error is that all the simulations in Figures 5.1a – 5.1f predict output values that are too high, with the exception of volume flexibility (y1, Figure 5.1a). It is not clear why this trend exists; perhaps there is some common source factor which is not measured and included in the model. Another possibility is that some source factor which is measured and modeled has a significant and consistent error. Good candidates are u19 (worker empowerment), u11 (average test station runtime), u23 (percent of subassemblies subcontracted), and u24 (percent of suppliers using SPC). These source factors contribute to the outputs in each flexibility type model. There are no source factors which contribute to all flexibility types except volume flexibility.
6 Implications

Results are described in Chapter 4. Hypotheses, simulations, and error are discussed in Chapter 5. However, we have yet to discuss the meanings of the results and simulations, and what these meanings imply.

Interpreting the Results

The results tell us three important things. First, Tables 4.2 – 4.7 allow for a consistency check between parameters generated using individual villages (with Juricic-generated inputs/outputs), and parameters generated using 81 points from the complete datamatrix. Ideally there would be general agreement as to the important flexibility sources. Important sources are those selected by the Juricic algorithm in the individual village models, and those with nonzero parameters in the 81-point model.

Inspection reveals mixed agreement. The majority of source factors assigned parameters of zero in the 81-point model were not selected by the Juricic algorithm in the individual village cases. This is encouraging. However, where this is not the case the 81-point model parameters tend to differ greatly. This is understandable since village models do not use identical sets of inputs and outputs, but we would like to see the Juricic algorithm select nearly identical input and output sets for all villages. This would imply that important source factors for one village are important for the others. Perhaps with more
data, the Juricic village source factor sets would converge to resemble the 81-point model set. This needs to be explored.

A second important message from the results is that some flexibility types seem to be much more “modelable” than others. For example, the simulations of weighted technology level of PCBs and number of DCIs (both mix flexibility metrics), along with first-unit cycle time (the new product flexibility metric), agree well with real flexibility outputs. However, the other simulations agree quite poorly, not merely a little worse. The reason for this lies with either 1) the metrics chosen for source factors; 2) the metrics chosen for the poorly-modeled flexibility types, or 3) the concept of what those flexibilities are. It may also be some combination of the three. Regardless, we failed to capture what is happening. This is another area which needs to be explored further.

A final message from the results is the relative importance of the source factors for each flexibility type, as described by the parameters in Tables 4.2 – 4.7. These tables constitute the roadmap mentioned in the abstract. The parameters should not be interpreted as exact factors to be used in calculations; rather, they should guide managers’ thinking about which source factors are the most influential on each flexibility type. Once a need for more or less of a certain flexibility is identified, these tables can focus planning and investment on areas with the highest relative payoff. Table 4.8 summarizes the most important features of the roadmap.

Implications

The results hold two dire implications for the flexibility framework used in this research (see Chapter 3 for an outline of the framework). Most importantly, the flexibility sources
and types, as measure in this thesis, do not describe a dynamic system. This may mean one of two things.

One, it may mean manufacturing flexibility is not a dynamic process. In this case flexibility may be simply an operating condition, like voltage to an electric motor, that is “applied” by choosing machines, layouts, personnel, etc.

Two, it may mean that the flexibility framework does not describe the fundamental dynamic “states” of factory flexibility, but merely some loosely related output variables. My intuition says that both of these possibilities are true. Flexibility is probably set to some extent the instant a new machine is brought into the factory, which supports the implication that flexibility is not a dynamic process. But flexibility also depends on people, who have to be trained and work up learning curves. In this case I would expect true dynamics, which the framework does not capture.

The second implication for the flexibility framework concerns the differences between mix and new product flexibility. Consider Table 4.8, which lists the top 5 most important source factors for each flexibility type. The top 3 source factors for y4, y5, and y6 are identical, and the top 5 are nearly identical. This implies a natural grouping, as if y4, y5, and y6 are metrics for the same flexibility type. However, y4 and y5 are supposedly mix flexibility metrics, and y6 is the new product flexibility metric.

This is reminiscent of the comment in Chapter 3:

...mix flexibility is similar to new product flexibility but on a much shorter time scale. The difference comes down to the difference between changeovers (mix flexibility) and full-scale retooling/retraining (new product flexibility). Changeovers by definition mean retooling for a product which has been produced before. Learning curve effects
will be smaller and shorter in duration than for true retooling.

Perhaps this difference between changeovers and retooling leads us to what Stan Gershwin informally refers to as “one month mix flexibility” versus “one year mix flexibility.” The former is the amount of product mix a factory can produce in one month, the latter in one year. One month mix flexibility (or one week, or one day, etc.) depends on a factory’s ability to easily perform changeovers; one year mix flexibility depends also on the ability to retool.

This can be conceptualized as a sort of spectrum, with a loose division into mix and new product flexibility. Impacts associated with varying product mix will be of smaller magnitude and shorter duration than impacts associated with product family changeovers. Figure 6.1 illustrates this concept.

Figure 6.1: Classification of changeover effects into mix flexibility and new product flexibility regimes.
It may be interesting to consider what "small" and "large", or "short" and "long" changeover effects actually look like in a factory.

**Future Work**

The most straightforward way to proceed with this research is to collect more data. With three or four times the data, we would be able to model and simulate individual villages using all source factors and flexibility types. In addition, over the next few years other effects could presumably be observed, such as test station replacement and information system upgrades. Finally, more data would allow even more accurate modeling of all flexibility types.

Besides flushing out this study with more data, plenty of other work needs to be done. Similar studies need to be performed in other industries and other regions of the world. It is not clear how results will compare; EDSG is performing according to the unique market pressures placed upon it. Perhaps EDSG is more flexible than recent data shows, but does not currently have the need to exploit this flexibility. If this is the case, results will not likely be generalizable across company, industrial, or national boundaries. However, the results of this thesis and work by Suárez (18) and Suárez et al. (8) will carry special weight if similar results are found across such borders.

The relevance of this work will also increase if complementary research is performed from the customer end. This thesis and related works define metrics for manufacturing flexibility which are useful in a relative sense (for example, as a roadmap of important source factors). However, these metrics are not fundamental units like meters or kilograms. Everybody understands what is meant by one meter, but it is not clear what a volume flexibility of 0.8 means (besides the fact that it's bigger than 0.7). This situation
could be ameliorated by finding some way to map our current definitions of flexibility onto customer or market demands; a volume flexibility of 0.8 means much more when the market demands 0.9.

Finally, another way to clarify the meaning of flexibility metrics is to define a new framework altogether. The most useful way would be to define flexibility in such a way that flexibility gains or losses are assigned dollar values. This would not only bring flexibility metrics into the realm of fundamental units, but would allow for judicious comparison of various factory strategic and operating decisions with flexibility. For example, in some scenario it might be financially beneficial to sell a factory rather than invest enough to meet market flexibility demands. Our current flexibility metrics do not support such decisions (for an interesting discussion on this example, see Kulatilaka 1988).

The Final Word

The results and conclusions of this thesis may or may not apply to other factories or industries. The only thing we can say with any certainty is that within EDSG, using the given framework and metrics as defined, the identified relationships were observed. Hopefully the observations will prove useful for management at EDSG, and as a foundation for further study.
References


Adapted from a Hughes-proprietary document circulated internally during Summer 1992.

22 Harlan Patterson of EDSG is credited with coining the phrase "Manufacturing Villages" during Fall 1991.


Other Sources


This appendix presents a brief description of the functional, geographical, and personnel boundaries which define the manufacturing villages in EDSG.
Table A.1: Fabrication, integration, and test operations performed in common assembly.

<table>
<thead>
<tr>
<th>Aqueous Cleaning</th>
<th>Maintenance Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto Bond</td>
<td>Manufacturing Procedures</td>
</tr>
<tr>
<td>Auto Insertion</td>
<td>MAPL</td>
</tr>
<tr>
<td>Bonding</td>
<td>MARA/DAK Maintenance</td>
</tr>
<tr>
<td>Build Schedules</td>
<td>Master Schedule (Customer Demand)</td>
</tr>
<tr>
<td>Bulk Tinning</td>
<td>MRO Stores</td>
</tr>
<tr>
<td>Calibrated Tool Crib</td>
<td>Oven Curing</td>
</tr>
<tr>
<td>Calibration</td>
<td>PADS Input</td>
</tr>
<tr>
<td>Card Conditioning</td>
<td>Paralene Coating</td>
</tr>
<tr>
<td>CAVS Programming</td>
<td>Parts Ordering/Status</td>
</tr>
<tr>
<td>CAVS Testing</td>
<td>parts Replacement</td>
</tr>
<tr>
<td>Change Control/Planning</td>
<td>Performance/Cost Reporting</td>
</tr>
<tr>
<td>Cleanliness Testing</td>
<td>Perishable Tools</td>
</tr>
<tr>
<td>Component Forming</td>
<td>Process Engineering</td>
</tr>
<tr>
<td>Component Sequencing</td>
<td>PWB Repair</td>
</tr>
<tr>
<td>Component Tinning</td>
<td>Receiving</td>
</tr>
<tr>
<td>Computer Maintenance (PC)</td>
<td>Rework Order Generation</td>
</tr>
<tr>
<td>Conformal Coating</td>
<td>Rework Planning Generation</td>
</tr>
<tr>
<td>Degassing</td>
<td>Robot Masking</td>
</tr>
<tr>
<td>Dispatching</td>
<td>Robot Trimming</td>
</tr>
<tr>
<td>Encapsulating</td>
<td>Route Sheet Generation</td>
</tr>
<tr>
<td>Flux Cleaning</td>
<td>Semi-Auto Insertion</td>
</tr>
<tr>
<td>Functional PWB Test</td>
<td>Shipping</td>
</tr>
<tr>
<td>General Maintenance</td>
<td>Solvent Storage</td>
</tr>
<tr>
<td>Hand Solder</td>
<td>Stationery Stores</td>
</tr>
<tr>
<td>I.R. Solder</td>
<td>Surface Mount Assembly</td>
</tr>
<tr>
<td>Initial Planning</td>
<td>Surface Mount Rework</td>
</tr>
<tr>
<td>Inspection</td>
<td>Test Equipment Maintenance</td>
</tr>
<tr>
<td>Kitting</td>
<td>Test Planning</td>
</tr>
<tr>
<td>Line Coordination</td>
<td>U.V. Coating</td>
</tr>
<tr>
<td>M.R.B./QAE</td>
<td>Unit Level PWA Rework</td>
</tr>
<tr>
<td>Machine Maintenance (PM)</td>
<td>Vapor Phase Solder</td>
</tr>
<tr>
<td>Machine Programming</td>
<td>Wave Solder</td>
</tr>
<tr>
<td></td>
<td>Yield/Defect Reports</td>
</tr>
</tbody>
</table>
Figure A.1: Physical layout of a typical EDSG manufacturing village.
Table A.2: Typical roster of EDSG manufacturing village personnel.

<table>
<thead>
<tr>
<th>Full-Time Personnel</th>
<th>Part-Time Personnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection</td>
<td>Business Office</td>
</tr>
<tr>
<td>GDLS/DPRO</td>
<td>Manufacturing Engineer</td>
</tr>
<tr>
<td>Parts Control</td>
<td>Materiel</td>
</tr>
<tr>
<td>Project Planner</td>
<td>Project Manager</td>
</tr>
<tr>
<td>Supervisor</td>
<td>QAE</td>
</tr>
</tbody>
</table>

Table A.3: Processes performed in a typical EDSG manufacturing village.

<table>
<thead>
<tr>
<th>Process</th>
<th>Village Process</th>
<th>Outside Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Other PCB Processes</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Bar Code Reading</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Bonding</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Calibrated Tool Crib</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration Accountability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Computer Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frozen Storage</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>General Maintenance</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>GFE Lock-Up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFE Shipping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand Component Forming</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Hand Component Tinning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand Solder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Maintenance</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Maintenance Repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing Procedures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAPL or Equivalent</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Master Scheduling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRO Stores</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRO Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation Instruction Sheets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oven Curing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overflow Storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paint Touch-Up</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Parts Ordering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parts Replacement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

102
Table A.3, Continued: Processes performed in a typical EDSG manufacturing village.

<table>
<thead>
<tr>
<th>Process</th>
<th>Village Process</th>
<th>Outside Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts Status</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Parts/Dispatch/Inventory Control</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PCB Repair (Limited)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Performance/Cost Reporting</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Perishable Tool Crib</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Perishable Tools</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Planning</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Point of Use Stores</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Preventative Maintenance</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Program Status</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Receiving</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Receiving Inspection</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Receiving Test</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Rework Planning</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>SMC</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Smock Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Solvent Storage</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Stationary Stores</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>STE Maintenance</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Stenciling</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Strip Coating</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Test/Yield Reporting</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tool Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Tool Storage</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tooling Storage</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
The following pages contain the questions used to compile the questionnaires circulated through EDSG. After each question there is a brief description of the goal of the question (i.e., what metric it is used with) and the job category of the people who were asked the question.

There are a few questions which are not used in the analysis. In such cases, either data was not available or the question serves merely to enhance understanding about village operations.
HUGHES ELECTRO-OPTICAL AND DATA SYSTEMS GROUP
MANUFACTURING VILLAGE

MASTER QUESTIONNAIRE

for a Study of Manufacturing Flexibility by the
Massachusetts Institute of Technology
Sloan School of Management
Cambridge, Massachusetts

1992
Volume Flexibility

V1. Please provide a monthly production histogram for each deliverable control item produced by your village over the past 24 months (histogram should show units produced per month). For June 1991 and June 1992 only, provide this production information weekly.

used to derive production volume fluctuation as per Suárez. 

also, used to determine production output by product type and time period. 

Progr Mgr

V2. Give the maximum production capacity per deliverable control item in units/month. Please give this information for both June 1991 and today.

used in conjunction with production rates to check estimates of theoretical maximum and minimum production rates.

also used with M7, V3, and V6 to determine new product learning curve by production cycle time and yield.

Test Engnr

Deliverable Ctrl Item June 1991 Max Prod Capac Current Max Prod Capac

V3. Give the overall yield rate for the production process of each deliverable control item. Please give this information for both June 1991 and today.

used in conjunction with production rates to check estimates of theoretical maximum and minimum production rates.

also used with M7, V2, and V6 to determine new product learning curve by production cycle time and yield.

Test Engnr

Deliverable control item June 1991 Yield Rate Current Yield Rate

V4. For each deliverable control item, estimate the theoretical maximum production rates in units/month. Please do this for both June 1991 and today. One way to think of this might be: if production was raised higher and higher, what would the first bottlenecks be? What are the limitations or contingencies associated with those bottlenecks?

an idealized measure of volume flexibility, if the data checks.

Progr Mgr

Deliverable Control Item June 1991 Max Prod Rate Current Max Prod Rate

V5. For each deliverable control item, estimate the theoretical minimum production rates. Please do this for both June 1991 and today. One way to think of this might be: how far can we lower production and still justify the village's existence?

an idealized measure of volume flexibility, if the data checks.

Progr Mgr

Deliverable Control Item June 1991 Min Prod Rate Current Min Prod Rate


used in Suárez's volume flexibility metric.

also used with M7, V2, and V3 to determine new product learning curve by production cycle time and yield.

Test Engnr

Deliverable Control Item June 1991 Min Prod Rate Current Min Prod Rate

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Mix Flexibility

M1. Please provide some form of indentured parts lists for all deliverable control items produced by your village. These lists should be detailed enough to show all incoming subassemblies (i.e. boards from Common Assembly) and any parts which come in to the village individually. Give names and very brief descriptions of each deliverable control item.

used to determine categories of products.

Prog Mgr

M2. Briefly describe the customer use of each deliverable control item produced by your village. Please include the vehicles and roles for which the units are intended. For example: unit can be mounted on 500 MD and Blackhawk helicopters, and is used for surveillance and navigation.

used to determine categories of products.

Prog Mgr

Deliverable Control Item Customer Use

M3. List the mass (in kilograms or pounds) of each deliverable control item produced by your village.

Prog Mgr

Deliverable Control Item Mass (denote units)

M4. List the volume or dimensions of each deliverable control item produced by your village. Please denote units.

Prog Mgr

Deliverable Control Item Volume or Dimensions (denote units)

M5. For each program, evaluate the technological difficulty of the test engineering package from 1 (below average) to 5 (above average).

Test Engnr

Program Technological Difficulty of TE Package

<table>
<thead>
<tr>
<th>Program</th>
<th>below average</th>
<th>above average</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>EN6</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>GPS/LOS</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>TOW/CNITE/LYNX</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>HIRE</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>HNV5</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>AAS38</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
</tbody>
</table>

M6. Are there boards in any deliverable control item which are NOT obtained from Common Assembly? (Yes or No)

Prog Mgr
M7. Please provide charts of product lines longest cycle units, by month, from June 1991 — June 1992. These 12 charts should show

- data for each village product line (M1, EN6, GPS/LOS, TOW/CNITE/LYNX, HIRE, HNVS, AAS38, Common Assembly)
- the cycle time goals for each product during each of the 12 months

Proj. Mgr
also used with V2, V3, and V6 to determine new product learning curve by production cycle time and yield.

The following questions apply to the Common Assembly village only. These questions should be sent to a village manager (Distribution List 5) if and only if the answer to M6 is yes.

Detail on mechanical and optical hardware is omitted due to the slower pace of technological development

Common Assembly: For each board, Distribution List 5: For each board not supplied by Common Assembly,

M8. Is the board 1 or 2 sided? __________

M9. Does the board utilize a heat sink(s)? (yes or no) __________

M10. What are the board dimensions in centimeters? ________________

M11. How many layers does the board have? __________

M12. Classify the board as: • low frequency digital/power supply ______

• analog ______

• high frequency digital ______

(if mixed, you may choose more than one category)

M13. Please list the number of components in each class:

• discrete ______ • IC ______

• LSI ______ • hybrid ______

• VLSI ______

from parts layout?

M14. The following three pages list 16 categories of component packaging styles. Please tabulate the number of each style used on the board. Sum by pin numbers and divide by 16 to get 16-pin IC equivalents.

M15. Are the test points in the circuit or at the connector? ________________

M16. Is component insertion performed • manually ______

• automatically ______

• both manually and automatically ______
New Product Flexibility

N3. For each deliverable control item that the product line village makes, when was the WAD for production first received? When was the first production unit shipped? 

*an attempt to isolate "cycle times" for the villages; relevant cycle time is "production gear-up" cycle time since village doesn't do prime hardware design. Suárez used board design cycle time when examining the factory as a whole.*

Division Mgt

<table>
<thead>
<tr>
<th>Deliverable Control Item</th>
<th>Production WAD Received</th>
<th>First Unit Shipped</th>
</tr>
</thead>
</table>

N4. Please denote the start of each current village program on the following timeline:

*Division Mgr*

*used to determine how many new products have been introduced over what time frame.*


| - - - - | - - - - | - - - - | - - - - | - - - - | - - - - | - - - - | - - - - | - - - - | - - - - | - - - - | - - - - |

Current Village Programs: EN6, M1, GPS/LOS, TOW/CNITE/LYNX, HIRE, HNV5, AAS38.
Production Technology

We are trying to assess the level of production technology used in EDSG's manufacturing villages. For each major test station or machine in your village, please answer the following questions:

Village Mgr

Name or description of test station or machine: __________________________________________

| PT1. What is the approximate age of this unit? |
|-----------------|-----------------|-----------------|-----------------|
| 0-3 yrs         | 3-6 yrs         | 6-9 yrs         | >9 yrs          |
| Y               | N               |                 |                 |

<table>
<thead>
<tr>
<th>PT2. Is there a need for controller(s)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
</tr>
</tbody>
</table>

| PT3. If controller(s) are needed, are the current controller(s): |
|-----------------|-----------------|
| Digital         | Analog          |

<table>
<thead>
<tr>
<th>comments:</th>
</tr>
</thead>
<tbody>
<tr>
<td>______________________________________________</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PT4. Is the unit interface menu-driven?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
</tr>
</tbody>
</table>

| PT5. Does the unit have built-in test capability? auto-calibration capability? |
|----------------------------------------|-----------------|
| Y                                      | N               |

<table>
<thead>
<tr>
<th>PT6. If the unit has auto-calibration capability, is this capability end-to-end (from first to last test phase)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PT7. Does the unit utilize VXI technology?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
</tr>
</tbody>
</table>

| PT8. Is the use of this unit generic (for many products) or specific (one product)? |
|----------------------------------------|-----------------|
| generic                                | specific        |

PT9. For the following three steps (load part or batch, operate the machine or run test, and unload) please check the level of automation: used to examine manned vs. automated equipment, as well as labor support needed to run equipment.

<table>
<thead>
<tr>
<th>Load</th>
<th>Operate or Run Test</th>
<th>Unload</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PT9. For the following three steps (load part or batch, operate the machine or run test, and unload) please check the level of automation: used to examine manned vs. automated equipment, as well as labor support needed to run equipment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>totaly automated</td>
</tr>
<tr>
<td>semi-automated</td>
</tr>
<tr>
<td>not automated</td>
</tr>
<tr>
<td>if semi- or not automated, who performs these three operations (i.e. test tech, etc)</td>
</tr>
</tbody>
</table>

PT10. If you were to fill out this questionnaire 18 months ago, would any responses be different? If yes, please explain.
Production Management Techniques

PM1. What percentage of village personnel participate on teams? 

Village Mgr

PM2. Provide histograms or data showing WIP and inventory for each deliverable control item over the last 18 months.

Prog Mgr

PM3. How many management levels are there, starting from the direct worker supervisors to product line manager? What was the case 18 months ago?

Village Mgr

PM4. How much control or influence does the village workforce have over the following aspects of their jobs:

Materials (incoming subassembly quality, etc)
- no influence at all
- some influence
- a lot of influence
- total control

Machines (tools, test stations, etc)
- no influence at all
- some influence
- a lot of influence
- total control

Measurement (how worker performance is measured)
- no influence at all
- some influence
- a lot of influence
- total control

Man (training, team issues, etc)
- no influence at all
- some influence
- a lot of influence
- total control

Methods (the way specific tasks or tests are performed)
- no influence at all
- some influence
- a lot of influence
- total control

PM5. Estimate the downtime for each test station as a percentage of total available time.

Village Mgr

used with PM6 to find production rates per machine.

PM6. What is the approximate average time to:
- setup for a test on each station?
- run a test on each station?

Village Mgr

used with PMS to find production rates per machine.
PM7. Provide a village layout which shows:

- major test station and machine locations
- parts stores
- finished goods stores
- buffers (for WIP)
- material flow for each deliverable control item
  - if there is more than one possible path, please denote it

used with PM8 and PM9 to determine buffer size in theory, practice, and goal.
also used to determine cell layout, flows and routings, and alternative routings.

PM8. Please provide charts or data which show WIP for each village, by month, from June 1991 — June 1992. Please give the WIP goal for each of these 12 months.

used with PM7 and PM9 to determine buffer size in theory, practice, and goal.

PM9. Please provide charts or data which show village inventory levels, by month, from June 1991 — June 1992. This inventory should include WIP, rework, RIT, stores, and furnished goods. Please provide the inventory goal for each of these 12 months.

used with PM7 and PM8 to determine buffer size in theory, practice, and goal.

PM10. How does production information (namely, production schedules) get to the manufacturing villages? Please:

Planning Dpt

used to determine how production is scheduled: and what, how, and how accurately product requirement (demand) info is provided to the village. Also, how this info is shared in the village (kanbans?).

- give the name of the scheduling document(s)
  ________________________________
  if applicable

- if scheduling documents are not used, describe how scheduling information gets to the village
  ________________________________
  ________________________________
  ________________________________

- describe the person this information goes to (i.e. village supervisor)
  ________________________________

- how often is this information given to the village
  ________________________________

PM11. Who schedules machine setups or changeovers? What information is this decision based on?

Prog Mgr

to determine how setups/changeovers are scheduled.
PM12. Who decides batch sizes? What information is this decision based on? 

_Prog Mgr_

_to determine how batch sizes are decided._

PM13. Who decides that village workers should work overtime? What information is this decision based on? 

_Prog Mgr_

_to determine how OT and other operating decisions are decided._
Supplier/Distributor Relationships

SD1. By village, how many hours were spent over the last year by Hughes personnel at supplier sites? How many hours were spent by suppliers at Hughes?

<table>
<thead>
<tr>
<th>Village</th>
<th>HAC Personnel Hours Off Site</th>
<th>Supplier Hours On Site</th>
<th>Change from Previous Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS/LOS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOW/CNITE/LYNX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIRE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HNVS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AAS38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common Assembly</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SD2. What percentage of subassemblies are currently subcontracted? (versus being built by EDSG)
How about 18 months ago?

<table>
<thead>
<tr>
<th>Procurement</th>
</tr>
</thead>
</table>

SD3. What percentage of suppliers are using SPC?
How about 18 months ago?

<table>
<thead>
<tr>
<th>Procurement</th>
</tr>
</thead>
</table>

SD4. Estimate the number of suppliers for the village today:
18 months ago:

<table>
<thead>
<tr>
<th>Procurement</th>
</tr>
</thead>
</table>

SD5. To what extent do you assist your suppliers?

<table>
<thead>
<tr>
<th>Procurement</th>
</tr>
</thead>
</table>
Worker Training/Skills

WT1. Please list and describe the village workforce.

<table>
<thead>
<tr>
<th>Job</th>
<th># of Current Personnel</th>
<th># of Personnel 18 Months Ago</th>
<th># of Personnel 6 Months from Now</th>
</tr>
</thead>
</table>

VTlig Mgr

WT2. How many workers have a primary education?

secondary education?

college degree?

VTlig Mgr

WT3. Describe the training the village workforce has undergone in the past 18 months, including current training.

VTlig Mgr

<table>
<thead>
<tr>
<th>Name of Training</th>
<th>&quot;People&quot; or &quot;Technical&quot;</th>
<th>Date</th>
<th>Percent Participation</th>
<th>Avg Hours per Worker</th>
<th>Team or Individual</th>
<th>Usefulness (0-3, 3 best)</th>
</tr>
</thead>
</table>

"People" training refers to team training, employee empowerment, and other nontechnical topics. "Technical" training refers to SPC, kanban training, etc.
**Labor Policies**

LP1. For the last 6 quarters, list overtime hours and standard labor hours for your product line.  

*Division Mgt*

<table>
<thead>
<tr>
<th>Quarter</th>
<th>OT Hours</th>
<th>Standard Labor Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>1992</td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td>1992</td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td>1991</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>1991</td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td>1991</td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td>1991</td>
<td></td>
</tr>
</tbody>
</table>

LP3. How many job classes are there in the union workforce now? before the last round of negotiations? after the next round (make a guess)?  

*Labor Rep*
Product Development Process

DP1. List the number of subassemblies or individual parts inputted to the village per deliverable control item. 
*Get this data from question M1. This is an indicator of technology (less parts for the same type of product implies higher technology).*

DP2. What percentage of input subassemblies/parts are used in 2 or more deliverable control items? 
*An indicator of design history. Derive from M1.*

DP3. What is the weighted chip density in each final assembly? 
*Derive this from M5 and M4 data, as well as the board questionnaires.*

DP4. How many touch labor hours were spent on each deliverable control item? Please give the average hours per deliverable control item for June 1991 and May 1992. 
*This data is weighted by the complexity of the assemblies, which is derived from DP1 and DP3. DP4 is an indicator of design history.*

<table>
<thead>
<tr>
<th>Deliverable Control Item</th>
<th>Average Touch Labor Hours per Unit, June 1991</th>
<th>Average Touch Labor Hours per Unit, June 1992</th>
</tr>
</thead>
</table>

*Division Mgt*

*DP6 should only be asked of a village if the response to M6 was yes. Otherwise, only ask DP6 of Common Assembly. It goes in the board questionnaire. There is no DP5.*

DP6. How many new (previously not used by Hughes) electronic components are there in each board? 
*An indicator of design history.*

DP7. Please rate each PCB in this village's products using the enclosed scale (1-10). 
*Test Engnrg*
Accounting And Information Systems

AI1. Is an activity-based cost system in use?  

AI2. Is MRP in use?  

AI3. Is MRPII in use?  

AI4. Briefly describe the new demands placed on our accounting and information systems since the villages have been implemented, and the steps being taken to meet these needs.

*Special interest question.*
System Identification

This appendix develops the mathematical basis for the system identification algorithms used in the analysis. We start by briefly explaining the mathematical background in terms of a classical mechanical system. Later these results are analogized to production systems.

The first step in understanding system identification is knowing what is meant by a transfer function. The motion of any real mechanical system can be described as a function of time by one or more differential equations, which result from the application of Newton's laws to the system. For example, consider the spring-mass-damper system shown in Figure C.1. The position of mass $m$ is called $y(t)$ and is designated the output; some motion is forced upon the point $P$ which has position $u(t)$ and is designated the input.

![Spring-mass-damper system model](image)

**Figure C.1:** Spring-mass-dashpot system model.
If we define the sum of forces acting on mass $m$ as $F$, we obtain (through Newton's laws) equations describing the system's motion as follows:

$$m \frac{d^2y}{dt^2} = F$$  \hspace{1cm} (C1)

$$F = -c \left( \frac{dy}{dt} - \frac{du}{dt} \right) - k(y - u)$$  \hspace{1cm} (C2)

where $c$ and $k$ are constants associated with the physical properties of the damper and spring, respectively. Now if we assume there are no initial conditions (zero initial velocity and acceleration of the mass), we can take the Laplace transform of Equations (C1) and (C2) and express the results as

$$ms^2Y(s) = F(s)$$  \hspace{1cm} (C3)

$$F(s) = -c[sY(s) - sUs)] - k[Y(s) - U(s)]$$

$$= (cs+k) \left[ U(s) - Y(s) \right]$$  \hspace{1cm} (C4)

where upper-case $Y$ and $U$ are used to denote transformation of $y$ and $u$ from the time domain to the Laplace domain. Now the transfer function between $Y(s)$ (the output) and $U(s)$ (the input) is obtained by equating Equations (C3) and (C4) and is defined as

$$G(s) = \frac{Y(s)}{U(s)} = \frac{cs + k}{ms^2 + cs + k}$$  \hspace{1cm} (C5)
Note two properties of this transfer function. First, the input and output are arbitrarily defined. We could have designated the motion of any two points within the system in Figure C.1 to be \( u \) and \( y \). This would have resulted in a different transfer function describing the same system; thus, we see there are an infinite number of transfer functions describing the behavior of any system. The particular transfer function is selected based on viewpoint and convenience since some inputs and outputs are easier to measure than others.

Second, notice that we are dealing with the motion of the system in continuous time. To address the discrete time case, we simply use the \( Z \)-transform instead of the Laplace transform when converting the differential equations of motion in Equations (C1) and (C2). The resulting equations in \( z \) are combined to yield the canonical \( z \)-transfer function

\[
G(z) = \frac{Y(z)}{U(z)} = \frac{b_1z + b_2}{z^2 + a_1z + a_2} \quad (C6)
\]

where \( b_n \) and \( a_n \) are coefficients which depend on the physical system constants \( c \) and \( k \), and result from placing (C6) in its canonical form. The usefulness of this form becomes apparent when expanded into a difference equation. This is done by first expanding Equation (C6) as follows:

\[
Y(z) \left[ z^2 + a_1z + a_2 \right] = U(z) \left[ b_1z + b_2 \right] \quad (C7)
\]

Now a certain time is denoted by \( k \), and discrete steps forward in time by \( k+1, k+2 \), etc. Since \( z^n \) corresponds to \( n \) forward time steps, we can rewrite Equation (C7) as

\[
y(k+2) + a_1y(k+1) + a_2y(k) = b_1u(k+1) + b_2u(k)
\]
where lower-case $y$ and $u$ are used to denote the switch back to the discrete time domain. Finally, multiplying through by $z^2$ gives

$$y(k) = a_1y(k-1) - a_2y(k-2) + b_1u(k-1) + b_2u(k-2) \quad (C8)$$

This difference equation is often referred to as an Auto Regressive Moving Average (ARMA) model. This name comes from the property of Equation (C8) which makes the value of $y$ at any time step $k$ dependent upon values of $y$ and $u$ from a constant number of previous time steps. Notice that in Equation (C8), $y(k)$ depends upon values from two previous time steps; this corresponds to the order $n$ of the differential equations of motion (C1) and (C2). Since values from "older" steps (i.e. $k=3$, etc.) do not affect $y(k)$, in effect we are computing $y(k)$ by taking a moving average of previous $y$ and $u$, weighted by the coefficients $a_n$ and $b_n$.

The results in Equation (C8) can be greatly simplified by vector notation; such notation is convenient especially if the order $n$ grows large. We begin by defining $\Theta$ as a parameter vector which contains all information about the physical system model in terms of $a_n$ and $b_n$. In this example, $\Theta$ is expressed as

$$\Theta = [a_1 \ a_2 \ b_1 \ b_2]$$

We next define a state vector $\Phi$ which contains information about $y$ and $u$ from $n$ previous time steps:

$$\Phi = [-y(k-1) \ -y(k-2) \ u(k-1) \ u(k-2)]$$
Finally, we can express the scalar $y(k)$ in terms of $\Phi$ and $\mathcal{Q}$:

$$y(k) = \Phi^T \mathcal{Q} \quad \text{(C9)}$$

From this result we are prepared to address the problem of system identification. In other words, how can we discover the physical parameters of an unknown system? Since these parameters are given in $\mathcal{Q}$, it is obvious that by collecting sets of data for $y(k)$ and $u(k)$ over sufficient time steps, we can construct $\Phi$ and solve for the components of the parameter vector $\mathcal{Q}$ using, for example, Cramer's Rule.

When we use this technique to estimate system parameters, there will be some error $e$ associated with the estimation. In general, this error will be a function of $\mathcal{Q}_{\text{estimated}}$ and time steps $k$. We wish to minimize this error by varying $\mathcal{Q}_{\text{est}}$. One way to minimize is according to least squares, analogously to a least squares regression. This idea can be expressed as

$$\min_{\mathcal{Q}} \sum_{k=0}^{\infty} e^2(k; \mathcal{Q}_{\text{est}})$$

For convenience, we define some additional vectors. Scalar $n$ is the system order, and take $N$ as the data window length, or number of time steps over which we will minimize the error $e$. Now data for $y(k)$ are taken from $y(n)$ to $y(N)$, and these values can be expressed by the vector

$$\mathbf{Y}(N) = [y(n), y(n+1), \ldots, y(N)]^T$$

Also, we define the vector $\Phi$ as the collection of observed state vectors $\mathbf{q}$.
\[ \Phi(N) = [\phi(n), \phi(n+1), \ldots, \phi(N)]^T \]

and \( \xi \) as the collection of scalar errors from parameter estimation

\[ \xi(N, \Theta_{est}) = [e(n), e(n+1), \ldots, e(N)]^T \]

By noting that \( \xi \) equals the difference between the observed outputs \( Y \) and the outputs predicted by parameter estimation \( \Phi \Theta_{est} \), we can define a scalar error measure \( J \) where

\[ J = \xi^T \xi \]  

(C10)

This quantity is used to measure the "goodness" of the parameter estimator \( \Theta_{est} \) where

\[ \Theta_{est} = (\Phi^T \Phi)^{-1} \Phi^T Y \]  

(C11)

Equations (C10) and (C11) are presented in the form used to identify system parameters and check the accuracy of the estimation.

The motivation behind this exercise is to explain the mathematical principles behind system identification techniques. A simple physical model is used to accomplish this, but the results in Equations (C10) and (C11) are general and hold for any system. Even if nonlinearities are present in the system dynamics, rapid updating of \( \Theta_{est} \) will provide a locally linear model which may be used for analysis or control purposes. In addition, the results can be extended to cover multiple-input, multiple-output (MIMO) systems.
The goal of the analysis is to use these techniques to describe the relationships between the sources and types of flexibility, and hopefully offer insight into correct operational decisions based on the production system dynamics. To accomplish this, we must first define the inputs $y_n$ and outputs $u_n$ to the MIMO system(s) we wish to characterize. This is where precise analogies between mechanical and production systems must be drawn.

The analogies must satisfy the following criteria:

- inputs and outputs must be able to provide measurable, discretized data
- inputs and outputs must be observable over sufficient time steps for statistical validity of results
- the list of inputs should be exhaustive (but missed inputs can be detected by goodness-of-fit analysis of $\Theta_{en}$)

Within the boundaries of these criterion, great freedom is allowed in choosing inputs and outputs. Units are not a major consideration, although the system parameters described by $\Theta_{en}$ will depend on the units of the inputs and outputs. In addition, while an exhaustive set of inputs is ideal, one or more arbitrary outputs (there are infinity outputs) may be chosen as long as sufficient data can be collected at the output(s).

The seven source factors for flexibility described by Suárez et al. (5) serve as suitable inputs for an arbitrary production system, and the four flexibility types serve as suitable outputs. The main consideration when using these inputs and outputs are verifying the comprehensiveness of the input set, and keeping in mind that the system parameters identified by this technique depend on the unit(s) used by the inputs and outputs.
This appendix presents the actual code used to perform the Juricic algorithm (23) and Goodwin algorithm (24). The stock MATLAB routines (rank, ARX, and IV4) are not listed, but can be found in (25).
Juricic Algorithm

% INITIALIZE
% THE ALGORITHM
% 0. initialize: pick a timeseries
% 1. search for the next timeseries which is most linearly independent from the first
%    using the Nucleus Criterion
% 2. combine these 2 timeseries into a matrix
% 3. iterate until we're as linearly independent as we like (sigma!)

% the Nucleus Criterion: given database matrix M[NxK], p endogenous variables,
% and r exogenous variables, identify a subset (p+r rows) of linearly independent
% timeseries. By their linear combination we can express any other rows of interest. A
% measure of linear independence:

%  dr = det(M'M),  0£ dr£ 1
%  dr = 1: all M pairwise orthogonal

% CHOOSE:
ypicked=1;
upicked=14;
m=6;
r=19;

%loop is input datamatrix outer loop length
uloop=r;
yloop=m;

%bigd is factor for dru
ubigd=1e+27;
ybigd=1;

% input datamatrix loop
ulist=[upicked;0];
Mu=u(upicked,:);
V=[0;0];
for j=1:uloop;
% m is conservative; if ulist contains all nonzero elements, all y are lin.indep.
% with outer loop turned off, we will only find Mu and ulist for y(picked)
% build matrix "dru" which contains dr for all other u(i)
for i=1:r;
    Mtemp=[Mu;u(i,:)];
    dru(i,:)=det(Mtemp*Mtemp');
end;

dru=dru/ubigd;

% pick index in dru with maximum independence
% u(i)=u(ypicked) should be automatically eliminated since dr=0
%if max(dr) is not explicit, ties for nonzero maxes are included
if max(dr)>0
%extract index of max(dr)
  for i=1:r;
      if dru(i)==max(dru)
          Mu=[Mu;u(i,:)];
          V=[i;dru(i)];
          ulist=[ulist V];
      end;
  end;
else
  V=[0;0];
  %ulist=[ulist V];
  uflag=1
  %break
  %a flag of 1 denotes no independent input timeseries
  %if outer loop is run, flag should eventually equal 1
end;
end;

%print matrix containing the base of input timeseries and corresponding
%sigmas
ulist

%output datamatrix loop
ylist=[ypicked;0];
My=y(ypicked,:);
V=[0;0];
for j=1:yloop;
  %m is conservative; if ylist contains all nonzero elements, all y are lin.indep.
  %with outer loop turned off, we will only find My and ylist for y(picked)
  %build matrix “dry” which contains dr for all other y(i)
  for i=1:m;
      Mtemp=[My;y(i,:)];
      dry(i,:)=det(Mtemp*Mtemp');
  end;
dry=dry/ylbigd;

%pick index in dr with maximum independence
%y(i)=y(ypicked) should be automatically eliminated since dr =0
%if max(dr) is not explicit, ties for nonzero maxes are included
if max(dry)>0
%extract index of max(dry)
  for i=1:m;
      if dry(i)==max(dry)
          My=[My;y(i,:)];
          V=[i;dry(i)];
          ylist=[ylist V];
      end;
  end;
end;

else
  \%V=[0;0];
  \%ylist=[ylist \ V];
  yflag=1
  \%a flag of 1 denotes no independent input timeseries
  \%if outer loop is run, flag should eventually equal 1
end;
end;

\%print marix containing the base of output timeseries and corresponding
\%sigmas
ylist
Goodwin Algorithm

%STEP 0
%assemble output datamatrix y[m,N]
%cuto and paste from XL
%assemble input datamatrix u[r,N]
%cuto and paste from XL
%user parameters
%user pick s (order of B)
%user pick n (order of A)
%user pick q (datawindow size)
%user pick N (datamatrices' width)
%define r
%define m
%initialize
Dhat=eye(m,m);
F(0)=eye(m,m);
for k=1:q
    F(k)=zeros(m,m);
end;
ybar=0;
t=0;
------------------ Δ put this in a separate Mfile. open and run simultaneously with below.

%STEP 1
%first loop, in terms of t=N:1 (step -1)
for t=N:1:-1;
    %build ybar for all t according to formula 3.9 [ybar indexed by t, with t=1:N]
    %1 loop using k=0:q, dummy variable ysum is used
        k=0;
        ysum=zeros(F(k)*y(t-k));
        for k=0:q;
            ysum=ysum+F(k)*y(t-k);
        end;
        ybar(t)=ysum;
    %build Fu for all t according to formula [Fu indexed by j and t, with t=(t-1):(t-s)
% and j=1:r]
    %3 loops, outer is i=1:s, mid is j=i:r, and inner is k=0:q. dummy variables Fsum, Fj
% are used
    for i=1:s;
        for j=1:r;
            %time reference (t-i) held constant by outer loop
                k=0;
                Fsum=zeros(u[j:(t-i-k)]*F(k);
                for k=0:q;
                    Fsum=Fsum+u[j:(t-i-k)]*F(k);
                end;
                Fj(j)=Fsum;
            end;
        end;
    end;
\[ F_{u(t-i)} = F_j \]

end;
%of i=1:s loop
end;
%of first loop

%start of next loop, in terms of t=N:1 (step -1)
for t=N:1:-1;
  %build \( x \) for all \( t \), by calling \( ybar[(t-1):(t-n)] \) and \( F_u[(1,t-1):(j,t-1);(1,t-s):(j,t-s)] \)
  %according to formula 3.8 \[ x \] indexed by \( t \), with \( t=1:N \). note that this call uses a
  %subset of ybar.
  
  \[ x(t) = ybar(t-1) \]
  for \( i=2:n; \)
  %note this requires \( n>=2 \)
  \[ x(t) = [x(t) \cdot ybar(t-i)]; \]
  end;
  
  for \( i=1:s; \)
  \[ x(t) = [x(t) \cdot F_u(t-i)]; \]
  end;
end;
%of next loop

%build alphahat using \( x[1:N] \), \( ybar[1:N] \), and \( D \) according to formula 3.4
% product of two loops, dummy variables \( Lsum \) and \( Rsum \)
\[ t=1; \]
  \[ Lsum = zeros(x(t)'*inv(Dhat)*x(t)); \]
  for \( t=1:N; \)
    \[ Lsum = Lsum + x(t)'*inv(Dhat)*x(t); \]
  end;
  \[ Lsum = (Lsum/N); \]
\[ t=1; \]
  \[ Rsum = zeros(x(t)'*inv(Dhat)*ybar(t)); \]
  for \( t=1:N; \)
    \[ Rsum = Rsum + x(t)'*inv(Dhat)*ybar(t); \]
  end;
  \[ Rsum = Rsum/N; \]
alphahat = \( inv(Lsum)*Rsum \)

%extract \( a(k) \) and \( B(j) \) from alphahat, which is a long vertical vector
%first \( n \) elements of alphahat are \( a(1) \ldots a(n) \)
%next \( m \) elements of alphahat are first column of \( B(j) \), \( j=1 \)
%first \( m \cdot r \) elements of alphahat after first \( n \) are components of \( B(j) \), \( j=1 \)

for \( i=1:n; \)
  \[ a(i) = alphahat(i); \]
end;

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for j=1:s;
    for i=1:r;
        Bi(i)=alphahat(n+(m*(j-1))+i);
    end;
    B(j)=Bi;
end;

%STEP 2
%first loop, in terms of t=N:1 (step -1)
for t=N:1:-1;
    %build nubar for all t according to formula 3.12 [nu indexed by t, with t=1:N]
    % difference of two loops, one using k=0:n and the other using j=1:s
    % note that these loops call a's and B's from alphahat.
    % dummy variables Lsum and Rsum

    k=0;
    Lsum=zeros(a(k)*y(t-k));
    for k=0:n;
        Lsum=Lsum+a(k)*y(t-k)
    end;

    k=0;
    Rsum=zeros(B(j)*u(t-j));
    for j=1:s;
        Rsum=Rsum+B(j)*u(t-j);
    end;

    nubar(t)=Lsum-Rsum;
end;
%of first loop

%start of next loop
for t=N:1:-1;
    %build gamma for all t according to formula 3.13 [gamma indexed by t, with %t=1:N]. call nubar subset (t-1):(t-q). dummy variable gammadum.
    gammadum'=nubar(t-1)';
    for i=2:q;
        gammadum'=[gammadum' nubar(t-i)']
    end;
    gamma(t)'=gammadum';
end;
%of next loop

%build Fhat using nubar[1:N] and gamma[1:N] according to formula 3.10.
% product of two loops, dummy variables LsumF and RsumF

LsumF=0;
RsumF=0;
for t=1:N;
LsumF=nubar(t)*gamma(t)';
RsumF=gamma(t)*gamma(t)';
end;
LsumF=LsumF/N;
RsumF=RsumF/N;
Fhat=LsumF*inv(RsumF);

%extract F(k) from Fhat
for k=1:q;
    Fdummy=0;
    for j=1:m;
        Fdummy(j)=Fhat(:,((k-1)*m)+j);
    end;
    F(k)=Fdummy;
end;

%STEP 3
%first loop
 t=N:1:-1;
    %build omegabar for all t calling nubar[t:t-q] and F[k=0:q]according to
    %formula 3.15, dummy variable dummy.

    k=0;
    dummy=zeros(F(k)*nubar(t-k));
    for k=0:q;
        dummy=dummy+F(k)*nubar(t-k);
    end;
    omegabar(t)=dummy;
end;
%of first loop

%build Dhat using omegabar[1:N] according to 3.14. 1 loop, t=1:N, dummy variable
%DumDum
 t=1;
DumDum=zeros(omegabar(t)*omegabar(t)');
    for t=1:N;
        DumDum=DumDum+omegabar(t)*omegabar(t)';
    end;
Dhat=DumDum/N;

%STEP 4
%check for convergence using equation 3.1
%1 loop using t=1:N which calls omegabar and Dhat, and outputs to user
 t=1;
summage=zeros(omegabar(t)'*inv(Dhat)*omegabar(t));
    for t=1:N;
        summage=summage+omegabar(t)'*inv(Dhat)*omegabar(t);
end;
J=(-m*N*log(2*pi)/2)-(N*log(det(Dhat))/2)-(summage/2)

%check for convergence using inspection of parameters of a and B
a
B

%goto step 1