A SIMULATION-BASED CONCURRENT ENGINEERING APPROACH FOR ASSEMBLY SYSTEM DESIGN

by

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ABSTRACT

Production system design, concurrent engineering, and lean manufacturing are each well-documented and well-researched subjects on which much literature is available. However, there is less written about the overlap of all three, and the interdependence they have on one another. This thesis, based on the development of a critical radar component at Raytheon Electronic Systems, shows how the three topics can be linked through the use of a simulation-based production cell design process.

There are three distinct research areas discussed in this work. First, a simulation-based process for assembly cell design is proposed and used for the initial design of a work cell. The process simulation tool ProcessModel is used as a design palette, and its output is used in other spreadsheet and graphical tools. Second, the thesis explores the value of implementing this process concurrently with product design. Many companies begin production system design only after drawings are released and the assembly process is fairly well determined. By starting earlier, this project shows that transition-to-production lead time can be shortened, and design for manufacturing and assembly (DFMA) recommendations can be more easily justified. Third, the project provides a case study showing why lean manufacturing cannot always be easily implemented in manufacturing if the product was not designed with lean thinking in mind. Characteristics such as yield and labor variability are more important if a lean system is to be designed, and must be accounted for in the design phase. The simulation-based approach provides a framework in which manufacturing and production personnel can analyze the impact of design factors on the "leanability" of the system and provide feedback to design personnel.

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1.0 INTRODUCTION

1.1. Background

Raytheon Electronic Systems, Air/Missile Defense Systems (A/MDS) is in the midst of developing an advanced ground-based radar for a missile defense application. Three developmental systems will be built over the next five years, funded by the U.S. government. One of the critical components of the system is the antenna subassembly. This is the microwave "front-end" of the radar system, in which the radar waves are guided, transmitted, and received. With almost 3200 of them in each radar system, this assembly is one of few relatively high-volume components. The high-tech nature of world-class defense systems, as well as the inherent precision necessary for radio frequency (RF) products, render the antenna subassembly a critical design and manufacturing issue for the radar system as a whole.

Additionally, the company initiated a corporate-wide Raytheon Six Sigma (R6σ) process improvement program two years ago, which includes significant attention to lean principles, and is striving to implement these principles throughout the factory and in product development. At the Andover plant where these radars will be assembled significant progress has been made in training a large number of employees in these principles, and initiating process improvements. Because the program is only two years old, though, most production process improvements occurred on the manufacturing floor, where there was little involvement necessary from designers. The transition of a new product from design to a lean or six sigma environment – particularly a complex product like the antenna subassembly – is a new challenge for the plant.

1.2. Project Setting and Motivation

This project was conducted at Raytheon's Andover, Massachusetts plant from June through December, 2001, through an internship arranged through MIT's Leaders For Manufacturing (LFM) program. In June, the design of the antenna subassembly was thought to be near completion. Throughout June and July, Raytheon assembled over 50 antenna subassemblies for a "pilot" radar array – the first articles built with a production-representative process. The pilot assemblies were built by process engineers skilled in assembly and manufacturing processes who would be responsible for creating the process sheets that would be transitioned to production.

The Manufacturing Engineering group - ultimately responsible for designing, implementing, and operating the production system – had not yet begun the manufacturing system design task. Typically their work would commence after the actual assembly process was fairly complete. This group did not expect to begin laying out the actual production floor until late fall or winter, which would provide the proper lead time to have the system up and running for production ramp-up planned for June 2002.

Raytheon management felt that the antenna subassembly project would present a good opportunity to examine its manufacturing system development process. Because of the complexity and production volume of the assembly, both production cost and stable, reliable output were areas of concern. Likewise, a tight schedule made transition-to-production time equally important. The antenna subassembly project presented an opportunity to examine the use of process improvements often championed by six sigma programs or lean manufacturing literature in a new production cell, as well as to examine the process for designing and developing production work cells in the future.

The author worked primarily with the Surface Radar Operations Group, which is closely linked to the manufacturing engineers, process engineers (who are sometimes called "concurrent engineers"), and program office but does not have direct authority over any of them. Thus, the author was well integrated with the key personnel in design and production, but acted largely independently. The intent of Raytheon management was to get an outsider's viewpoint and independent assessment, rather than one that was unduly influenced by motivations specific to the radar program.

1.3. Goals and Objectives

There were two overarching goals that Raytheon management outlined for this project. They were:

1) **Provide a baseline design for the antenna subassembly production system**. This design would include an analysis of production costs, lead times, etc., as well as a physical layout of the work cell. The objective was to get an earlier look at the production requirements (e.g. number of workers, time, floor space) as well as identify critical issues. Also, Raytheon wished to design six sigma and "lean" methods into the system to the extent possible, not only to reduce inventory and lead times, but also as learning tool for future applications.
2) **Develop a process for production system design that could be integrated with existing systems and processes**. Raytheon was not only interested in the antenna subassembly application, but also in the process and tools used to design the system. Management recognized that the current process used at the company had not changed significantly over many years, and that there may be opportunity to refine the process consistent with Raytheon Six Sigma and other initiatives going on throughout the company.

More than halfway through the research project, in October of 2001, the surface radar program office launched a redesign of the antenna subassembly that would continue through the following spring. This was driven primarily by technical problems discovered after the pilot build, but was partly justified by some of the early results of the manufacturing system design work conducted for this study which showed that the part was not as producible as originally believed. The redesign schedule made it virtually impossible to complete an assembly cell design by December, so much of the focus of this work was turned to the second objective – the production system design *process* rather than the system design itself. A somewhat fortunate consequence of the redesign is that it provided the opportunity to perform production system design work concurrently with product and process design work. This change allowed the first-hand examination of how well these processes could be integrated under the existing concurrent engineering practices in A/MDS, which ultimately became a key component of this thesis.

1.4. Project Approach

The following approach was followed to conduct the research described in this thesis:

1. **Participate in pilot build to learn product assembly process**. The author spent almost a month working with the process engineers in a Raytheon laboratory to build the first antenna subassemblies, thus becoming familiar with the part, the assembly processes, and the product/process development process.
2. **Outline work cell design approach and tools**. Academic literature was surveyed, and an approach was proposed that would best work for the antenna subassembly project. The approach, detailed later in the thesis, depends on some lean manufacturing methods and the simulation tool ProcessModel.
3. **Use this process for the preliminary design of the antenna subassembly work cell**. Because the product design and assembly process were not finalized, the intent was to figure out what the work cell would look like given the existing state of the product development.
4. **Identify areas of concern and areas of opportunity for production**. Based on the initial design and analysis, producibility challenges were identified that could be addressed through design or process changes, and these concerns were conveyed to the designers and process engineers.
5. **Iterate on the design**. Working with process engineers, process changes and production equipment options were identified. The production system design was then updated, and the impact of the process change analyzed.
6. **Assess the benefits of performing these efforts while product design is incomplete**. Although data was incomplete, analysis of the work cell design changes as well as program management input provided an assessment of the benefit to integrating work cell design early in product development in terms of dollars and time saved.
7. **Recommend a long-term concurrent process**. Interviews were conducted with engineering and manufacturing personnel to understand the current state of Raytheon's product development and organizational processes, and to determine how work cell design might become part of those processes.

8. **Institutionalize the design process**. Take steps necessary to facilitate the transfer of the work cell design process to permanent A/MDS employees.

1.5. Structure of Thesis

This thesis discusses production system design, concurrent engineering, and lean production processes, and how these three concepts can be intertwined. Thus, the concepts are often treated together, rather than separately.

Chapter 2 reviews the concepts of production system design, concurrent engineering, and lean manufacturing. A review of some of the most widely used literature about these concepts is included. Each section ends with a short discussion of how the concept is used by A/MDS.

Chapters 3 and 4 present the production system design process proposed and used by the author. A discussion of each of the process steps is mixed with a description of how that step was actually used in the design of the initial antenna subassembly work cell design. Chapter 3 is based on the work completed prior to the launch of the antenna subassembly redesign, while Chapter 4 focuses on the revision and continuation of the work cell design during the product redesign. Together, these two chapters narrate the work performed during the internship. They describe what was done and how it was done.

A discussion of the key points of the thesis is provided in Chapter 5. The discussion presents the author's views about what the Raytheon experience demonstrated about the production system design process, concurrent engineering, lean manufacturing, and the overlap of the three. If chapters 3 and 4 present what was done and how it was done, chapter 5 discusses why it was done and what benefit it provided.

Chapter 6 provides suggestions for future work at Raytheon, including the steps necessary to implement some of the changes suggested.

A brief summary of the conclusions reached is presented as Chapter 7.

2.0 REVIEW OF KEY CONCEPTS

2.1. Production System Design

There is no one way to design a production system, especially for a new product. In fact, much of the literature about production system design seems to presume that a well-defined production process is already in place, with yield, machine and labor time, and other variables being known entities. While the term “production system design” does not imply a specific process, it at least implies a list of tasks that must be completed.

Nevins and Whitney, et. al. (1989, 280) suggest the following process:

1. Analyze the product and necessary fabrication and assembly operations. Determine alternative fabrication methods, fabrication and assembly sequences, and candidate subassemblies. Determine fabrication and assembly process requirements. Assess the maturity of these processes and estimate process yields.
2. Select an assembly sequence for use in assembly system design.
3. Determine the production capacity required of the system, taking yield into account.
4. Tabulate feasible fabrication and assembly techniques (equipment and people) for each operation and estimate the cost and time for each.
5. Select a set of equipment or people that can make the product at the required rate for a reasonable cost.
6. Either make preliminary economic analysis or proceed to detailed workstation design and then perform economic analysis.

No matter what actual process steps are undertaken to complete the design activities, certain topics must be addressed for the design to be complete. The list of activities below is adapted from Nevins and Whitney, et. al. (1989, 281) which explains the steps in more detail. This is a fairly comprehensive and general list which provided guidance for the antenna project.

1. **Capacity planning**. Ensuring that the system will produce the required volume of parts – at acceptable quality – per unit time.
2. **Resource choice**. Deciding which resources (people, equipment, etc.) should be used to perform each operation.
3. **Task assignment**. Deciding which tasks will be performed by which resource.
4. **Workstation design**. Detailed design of each work station.
5. **Floor layout**. Arranging the resources into an effective layout on the factory floor.
6. **Material-handling equipment choice**. Deciding how to move assemblies within the system.

7. **Part provisioning**. Deciding how parts will be fed to equipment or people.
8. **Economic analysis**. Determining if the system design will meet economic criteria.

2.1.1. Production System Design at Raytheon's Andover Plant

There was no widely-used, documented, step-by-step process for production system design in place at the Andover plant. The responsibility for production system design for the antenna fell to a group of manufacturing engineers, comprised largely of personnel degreed in industrial or manufacturing engineering. Based on the process sheets developed by process engineers, the manufacturing engineers would lay out the assembly system using AutoCAD. Thorough standard labor time studies were used to aid in the layout and help balance the line, which means to subdivide the work content such that each worker on the assembly line has as equivalent an amount of work as possible.

2.2. Design for Manufacturing (DFM) and Concurrent Engineering

2.2.1. Concept Definition and Literature Review

There has been a well-documented effort by many manufacturing companies to better integrate design and manufacturing activities in an effort to reduce product development time, reduce total product cost, and improve quality (Whitney 1988, Dean and Susman 1989). Often, these companies are trying to get away from a serial product development process, in which designs are "thrown over the wall" (Adler 1992) from designers to process engineers and manufacturing personnel, who then struggled to produce products that were designed without their input. Adler (1992) reports that in one study of a company that followed this traditional process, engineering changes accounted for 20% of the company's overhead cost, and 80% of these changes could have been avoided through better coordination. Whitney (1988) states that 70% to 80% of the production costs of various products are determined in the design phase. The motivation for better integration is obvious.

The methodology of generating more producible products through better design is commonly and generally known as design for manufacturing (DFM). Design for assembly (DFA) is sometimes used as a more specific subset of DFM. The general principles of DFM are:

- Detail design decisions can have substantial impact on product quality and cost.
- Development teams face multiple, and often conflicting, goals.
- It is important to have metrics with which to compare alternative designs.
- Dramatic improvements often require substantial creative efforts early in the process.
- A well-defined methodology assists the decision-making process. (Ulrich and Eppinger 1995, 181)

Cross-functional teams are widely regarded as one of the most effective ways to implement DFM (Dean and Susman 1989, Whitney 1988). These teams, at a minimum, force design engineers and manufacturing engineers to work together throughout product development. Concurrent engineering (CE) is a term used by many companies to describe their new integrated approach. Swink (1998) suggests that the two aspects of CE that set it apart from traditional new product development approaches are cross-functional integration and concurrency. Typical approaches consist of functional organizations such as design and production that operate serially; when one functional organization is complete, it hands it work to the next. In CE, "integrated, multi-functional teams work together, simultaneously attacking multiple aspects of new product development" (Swink 1998, 103-104). Other companies have used the names "simultaneous engineering," "integrated product-process development (IPPD)," "early manufacturing involvement," or "concurrent design" to describe the same concept.

Whatever the name, the approach allows manufacturing engineers to influence the design in such a way that makes it easier and less costly to produce. Ideas they might have to lower costs or increase quality are passed to designers early in the design cycle. Designers get early feedback on production costs and challenges, when it is easiest and least costly to make design changes. Manufacturing personnel gain earlier insight into production challenges, which allows them to try to influence design choices or at least get a head start in developing solutions. These benefits should reduce costs and transition-to-production time.

2.2.2. Concurrent Engineering at Raytheon's Andover Facility

Raytheon management recognized the benefit of concurrent engineering, and had adopted a team-based approach to product development years before this project began. The people within A/MDS most responsible for concurrent engineering activities are product development engineers (PDEs), who are based at the Andover plant and work closely with product designers throughout the development cycle. PDEs seek to identify producibility concerns early, participate in DFM reviews, and shorten development times by working on transition to production issues well before design is complete. One year prior to this research study, the same Surface Radar Operations group hosted a different LFM internship to examine existing CE metrics and implement new ones (Tedesco 2001). An outcome of that project was a metric-tracking process called "As Designed/As Proposed" (ADAP) which has since taken hold widely within A/MDS. ADAP appears to have strengthened the CE process and the role of PDEs.

Production system design, however, is not a strong component of the CE process in A/MDS. Because the CE process is already in place, and the concept is widely accepted in the organization, the intent of this project was to develop a production system design process that could fit within the existing framework, and show that such a process can enhance the design-manufacturing coordination that already exists.

2.3. Lean Manufacturing

2.3.1. Concept and Literature Review

Lean manufacturing has its roots in the production system Toyota invented in the post-World War II years. Led by Taiichi Ohno, Shigeo Shingo, and others, Toyota created a manufacturing philosophy, commonly known as the Toyota Production System (TPS), built around the fundamental tenets of establishing flow and eliminating waste (Ohno 1988, Hilbert 1998). The actual term "lean manufacturing" became popular throughout the manufacturing world following the landmark study of world automobile manufacturing under MIT's International Motor Vehicle Program in the book *The Machine that Changed the World* by Womack, Jones, and Roos (1990) – which contrasted Toyota's success with competitors worldwide - and Womack and Jones' follow-up work *Lean Thinking* (1996) – which demonstrated that the same manufacturing philosophy can have a big impact in other industries.

There is now a broad base of literature covering examples of lean production and the methods and techniques used to implement it. There are a number of elements of the approach that are common to the vast majority of the literature:

- **Single Piece Flow**. Parts move through the system individually, rather than in larger batches as is common in many manufacturing environments. This single-piece movement of parts can drastically reduce work-in-process (WIP) inventory.
- **Pull Production**. At any work station, the operator only begins to work on a part if he receives a signal from the downstream station that another part is needed. In this way, inventory never builds up behind a work station. This contrasts with traditional "push" systems, in which raw material is released to the shop floor based on a master planning schedule.
- **Simple Material Flow**. The factory floor is set up to the extent possible such that the part can be easily transferred a short distance from one operation to the next, rather than being moved across the factory by material handlers (a process which lends itself to batching). Sometimes **cellular manufacturing** is used to achieve this objective. Workstations and machines are arranged in a small "cell" in close proximity to allow small-lot part movement, quick feedback, and multi-tasking of workers. A good review of U-shaped production work cells can be found in Black 1991.
- **Level Production**. Because a lean system is not well-situated for daily fluctuations in throughput, short-term demand variations are smoothed out over a period of time so that the production rate can remain steady.
- **Visual Control**. Visual cues are set up so that it is easy to tell if and where problems occur in the system, for inventory and material management, and for maintaining neatness in the workplace. Grief 1991 is a good reference for implementing visual control.
- **Standard Work**. Every step of every job is studied and documented thoroughly with the goal that it will be performed in exactly the same way, in the same amount of time, with the same result every time, by any operator.

- **Worker Involvement for Continuous Improvement**. Workers are empowered to stop the line if they observe a problem, are involved in the design of the work, and are expected to recommend ways to improve the system.

Spear and Bowen (1999) noted that companies from a wide range of industries around the globe have tried to imitate Toyota's success with the Toyota Production System, but few have been successful. They conclude that many of the imitators confuse the tools and practices they observe in plant tours with the system itself. This is partly because the underlying rules of TPS have never been written down or made explicit, and are not obvious to the casual observer. The "tacit knowledge" that forms the basis of TPS can be written in the form of four rules:

> **Rule 1**: All work shall be highly specified as to content, sequence, timing, and outcome.
> **Rule 2**: Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses.
> **Rule 3**: The pathway for every product and service must be simple and direct.
> **Rule 4**: Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization (Spear and Bowen 1999, 98).

Hopp and Spearman (2001) summarized both the benefits and problems American companies have had in trying to adopt lean production. They discuss key insights from JIT that "deserve a prominent place…in manufacturing management," including using the production system itself as a control, the importance of controlling work-in-process (WIP) inventory, and the necessity of continuous improvement. They go on to discuss how JIT has been misinterpreted and misused by many managers:

> What was described in the American JIT literature as a *system* is really a loosely coordinated *collection* of techniques infused with an inspiring stream of romantic rhetoric. The well-publicized success of the Japanese in the 1980's, appealing JIT slogans, and the apparent simplicity of JIT techniques led us to expect far more than we received from the JIT "revolution." (2001, 181)

Toyota developed a series of tools and techniques consistent with their low-inventory, continuous flow philosophy. The lesson is that a company hoping to match Toyota's success cannot hope to achieve their goals simply by imitating these tools and techniques.

Rather, the company as a whole (and not just the manufacturing function) must first subscribe to the same philosophy.

This same principle is emphasized by the Lean Aerospace Initiative (LAI) at MIT. LAI is a partnership launched in 1993 by leaders in the U.S. Air Force, the Massachusetts Institute of Technology (MIT), labor unions, and defense contractors in an effort to use lean principles to revolutionize the industry. LAI's "Production Operations Level Transition-To-Lean Roadmap" (2000) presents a seven-phase process for transitioning an organization to full lean implementation. The prerequisite ("Phase 0") and Phase 1 of the program entail adopting the lean paradigm and preparation. These steps rely heavily on senior management buy-in and laying the foundation in the workforce through training, communication, and assigning key personnel and teams to the overall transition. Actual designing of a lean production system does not begin until Phase 4. The key point is that an organization cannot simply jump straight to the design of a lean production system based on the principles outlined above and expect to reap the benefits. A larger organizational transformation is required first.

2.3.2. Lean Manufacturing at Raytheon

Raytheon did not have an explicit "lean manufacturing" program in place. Lean concepts were prevalent, however, in their corporate-wide Raytheon Six Sigma (R6σ) program launched in 1999. The concept of six sigma, a quality program developed largely by Motorola in the 1980's, has been adapted by many companies such as AlliedSignal (now Honeywell) and General Electric as a more generalized continuous improvement program. Dan Burnham, a former AlliedSignal executive, quickly implemented R6σ after becoming Raytheon's CEO as part of a strategy to improve overall operational performance and provide a foundation for continuous process evaluation and improvement.

R6σ is taught to a large number of engineers and managers throughout the company who are subsequently qualified – in ascending order of degree - as "specialists," "experts," and "champions." These personnel participate in and lead improvement programs throughout the company. Their training, depending on level, includes formal classroom instruction, online materials, and project work. It is in these training materials that the company's interest in lean can be found. Training documents, for example, highlight the virtues of single-piece flow, cellular manufacturing, and just-in-time production. There is no "lean manufacturing" program at Raytheon, but R6σ provides the basics of one.

3.0 PRODUCTION WORK CELL DESIGN

This chapter will outline the process used to design the production system for the antenna subassemblies. Partly because there is a substantial amount of manual labor involved in the assembly process, and partly due to Raytheon's six sigma initiative, there was from the outset a presumption that this system would be based to some degree on the U-shaped production cell concept popular in lean manufacturing literature. Therefore, the terms assembly system, production system, and assembly cell are used interchangeably throughout.

3.1. The Antenna Subassembly

Before discussing the design of the production system, it is appropriate to provide some understanding of the product itself. Because of the sensitive nature of the product, some details and photographs cannot be included; however, the following description should be adequate to understand the production challenges.

The antenna subassembly consists of a number of metallized ceramic polarizers, each several inches long with roughly a half-inch square cross section. One end of these polarizers is bonded to an aluminum housing using either silver epoxy or a soldering agent (the design choice had not been finalized). A set of two microwave radio frequency (RF) cables is bonded to the other end of each polarizer, also using either silver epoxy or solder. These cables are formed to a specific shape, and the ends are soldered to an output circuit, which itself has been bonded to a metallic output island. A number of round ceramic "windows," each with a diameter less than one inch, are bonded to the main housing unit – two corresponding to each polarizer. The entire assembly, when complete, has the approximate outer dimensions of 9" x 4" x 1".

There are a number of factors which make this assembly particularly difficult. The solder joints connecting the RF cables to the output circuit must be smooth and precise to meet RF requirements. This makes automation difficult, and thus requires skilled operators and takes a good bit of time. The silver epoxy (which may be replaced with solder) used for bonding must be injected in precise amounts at precise locations. These injections entail timely operations that require a good bit of operator judgment and result in significant part-to-part variability. Insufficient epoxy placement often results in excessive electrical loss or a short circuit, either of which would require downstream rework. The polarizers are very fragile, and several operations must be done very carefully to avoid chipping – another defect that would require rework. Alignment of these parts relative to one another must be precise. Intricate fixturing has been designed to meet this requirement, but a good deal of operator judgment and care is still necessary. In general, many of the assembly operations required to build this component require dexterity, judgment, and care from the operators – qualities that run counter to the objective of designing "standard work" into assembly processes. The types of alignments necessary, the fragility of the parts, and part-to-part variations hinder efforts to automate or mechanize these operations. Largely for these reasons, yield and quality are primary concerns for the antenna subassembly.

3.2. Initial Data and Assembly Process Flow

Almost two years of product and process design had been invested into the antenna subassembly. The design had passed the customer-mandated preliminary design review (PDR), and was several months away from the critical design review (CDR) milestone. Process engineers had been working for months in their lab experimenting with different assembly and bonding techniques, and had worked with a vendor to develop some fairly elaborate fixturing that would aid the assembly operations. Process sheets – the documentation that would eventually be provided to the shop floor as a step-by-step assembly manual for the operators – were in draft stage.

One of the requirements for the radar program was to produce a "pilot" radar array for test purposes that would have 44 antenna subassemblies in it. The antennas for the pilot – over 55 in total (including spares and rejected parts) - were assembled by both Raytheon and a local contractor at the beginning of this research project. Much of the initial data from which design activities could begin came from these pilot build activities. Although the assembly process steps were sure to change to some degree prior to production, the

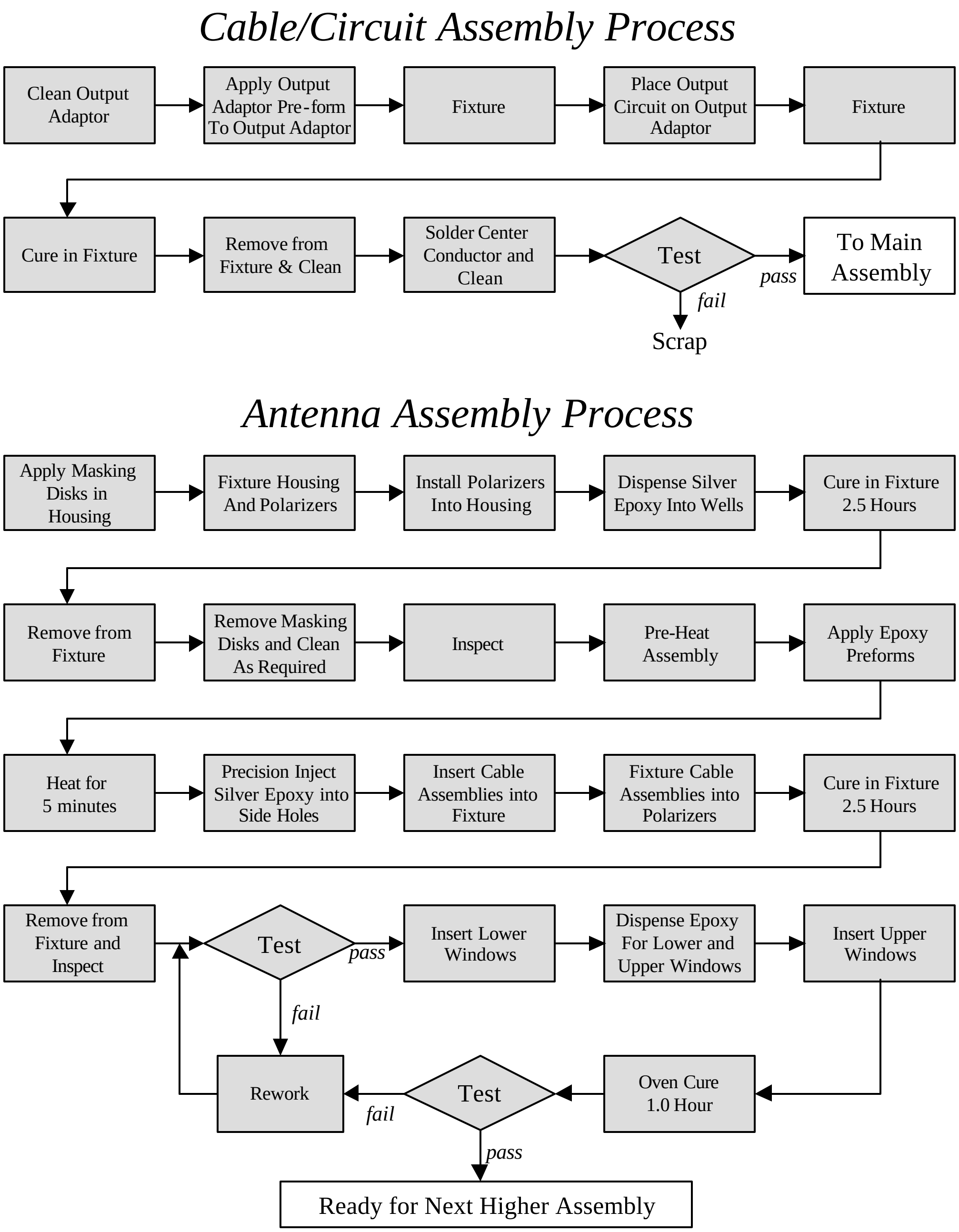


Figure 3-1: Generalized assembly process flow for the antenna subassembly

process used for the pilot build provided the starting point for the design of a production system. From the pilot build came initial measurements of labor times and process yields. A generalized process flow is provided as Figure 3-1. It is not comprehensive; rather, it is meant to give a basic sense of the number and nature of operations required.

3.3. Assembly System Design Process

3.3.1. A Process for Concurrent System Design

The basic process used to go forward with assembly system design is included as Figure 3-2. This process was conceived based on some of the literature discussed in Chapter 2, as well as on some of the resources available at Raytheon. This process is meant to yield a preliminary design only. A final, detailed design of a production system would require additional steps such as workstation design and specific equipment design and/or selection.

Prior to beginning any system design, it is necessary to have a candidate sequence of assembly steps, or process flow. At Raytheon, the process flow was determined by process engineers, and documented on process sheets that could be used by a production operator.

The starting point for the design is to determine the takt time. Takt time is defined by the simple equation below.

$$\text{Takt Time} = \text{Available Time} / \text{Average Daily Demand}$$

For example, to meet a demand of 80 units per day in an eight hour shift, the takt time would be 0.1 hours, or six minutes. In a steady production environment where units are worked individually rather than in batches, one unit of acceptable quality would be completed by the production system every six minutes. Sometimes the takt time is referred to as the “drumbeat” of the factory. In a truly lean assembly line, takt time would pace production. At the end of each takt interval, each operator would pass a completed part to the downstream operation, and simultaneously receive a part from the upstream operation.

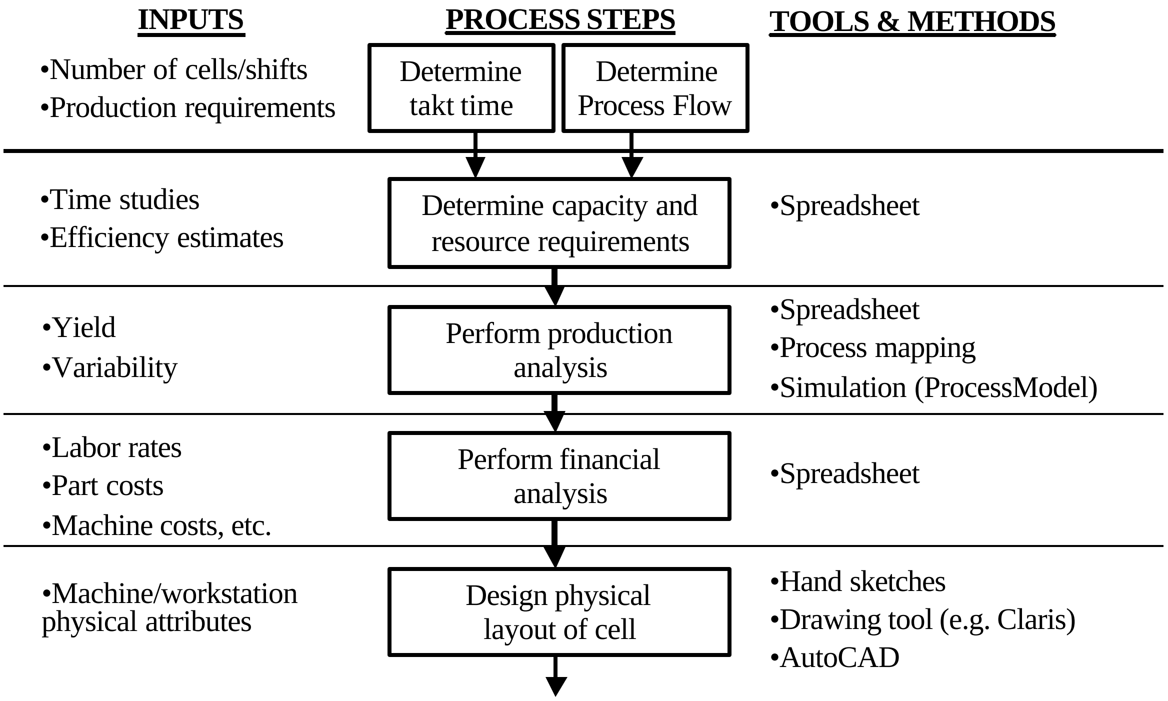


Figure 3-2: Proposed process for preliminary design of an assembly cell

By determining the takt time first, it is easier to envision how the assembly operations must be broken up and assigned to resources to meet production requirements. This will be demonstrated in section 3.5.2. It should be noted that factors such as break time, expected down time, and yield need to be included in the takt time calculation.

The next step is to determine resource requirements, particularly in terms of work stations, machines, and workers. To do this, one must start with at least reasonable estimates of the amount of labor time it takes to perform tasks, and candidate machines or equipment for other tasks (with their associated capacity and task times). Factors such as machine uptime and labor efficiency are important. Using a spreadsheet, adjacent tasks are grouped such that an operator or machine can complete them within the necessary takt time.

Production analysis follows the determination of resource requirements. This step entails gaining a deeper understanding and insight into how the proposed production system will operate. Variability (in terms parts availability, labor times, and other factors) is taken into account. The basic idea is to take the process flow, work assignment, and resource allocations determined in earlier steps and model the system using a simulation tool. The simulation is used partly as a test to ensure the system visualized will provide the anticipated output, and partly as an analysis tool to understand where inefficiencies exist and optimize the system. In this way the simulation tool can be used as a sort of design palette, where the designer can experiment with different resource and task assignments, part flow strategies, and batching and queuing policies.

Once the designer is satisfied that the system is adequately designed to meet requirements, the system needs to be analyzed from a financial standpoint. A spreadsheet is created to examine total fixed and variable cost of the system based on labor, part cost, machine cost (fixed and variable), and other costs such as support, overhead, and setup. To get an accurate estimate of cost, one must be careful to consider factors such as scrap, rework, and the efficiency of operators (especially during the ramp-up phase). If the cost appears to be unacceptable, the designer can return to the simulation package and attempt to design a better system. Also, now that the cost drivers are better understood, it is valuable to pass this information back to the product designers, who may be able to alleviate production costs through part design modifications.

The final step that can be performed prior to detailed work cell design (which should start only after the product and assembly process are complete) is initial layout. This involves translating the process model into a visual rendering of the system. Drawing software is used to arrange work stations, people, machines, and storage areas on a manufacturing floor. If there is already a designated area of the factory in which the production cell must fit, it is important to define the boundaries in the drawing. This exercise provides an initial estimate of the floor space required, and helps ensure the early discovery of any unwanted surprises such as the realization that additional floor space must be found.

This design process, like any design process, is meant to be iterative. At any time, if the designer realizes that objectives are not being met or there is an opportunity to improve system performance, he may return to an earlier step. If possible, lessons learned from these production system design activities should be used to reexamine the assembly process and sequence. Ideally, these lessons could also be used to influence the product design itself. This idea will be explored more fully in chapters 4 and 5.

3.3.2. ProcessModel Software

There are numerous simulation packages available on the market that can be used for production system design work. Some are provided specifically for that purpose, others (such as ProcessModel) are more general. They have varying degrees of complexity, ease-of-use, flexibility, and graphical capability, and the cost varies accordingly.

Several packages were considered for this project. ProcessModel – a flexible tool that allows the user to map and simulate any process - was ultimately selected for both technical and practical reasons. They were:

- **Ease of use**. The author had limited time to learn the software given the confines of this project. More importantly, the intent was to leave behind a tool that would be adopted by Raytheon's product development engineers and manufacturing engineers. Software that is easy to use and easy to learn is more likely to be institutionalized.
- **Adaptability**. There are a number of inherent features in ProcessModel that enable simple yet effective modeling of a production system. They include the ability to batch parts, model variability, assign resources such as labor and equipment, and specify labor shifts.
- **Accessibility to Author**. The company provided a free trial copy for use during this project. This was a definite obstacle to the use of alternate packages.
- **Accessibility to Raytheon**. ProcessModel was already being used in other Raytheon facilities for other purposes. Thus, the software vendor already had a Raytheon company representative, and there was an existing (yet limited) internal user base. These resources would make the eventual justification and adoption easier.

- **Graphical output**. Although the software does not provide a 2-D or 3-D rendering of the production system as do some other, more expensive packages, the simple animations of parts flowing through the process, queues building, and workers working is sufficient to communicate issues to other stakeholders, and for the user to grasp insight into the actual operation of the system.

For these reasons, ProcessModel became a logical choice for this research project. Given other circumstances, it is entirely possible that alternate software packages would have worked equally well or better; however, the intent here was to define a design process and design a work cell, not to evaluate software.

3.4. Design Objectives

Before embarking on any design activity, one should obviously understand the objectives of the design. The objectives of the antenna subassembly production system are outlined in Table 3-1.

Reduce Unit Production Costs	Drivers: Standard labor content, quality, machine operating costs, labor efficiency
Reduce Fixed Costs	Driven by machine and equipment cost, setup costs
Reduce Schedule Risk	Ensure predictable and timely output; driven by quality, variability, cycle time, and control
Minimize Floor Space Usage	Must fit into allocated space; Additional space savings would open up even more space to the rest of the factory

Table 3-1: Design objectives for the antenna subassembly production system

3.5. Takt Time, Capacity and Resource Requirements

3.5.1. Takt Time Calculation

Takt time is available time divided by maximum demand. Because there are almost 3200 antenna subassemblies per radar system, and only one radar system would be under production at a time in the foreseeable future, Raytheon has the luxury of planning for stable, predictable demand. The production schedule called for a maximum rate of 30 antennas per day, and would only need to exceed that if production fell behind schedule for some reason.

For this project, it was agreed to design the system for one shift operation. This decision was due to a number of factors. First, the first shift has a cost benefit – labor is cheaper. Also, management is more comfortable with the consistency and quality of the labor on the first shift. Additionally, by designing the system to meet production requirements in one shift, the second shift is available as buffer capacity in case production hiccups set the project behind schedule. It is assumed that in the course of a shift, the line will be up and running an average of 85% of the time, consistent with similar production lines in the plant.

The takt time is thus calculated to be:

$$\text{Takt time} = \frac{\text{8 hours} * 85\%}{\text{30 units}}$$

$$= 13.6 \text{ minutes}$$

Yield must be taken into account where necessary. When the antenna subassembly failed tests, in almost all cases it would be reworked rather than scrapped. Some assembly steps would not have to be repeated, so the 13.6 minute takt time for that step is accurate. Other operations would have to be redone, so effectively more than 30 units per day must be produced at these work stations. This problem is illustrated below.

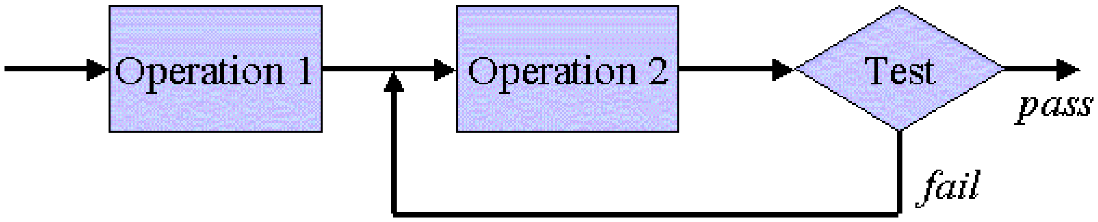


Figure 3-3: Part flow for a rework operation

In Figure 3-3, if the part fails test then Operation 2 must be repeated. If the yield for Operation 2 is 75% (and quality is 100% for parts flowing out of Operation 1), then 25% of the parts that are tested will be returned to the queue for Operation 2. If 100 parts must be produced per day, then the necessary capacity of Operation 2 is calculated as:

$$\begin{aligned}\text{Capacity} &= 100 + 100*(.25) + 100*(.25)^2 + 100*(.25)^3 + \ldots\ldots \\ &= 133 \text{ units}\end{aligned}$$

In this example, Operation 2 must be designed to handle an average of 133 units per day to meet the 100 unit production requirement. Because failures are random and unpredictable, this kind of backflow introduces a source of variability that requires additional attention. This is a problem for which simulation is well-suited, and will be addressed in subsequent sections.

3.5.2. Work Assignment and Resources

Once the takt time was known, the assembly operation steps were divided into groups that would fit within the takt time. That way, each operator can meet his daily production requirements as long as he is never starved for parts. Using the logic outlined above to account for rework and yield, a spreadsheet was created to divide tasks into workstations and assign resources. Figure 3-4 displays a segment of the spreadsheet.

The task time for each line item in the spreadsheet was determined by time studies performed by industrial engineers at Raytheon. Some are estimates, because they are operations that have not been studied before and have not been performed repeatedly yet at this stage of system design. Tasks were grouped into workstations, with a goal of getting as close to the "Max Time per Unit" as possible without exceeding it. The Max Time per Unit is equal to the takt time, but depends on the operation because some operations, like the second oven cure, are repeated for reworked items. In some cases it is not possible or practical to break up the work such that labor time is less than takt time – as is the case for Station 3 in the spreadsheet. In this case more than one operator will need to be assigned to this task. The spreadsheet also shows the necessary capacity of equipment. For

	Task time	Units per day	Max task time per unit	Req'd stations	Operators/ station	No. operators
STATION 1						
Apply masking disks	4.0	30.0				
Fixture holder	0.7	30.0				
Load polarizer into holder	1.3	30.0				
Fixture polarizer	0.5	30.0				
Dispense epoxy into well	3.5	30.0				
TOTAL	**10.0**		**13.6**	**1**	**1**	**1**
OVEN CURE	180.0	30.0	**13.6**	**14**	**0**	**0**
STATION 2						
Remove from fixture	1.0	30.0				
Remove masking disks and clean	6.0	30.0				
Inspect	1.0	30.0				
TOTAL	**8.0**		**13.6**	**1**	**1**	**1**
STATION 3						
Preheat polarizer/housing ass'y	0.3	30.0				
Apply preforms	15.0	30.0				
Heat 5 min	0.3	30.0				
TOTAL	**15.6**		**13.6**	**2**	**1**	**2**
STATION 4						
Precision inject epoxy into pol	10.0	47.0				
Fixture cable ass'y into pols	3.5	30.0				
TOTAL	**13.5**		**13.6**	**1**	**1**	**1**
OVEN CURE	150.0	47.0	**8.7**	**12**	**0**	**0**

Figure 3-4: Sample spreadsheet used for task and resource allocation

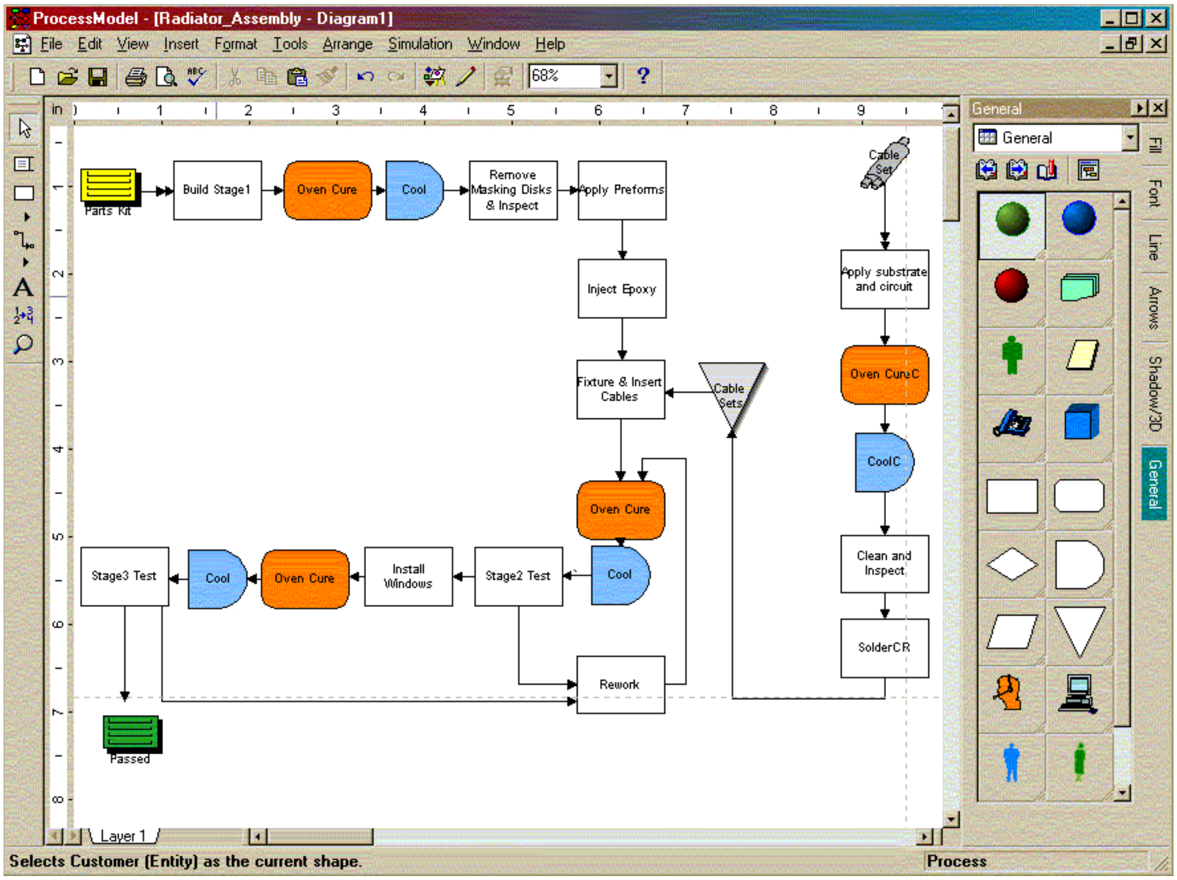
example, thermal ovens are needed for each oven cure cycle. If there is one oven for each cure cycle, then the capacity of the oven for the first oven cure cycle shown above must be at least 14 units at a time. This can be achieved by batching assemblies in groups of 14 and putting the entire batch in an oven at once, or by having a belt oven which would complete the cure of an assembly once every 13.6 minutes or so. In either case, the oven must be large enough to handle at least 14 units.

3.6. Creating a Computer Simulation

The spreadsheet provides the first conceptual look at the design of the assembly system, because it shows the number of people, workstations, and machines that will be necessary given the candidate assembly process. The next step is to ensure this concept will work, then refine and optimize it. Computer simulation is used for these tasks.

3.6.1. <u>Setting up the Model</u>

The first step in building the model using the ProcessModel software is to input the process flow. This represents the sequence of operations that the part or assembly undergoes before it exits the system as a completed piece of hardware. This process should be based on the assembly process as given in Figure 3-1. For simplicity, however, process steps were grouped into workstations consistent with the spreadsheet shown in Figure 3-4 so that the graphical output would more easily depict the final system layout.



Selects Customer (Entity) as the current shape.

Figure 3-5: Building an assembly process flow in ProcessModel

The process flow for the antenna subassembly production system is shown in Figure 3-5, as it appears in the ProcessModel window. The assembly sequence begins after a kit of hardware enters the system in the upper left of the diagram. The kit then travels through a series of processes, including manual labor steps, oven cures, and cool cycles. The subassemblies named "cable sets" go through their own sequence of operations prior to being attached to the main unit. These steps are shown down the right side of the diagram. Completed cable sets are stored in a buffer (the inverted triangle) until pulled from the "Fixture & Insert Cables" operation to be attached to the main unit. Completed antenna subassemblies exit the system on the bottom left. The other features noticeable in the diagram are the rework loops. If the antenna fails either of the two tests, it is sent for rework, after which it reenters the system upstream of the test. In reality parts may also be scrapped here, but because of the expense of the hardware this is rarely done, so that option was not included in early iterations of the model.

Once the process was built in the software, resources were assigned. For the first iteration, this involved only human resources, because the manual labor-intensive process required little in the way of expensive machinery (other than thermal ovens). The updated model diagram is shown in Figure 3-6.

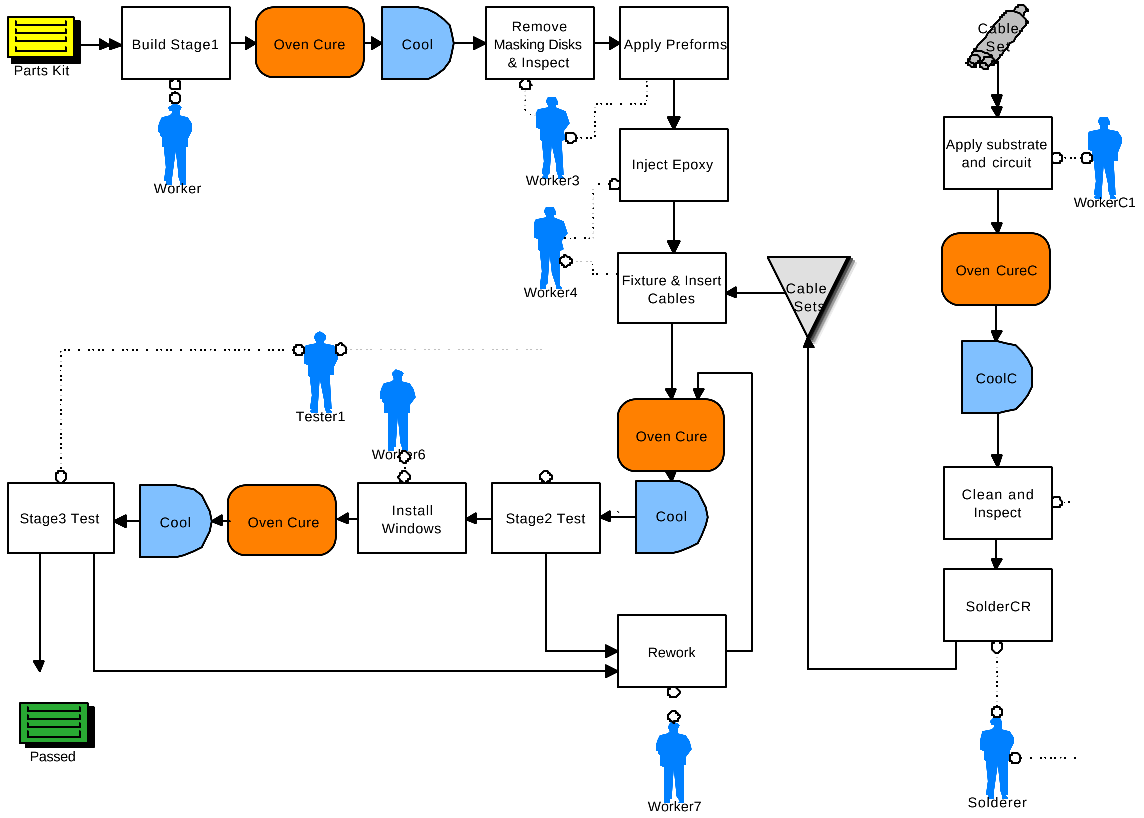
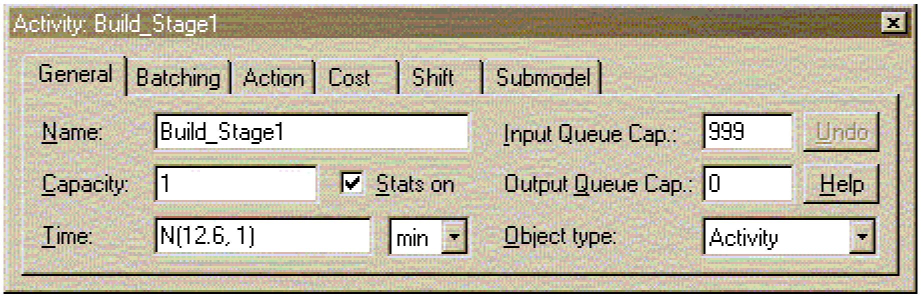


Figure 3-6: ProcessModel diagram for the antenna subassembly production system

Human figures representing operators are attached to specific operations. Eight operators can be seen in the diagram, representing 13 actual laborers (each figure may represent any number of laborers, as long as they have the same assignment and same availability).

The next step was to input relevant data. For each process step, or activity, this is done in the properties dialog box (shown in Figure 3-7).



Activity: Build_Stage1

Name: Build_Stage1

Capacity: 1

☑ Stats on

Time: N(12.6, 1) min

Input Queue Cap.: 999

Output Queue Cap.: 0

Object type: Activity

Figure 3-7: Properties dialog box for activity steps in ProcessModel

The dialog box shows some of the inputs that were made for the activity named "Build Stage1." The capacity entry shows that only one part may be in this activity at a time. The time entry shows that a normal distribution dictates how much time it takes to work on that part, with an average of 12.6 minutes and a standard deviation of 1.0 minute. There is no limit to how many parts may be in the input queue, and there is no output queue (completed parts are immediately sent downstream). Other tabs allow the user to input batch sizes, activity costs (separate from labor costs), labor shifts, and a number of other characteristics. Different properties boxes exist for resources (e.g. people), entities (e.g. parts and kits), and routings.

ProcessModel is inherently flexible, and allows the user to make a large number of inputs to customize and refine the model as much as desired. This flexibility enables the user to construct a model that closely reflects actual operation of the system, and to experiment with different operating policies to optimize the design. For this project, mostly basic features were used. The primary parameters that were set and modeled were:

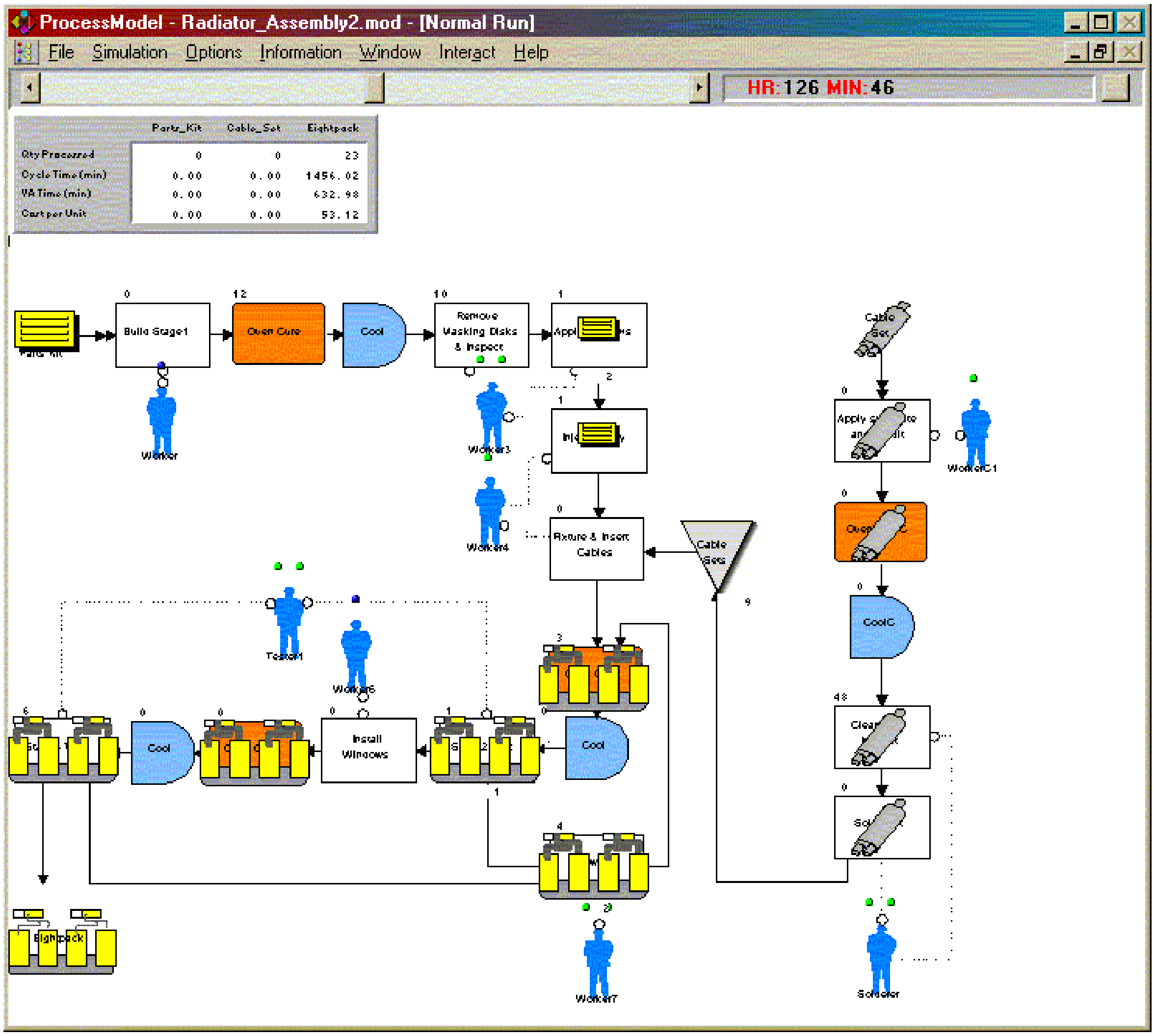
- **Parts arrival**. Parts may arrive continuously, periodically, in a specified pattern, or may be ordered.

- **Part move time**. This is the time it takes parts to move from one activity to the next.
- **Part batching**. Allows the user to set batch sizes.
- **Percentage routings**. This defines the percentage of parts that go down a particular routing. For example, after Stage 2 test 60% of parts move downstream, 40% go to rework.
- **Activity capacity**. Defines the number of parts that can be worked at one time at a given activity.
- **Activity time**. Defines how long it takes to perform an operation. The time may be constant, or may fit a number of different types of distributions.
- **Input and output queue sizes**.
- **Worker availability**. Sets the percentage of time a worker is available.
- **Worker shift file**. Defines a workers labor shift, including breaks.
- **Hourly cost**. Sets the hourly cost of labor.
- **Resource task assignment**. Defines how a resource responds to work requests.
- **Storage capacity**. Sets the capacity of buffers and inventory storage.

3.6.2. Running the Simulation

The simulation can be run for any amount of time. With ProcessModel it was important to run the simulation for a sufficient amount of time before taking data, so the system would first reach a steady state. A typical run in this project was 120 hour warm-up time, followed by an 8-hour run time (to represent one shift).

It is not necessary to always view the graphics when simulating the system. ProcessModel allows the user to skip the animation and just show the data output. Valuable insights can sometimes be gained through observation of the animation, however. Figure 3-8 displays a snapshot of the animation screen in ProcessModel. A clock in the upper right corner shows the time. Parts kits, cable sets, and antenna subassemblies can be seen at certain process steps. Numbers above process boxes show how many parts are in queue for that operation. Colored dots above the operators – one dot for each actual person – tell whether that operator is idle, busy, or unavailable. By watching carefully what happened on the screen, insight was gained as to where bottlenecks existed, why queues were building up, and why workers were idle.



	Parts_Kit	Cable_Set	Eightpack
Qty Processed	0	0	23
Cycle Time (min)	0.00	0.00	1456.02
VA Time (min)	0.00	0.00	632.98
Cost per Unit	0.00	0.00	53.12

Figure 3-8: Simulation graphics screen in ProcessModel

3.6.3. Simulation Output

Beyond the animation, ProcessModel provides a good bit of output for system analysis. The complete numerical output for the simulation shown above is provided as Appendix 1 (it is important to note that this was an early model and the data does not accurately reflect the current state of the system). The data provided includes:

- Each activity's current, maximum, and average contents, total number of entries, and average time per entry
- Each activity's percent utilization, percent partially full, percent of time blocked from delivering parts downstream, and percent of time waiting for parts or resources
- Each resource's percent utilization, number of times used, average time per usage, and percent of time down
- Number of entities that went through the system, their average cycle time, their average value added time, and their average cost

In addition to the numerical data, ProcessModel will provide a number of graphs and charts that help interpret and communicate key variables. The simulation output was used extensively for this project to figure out at which parts of the system problems may arise, and where further process work or system design could be done to improve system performance.

3.6.4. Iterating on the Design

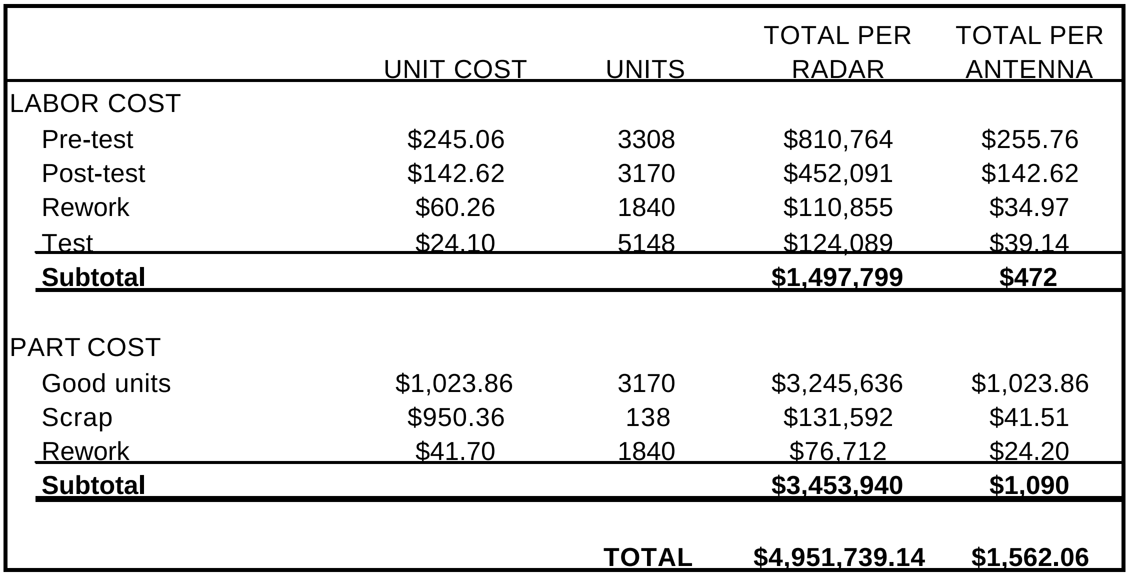
One of the benefits to using a PC-based simulation and modeling tool for design is that it is a relatively quick and simple process to change design parameters and iterate on the design itself. In this way the simulation tool was used as a design palette, constantly changed and updated as the design matured. Workers' priorities were reset to help alleviate bottlenecks, and batching strategies were modified to reduce inventory and cycle time without unduly increasing labor time or cost. Material release policies were changed to help even out material flow. These kinds of changes and modifications were continued until the design was near optimal. This design then served as a baseline – representing a reasonable approximation of the best that could be expected of a production system given the then-current state of the product design and documented assembly process.

3.7. Performing Cost Analysis

A spreadsheet tool was created to analyze manufacturing cost as best as possible and determine cost sensitivities. Although ProcessModel, if used carefully, can provide manufacturing cost as an output, the inputs cannot be changed quickly to examine sensitivities and run "what-if" scenarios.

Prior to this project, engineers at Raytheon were estimating cost by multiplying labor time study data by a "k-factor" to account for inefficiencies, then multiplying this time by a fully-burdened hourly labor rate. This labor cost was then added to material cost estimates. While this method is fairly effective for providing a rough estimate of cost – and Raytheon has demonstrated an ability to do it accurately – there is more to be learned with a detailed cost analysis.

The spreadsheet built for this analysis is based on both material cost and labor cost, so is meant to provide the variable cost of each unit. Fixed cost is considered separately. The standard labor time for each process step is an input. Process steps are broken into groups to separate those tasks that will be redone if a part is reworked, those that do not have to be redone if the part is reworked, and those that do not occur until after the test is complete, so they are never done more than once on any antenna subassembly. Material and part costs are treated the same way. That way, the true cost of quality can be calculated, using a rework rate and scrap rate as inputs. Labor hours are multiplied by a fully-burdened hourly labor rate and then divided by estimated labor efficiency, which is based on past experience. Labor efficiency is defined as actual labor hours charged divided by standard labor hours, so the spreadsheet just rearranges the equation.

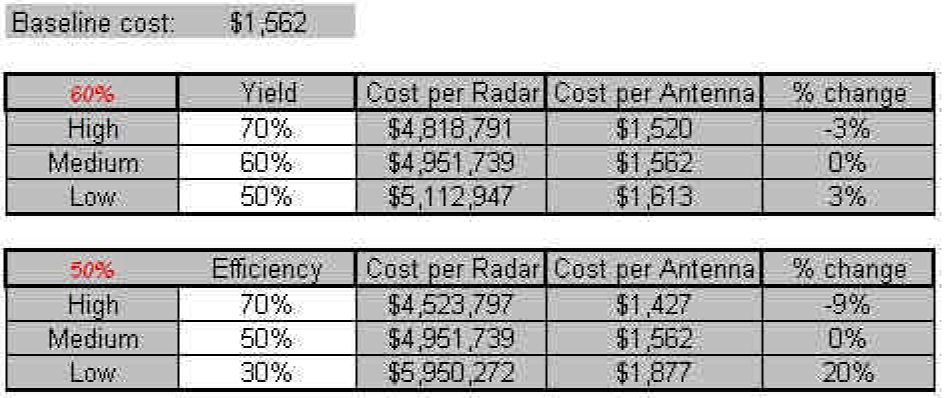


	UNIT COST	UNITS	TOTAL PER RADAR	TOTAL PER ANTENNA
LABOR COST				
Pre-test	$245.06	3308	$810,764	$255.76
Post-test	$142.62	3170	$452,091	$142.62
Rework	$60.26	1840	$110,855	$34.97
Test	$24.10	5148	$124,089	$39.14
Subtotal			**$1,497,799**	**$472**
PART COST				
Good units	$1,023.86	3170	$3,245,636	$1,023.86
Scrap	$950.36	138	$131,592	$41.51
Rework	$41.70	1840	$76,712	$24.20
Subtotal			**$3,453,940**	**$1,090**
		TOTAL	**$4,951,739.14**	**$1,562.06**

Figure 3-9: Output for production cost breakdown from cost analysis spreadsheet

Figure 3-9 shows the production cost breakdown for antenna subassemblies as provided by the analysis spreadsheet (true values have been disguised for confidentiality). The right-most column shows that the per-unit labor cost is $472, while the per-unit hardware cost is $1090. Moreover, it shows that scrap and rework together account for over $65 in cost per unit in parts alone, not to mention the additional labor costs.

A different sheet was created to calculate the sensitivity of cost to inputs such as labor efficiency, yield, and standard labor content. An example of some of these calculations is shown in Figure 3-10 (actual values still disguised). These calculations helped to justify design and process changes that would improve quality. They also show that if labor efficiency is improved significantly, it may be possible to save hundreds of thousands of dollars for each radar system built.



Baseline cost: $1,562

60%	Yield	Cost per Radar	Cost per Antenna	% change
High	70%	$4,818,791	$1,520	-3%
Medium	60%	$4,951,739	$1,562	0%
Low	50%	$5,112,947	$1,613	3%

50%	Efficiency	Cost per Radar	Cost per Antenna	% change
High	70%	$4,523,797	$1,427	-9%
Medium	50%	$4,951,739	$1,562	0%
Low	30%	$5,950,272	$1,877	20%

Figure 3-10: Cost sensitivity output

3.8. Designing the Physical Layout

Physical design of the work cell began once a process concept was in place that would meet production and cost objectives. While physical design is often not begun until product design is complete, there are benefits to performing at least a rough system layout while there is still an opportunity to influence design and process choices. At Raytheon, there was a fixed amount of floor space already allocated to the antenna subassembly production line, so it was important to learn early whether or not it would be possible to fit within that footprint. Equipment selection might need to be based on floor space issues. Further, physical design allows management to foresee requirements for such things as work stations and storage racks. Finally, a physical design provides a convenient and effective communication tool which can be used to explain the manufacturing system concept to engineers and managers.

The objective of coming up with a suitable floor layout for the baseline process was never met. Attempts were made to configure the system to fit within the 1000-square-foot area which management allocated for the antenna subassembly, but simply were unsuccessful. One of the lessons from the exercise is that if the process did not change, more space would be needed (at least several hundred more square feet). This information influenced future design iterations, because space become an area of concern and the largest space-takers (thermal ovens) were identified. Before a successful floor layout could be found, the product went into a redesign effort that made the point mute. The redesign will be explained in the next chapter, and the layout that was created is provided as Figure 4-2.

3.9. Searching for Design Improvements

Now that one iteration of a preliminary design was complete, it was time to begin looking for design improvements. Process improvements were one place to look. Many of the assembly operations documented for the antenna subassembly were sufficient for the pilot build, but were never refined or standardized for actual production operations. For example, the "Apply Preforms" operation entailed an operator placing tacky doughnut-shaped epoxy sheets on a small surface using tweezers under a microscope, while maintaining tight tolerances. Obviously there was room for improvement there, if the process designers put their effort into it. Also, there were opportunities for automating some of these steps. The benefit of process and equipment improvements could be shorter process time, higher quality, better reliability, safety, or perhaps something else.

A matrix was created to clarify where the best opportunities for improvement existed. Each operation was rated against a number of criteria related to sources of quality and other producibility issues. The first four columns related to quality: machine assignable causes, method assignable causes, operator assignable causes, and material assignable causes. Then there was a column for any other issues, such as undue labor time requirement. Next, there was a column for equipment design, which was meant to highlight the barriers that exist to the design or acquisition of a piece of equipment (like a fixture or robot) that would be able to do this step in a production environment. For each process step, notes and concerns were typed in the appropriate column. For example, “Cure time too short” was a comment under operator assignable causes for a cure operation, because there was a concern that the operator would not take the part out at the appropriate time. “Oven that controls time and temp” was listed under the equipment needs column for the same process step. Boxes that were of a major concern were shaded red, those of a more minor concern were shaded yellow – to highlight the problem areas that most needed to be address. Then each process itself was colored green, yellow, or red to indicate its readiness for production. This exercise was somewhat subjective, but served its purpose. A sample of the matrix showing a couple of the more troublesome processes is shown in Figure 3-11 (the letters R, Y, and G indicate color of the box).

PROCESS	MACHINE ASSIGNABLE CAUSES	METHOD ASSIGNABLE CAUSES	OPERATOR ASSIGNABLE CAUSES	MATERIAL ASSIGNABLE CAUSES	OTHER ISSUES	EQUIPMENT NEEDS
Apply preforms on top surface of polarizers, maintain concentricity, seat if needed (**R**)		Seating may move off-center; Pre-forms may fall off (**Y**)	Not concentric (causes loss or short) (**R**)		Difficult; long and extremely variable cycle time; Preforms must be kept in freezer	Easily and precisely dispenses epoxy on polarizers, using standard work with little variability (**R**)
Load cables into fixture, tighten clamshells (**G**)			Orientation or placement of cables incorrect	Cables not dimensioned properly; cables "lossy" (as delivered)		Ensures cables oriented correctly; Maintains precise alignment of port to center conductor; Rejects bad cables
Inject epoxy into side holes of polarizers (**R**)		Chip polarizer; Too much or too little epoxy (operator judgment) (**R**)	Does not inject epoxy into every hole			Controls amount of epoxy; Ensures every port filled; Does not damage polarizer (**R**)

Figure 3-11: Portion of matrix created for production process improvements

This matrix was not meant to provide any kind of compelling information that was not already known. Rather, it was put together as one way to consolidate the information that was already known, so that the weight of different production concerns could be judged more objectively. It served as a way to keep primary system design tasks in one place, and as a communication tool to show management and engineers exactly where in the process the largest areas of concern existed, and what might be done to alleviate those concerns.

At this point in the design process, there was a simulation model, a cost model, rough sketches of a physical layout, and a list of problems to address. Over a period a more than a month, process and manufacturing engineers worked to identify solutions to the problems highlighted in the production process improvement matrix. Some of this work was performed in a laboratory environment, such as experiments to examine using solder instead of conductive epoxy. Other efforts involved working with fixture and tooling designers to survey alternative means and processes for performing some of the necessary process steps. There was also a good bit of time spent working with automation vendors to learn what equipment was on the market that could perform the necessary functions, and to examine the feasibility of developing custom automation for some tasks.

It is beyond the scope and intent of this paper to list all of the alternatives considered; however, the continuous, iterative design process can be illustrated through the example of one such process change. A company named MRSI was found that produced a machine specifically for precision injection of epoxy. Discussions with engineers at MRSI ensued, and it was determined that it would be possible to program their machine to perform two of the most difficult assembly processes: injection of epoxy into small polarizer cavities and dispensing of epoxy that would replace the aforementioned epoxy preforms. They proposed doing a series of experiments to refine the process and demonstrate the precision and repeatability the machine could provide. Total machine cost would be $150,000[1].

Had this research not been underway, a decision whether or not to purchase the machine may have been largely subjective. There may have been some analysis based on the presumed higher yield and labor hours saved, but it would not have been very detailed.

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[1] Actual cost is disguised.

The exercise also raised questions about how else the machine might influence the system. What kind of routine maintenance was expected? If it took a half hour each day, for example, to load the epoxy, calibrate, and clean, the concept of cell operation would have to account for that. How often might the machine break down, and how long would it take to repair? These too affect the cell design and system performance. Would an operator have to dedicate her full attention to the machine during operation, or would it do its job independently?

The ProcessModel simulation was modified to model the changes should the MRSI machine be used. The exercise confirmed that two fewer full-time operators would be needed to meet production – one because of direct replacement by machine, and one because fewer parts would need to be reworked. Furthermore, higher quality subsequently reduced the testing load, because fewer parts had to be tested multiple times. Because the two test technicians would otherwise have been utilized very nearly 100% of the time, this helped eliminate a potential area of concern[2]. Perhaps these realizations could have been reached without the use of simulation, but the exercise of building a working simulation using the best available inputs at least brought these insights to light more quickly. Additionally, once the simulation was working the benefits of the new machine could more easily be demonstrated to management.

Cost-benefit analysis was straightforward using the spreadsheet described in section 3.7. Estimates for savings in standard labor and yield were entered. This showed that the machine had the potential to save almost $150 per antenna subassembly, which translates to over $400,000 per radar system. This savings was compared against known purchase value of the machine and estimated operating costs. The time value of money was taken into account. It became clear rather quickly that this machine represented a good investment, provided it was the only alternative to operating the process in its then-current

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[2] A utilization of 100% means that a resource has zero spare capacity. The slightest variation in demand could create a bottleneck.

state. Sensitivity analysis showed that even if labor and yield benefits were only half of the true estimated value, the machine would pay for itself rather quickly.

The next consideration was space. If the machine happened to take up more room than would be taken by the alternative processes, an analysis of how it would affect cell design would have been performed. In this case, however, the analysis was simple. One 4'x 3' machine would replace two workstations and at least one 3'x 2' rack. It would help alleviate the floor space issue described earlier.

Performing these "what-if?" design iterations also helped to assess what features Raytheon would want in the machine. MRSI suggested that the price of the machine would be reduced by about $25,000 if the material handling attachments were not needed. A sales engineer voiced his viewpoint that the attachments would be useful so that the parts could be batched in large groups. The machine would then run through a full day's batch in a couple of hours. This sort of batch-and-queue policy would not be consistent with the lean philosophy Raytheon advocated through its six sigma program. The simulations helped show why this would be a bad idea. By batching-and-queuing, cycle time and WIP would be higher. Worse, after the batch of parts would go through the machine, the final parts to be processed would remain in the output queue all day long, and sometimes overnight. The epoxy is no good if it sits for more than a few hours. In addition to the attachment decision, knowledge of necessary takt time (accounting for rework) aided the selection of other options, such as dispensing tips and programming alternatives.

A countless number of "what-ifs" scenarios were tested in an attempt to optimize the system. There were several team members involved in process refinement, each with their own ideas of how to make improvements. Having a baseline design concept, and a way to assess alternatives fairly quickly, ensured that everyone had the same understanding about how the system would operate. The baseline design – including the simulation, cost model, and layout – thus served as a referee while considering a large number of options. This process of design iteration and continuous improvement would have continued for several more months – limited first by the lead time needed to make equipment purchases

– had an antenna subassembly design flaw not been uncovered that rendered the current system design moot. That is the topic of the next chapter.

4.0 FEEDBACK INTO PRODUCT REDESIGN

Up to this point, feedback from system design activities had been fed back to process engineers, but not to product designers. The product design was thought to be essentially complete. The design task, in the eyes of program management, was coming to an end, and funding for design activities was soon to be discontinued. Any producibility concerns that remained – and there were many – were the problem of the process and manufacturing engineers.

That is how production system design would have proceeded, until a significant design flaw was uncovered. In August 2001, the antenna subassembly, for the first time, was subjected to environmental testing which consisted of thermal cycles and vibrations. Severe cracks occurred in the polarizers. Mechanical analysis over the next several weeks determined the cause to be thermal stresses caused by the silver epoxy used to bond polarizers to the main housing, combined with stresses partially caused by the RF cables that connected the antenna subassembly to the electronics module. The design as it then existed would not work; significant changes would have to be made.

Upon being informed of the problem, the program manager directed that a “tiger team” – a multidisciplinary team consisting of electrical designers, mechanical designers, structural analysts, process engineers, and manufacturing engineers – be formed to assess alternatives in as short a time as possible. Besides the multi-million dollar expense of launching a product redesign, the effort jeopardized the program schedule, which called for antenna subassembly production to start just nine months later.

4.1. The New Antenna Design

Within five weeks the tiger team came up with a new design configuration for the antenna subassembly. It looked essentially the same as the old design, but had a few notable changes. Additional flanges between each polarizer and the housing were added. Also, smaller diameter flexible RF cables would be used in place the rigid ones in the old design. Some details still needed to be worked out, but the concept was in place.

The new design required at least minor revisions to the assembly process. The process engineers, however, used the opportunity to introduce more dramatic process changes based on some of the learnings from the pilot build and the initial production system design work. The most dramatic change involved the RF cables. Instead of buying pre-made, formed cable sets that needed to be bonded to the polarizers, straight cables would be individually bonded to the polarizers, then formed with rollers. The loose ends were then coupled to an output platform. This modification circumvented two of the most difficult and troublesome process steps, but would not have been possible without designer involvement. A second modification involved sequence. In the old design, a number of polarizer-cable units were assembled into one housing to form an antenna subassembly, which was then tested. Almost all quality problems occurred at the interface between the cables and polarizers. Thus, by testing only at the full assembly level, there were many opportunities for failure per unit. The new assembly sequence called for testing of individual polarizer-cable units before they were attached to the main housing unit, effectively eliminating all of the defects before the assembly of a complete radiator unit. This substantially reduces test and rework requirements.

4.2. New Design of a Production System

The new process, in turn, required a new assembly system design. Fortunately, this was not too difficult to do. The hardest part was dealing with a relative lack of data. Over 55 units were built for the pilot array using the old process, so the team was able to gather some reasonable estimates on yield and standard labor times. Similar data was not available for the new process, however, so the team had to rely on unverified estimates. These estimates were made by process engineers, who were the most knowledgeable of the actual assembly operations.

The new process is shown below in Figure 4-1 in the form of a ProcessModel diagram. It is noticeably different from the earlier diagram (Figure 3-6). The most apparent difference is that there are more subassemblies that feed into larger assemblies. The subassemblies "RF cables" and "output islands" feed into the "polarizers" assembly.

Polarizers, in turn, feed into the main assembly (which begins as "housings"). Because of these feeder lines, this will not be one continuous production-line style work cell. In addition to the hierarchy of subassemblies, the diagram shows the new sequence of operations that need to be done to transform purchased parts into an antenna assembly, the routing of hardware (including the rework loop), and the resources – in this case people – necessary to perform the work.

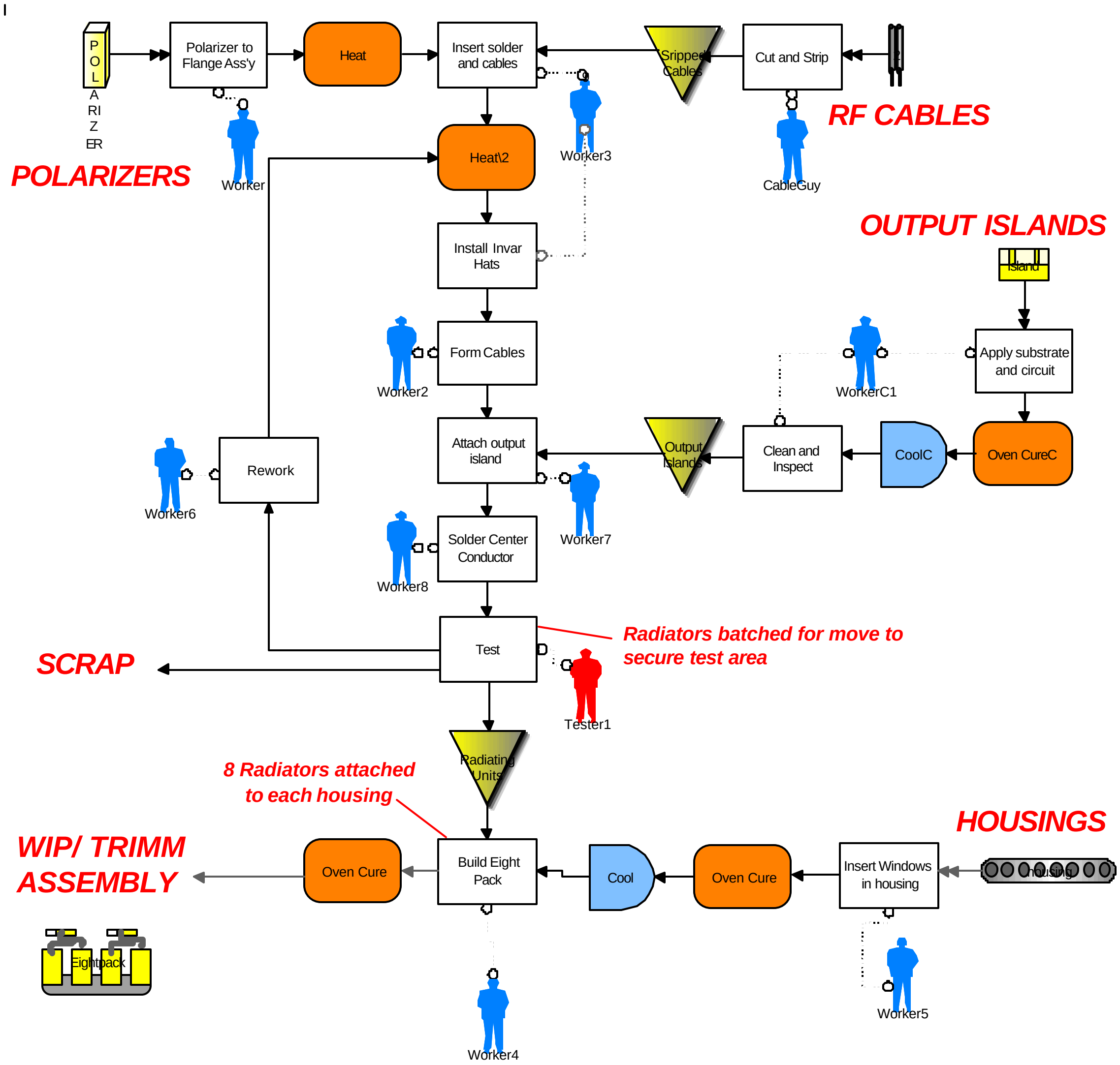

Figure 4-1: ProcessModel diagram for revised antenna subassembly product/process design

The next step, as described in Chapter 3 but not demonstrated, is to transform the model into a physical layout of the cell. For this new process, the corresponding layout is shown in Figure 4-2. The boundaries of the diagram represent the exterior of the plant floor space that management had already allocated to the antenna assembly cell (there is no actual wall at the bottom, but the lower edge of the diagram approximates the 1000 square foot limit). The diagram shows a candidate design of where workstations and work tables will be placed, where table-top thermal ovens will be installed, and where racks will be set up to serve as inventory buffer. The arrows show how material will flow throughout the cell (and out of the cell for classified testing). The diagram also shows where the operators will be positioned.

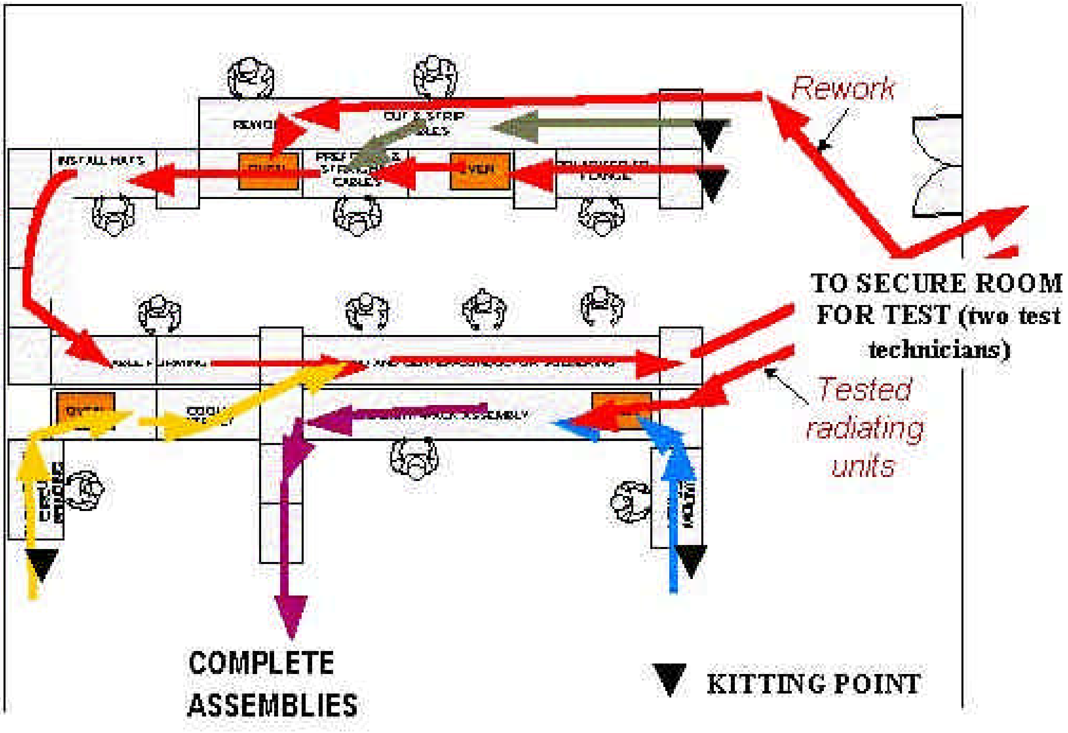

Figure 4-2: Rough cell layout and material flow for the new process

It is again appropriate to digress into lean manufacturing, which influenced (as it should) the physical layout. One of the primary principles of lean manufacturing is that material flows simply from one step to the next. This reduces the time and effort wasted on transporting material, and takes away an incentive to batch-and-queue. Once an operator is done with a process step, she can pass the part easily to the next station in little time. Because it is done so easily, she does not wait until she has a batch of parts to deliver, but rather passes each one along as it is complete. This enables single-piece flow. It also is compatible with the concept of visual control. Any worker can observe the rest of the system and see where problems exist. If an operator finds herself starved for parts, she can simply check with the person upstream from her to see where the problem lies. It is easy to see whether production from one's own workstation is needed downstream. Finally, the close proximity provides an environment for continuous improvement, because operators can work together to solve any problems as they come up.

The design shown is based on a U-shaped production cell, which is a popular layout for implementing lean. Antenna subassembly part kits would start at the second black triangle from the top, then follow the arrows around the interior of the cell. Subassemblies would begin at their on kitting points, follow the paths indicated by the arrows, and would be put into buffers (as shown in the ProcessModel diagram) in close proximity to where they will be attached to the main assembly. Nobody has to walk far to get what he or she needs. Racks are between workstations (racks are represented by the smaller rectangles, with no text) to hold work-in-process inventory, and may contain kanban squares to control exactly how many units may be placed there at a time. Completed antenna subassemblies exit the system at the bottom of the diagram. This exit location should be as close as possible to where antennas are needed downstream for assembly. Continuous flow is broken up only by the requirement to transport antennas out of the immediate area for testing, which must occur in a secure environment because of the technically sensitive nature of the data.

Together with the ProcessModel diagram, this diagram provides the current state of the assembly cell design. Obviously it is not final, nor can it be while the product design is incomplete. It does, however, serve as the baseline design for further revision, enhancement, and continuous improvement. It represents a realistic approximation of what the production system would look like – and how it would perform – should the product and assembly process be fixed at its current state (as of December 2001). Thus, it serves as a good communication tool to managers and project leaders who are concerned about the future production of the antenna subassembly. In the same fashion as described in section 3.9, this baseline can now be used to help assess potential production system improvements such as automation.

4.3. Comparison of the New and Old Systems

There is little benefit to walking through the design steps for the new assembly cell. The process steps are fundamentally the same as those detailed in Chapter 3. Cost analysis was performed. Iterations were made when process improvements or equipment options arose. The design was carried as far as it could given the best estimates and limited data available, and thus served as a baseline for continued design work and improvement.

The process of going through a complete redesign of the production cell allowed for a direct comparison of the new and old manufacturing systems in the early stages of product redesign. The results (as they stood at the end of the study) are presented in Table 4-1.

	Old Process	New Process
Laborers[3]	**13**	**12**
Floor Space	**~1250 ft^2**	**~1000 ft^2**
WIP (polarizers)	**973**	**505**
Total lead time (polarizer)	**4.1 days**	**2.1 days**
Yield (polarizer)	**94%**	**97%**
Yield (antenna subassembly)	**60%**	**99%-100%**
Labor + material cost per antenna	**$1562**	**$1475**

Table 4-1: Comparison of the new production cell design with the old (some numbers disguised)

The results, even though preliminary, are encouraging. The number of laborers decreased by one, despite the fact that some work has to be pulled in from suppliers under the new process. Floor space required decreases by approximately 20%, which is important because only 1000 ft^2 of space was allocated for this cell. Work-in-process inventory and

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[3] The new process actually pulls in labor from a supplier. Cable assemblies that were purchased in the old process are now produced within the work cell. This change was necessary because of the change in sequence in assembly operations.

total lead time decrease by almost 50% - a result of lower rework requirements and less reliance on a batch-and-queue operating principle. Most importantly, total cost is lower[4]. This is particularly significant because the design changes required to meet technical requirements (to pass the environmental test) were originally thought to add cost. There are extra parts in the new design that have to be purchased and installed. Also, the concept of testing individual radiators rather than entire subassemblies takes more time - and thus has a higher labor cost. The higher yield and revised process, however, combine to reduce cost more than the design changes increase it.

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[4] Although total costs are disguised, the estimated costs relative to one another in the table are accurate.

5.0 DISCUSSION

This experience provided a good bit of insight into the applicability of a new process and tools for production system design. Almost by accident – because of the unforeseen need for the antenna subassembly redesign – the project also highlighted some of the potential benefits of performing this type of work concurrently with engineering design and process development. Finally, this system design process provided a case study about the difficulties and potential pitfalls of trying to adopt lean manufacturing principles without a larger organizational and program management buy-in. Each one of these topics warrants a more thorough discussion.

5.1. Simulation-based Approach for Production System Design

5.1.1. An Approach for Assembly System Design

As discussed in Section 2.1, there are certain topics that must be addressed and decisions that must be made in the course of production system design. Capacity planning is perhaps the most important – one must be sure that the system will produce what it is required to produce. Floor layout and cost analysis are also very important details to consider early in the design process. Resources should be chosen as early as possible to reduce any lead time and make the necessary preparations.

Performing all of these things requires some kind of systematic process. Nevins and Whitney, et. al. (1989) present one possible process, as outlined in Section 2.1. This thesis proposes a somewhat different process (explained in Section 3.3.1), but one that relies on the same general sequence of steps: pick an assembly sequence, determine capacity requirements, select equipment and people to perform the tasks, perform cost analysis of the system, then iterate on the design until needs are met. Detailed design steps would follow. The most significant difference in the process presented here is the use of simulation to perform production analysis, and to serve as a sort of design palette. Only basic tools such as spreadsheets and drawing programs were used for other pieces of the process, such a cost analysis and layout design.

The value of this process is that it is structured and iterative. At Raytheon, there were a number of process engineers, manufacturing engineers, and managers who were involved in, or had cognizance over, the production system design for the antenna subassembly. At the time this project was underway, that group of people had no tangible baseline of a production system to discuss. Many ideas were thrown about, regarding equipment and process changes for different assembly steps, but there was no central focal point where all of this information was corralled. This project, particularly the simulation, provided a baseline design from which improvement discussions could be based. The process improvement matrix (Figure 3-11) was an attempt at centralizing concerns and improvement opportunities off of that baseline design. The layout design and cost analysis provided supporting data – the cost of the system in terms of dollars and square footage.

All of this output was produced for the purpose of continuous improvement. Design should inherently be an iterative process. Consider the example of an engineer designing a metallic structure for an aircraft. After choosing a material, the designer would probably proceed by drawing the part, perhaps on paper at first, but eventually on a computer using a CAD package. He would then analyze the part to ensure it would meet structural requirements, probably by importing the CAD drawing into a finite-element computer package. He would also determine critical metrics like weight and manufacturing cost. If the part failed to meet any of the predetermined criteria, he would make changes and go through the cycle again. Even if the part was judged to be feasible, the designer would probably spend some time iterating on the design to find ways to cut weight and cost – critical metrics for an aircraft design. He would "tweak" the design until he was satisfied there was little more to be gained.

Why shouldn't a production system design proceed in much the same way? Unfortunately, in many cases it does not. The design process in some cases is more serial than iterative. Design changes are not made until the production system is already in place and operating, at which time it may be expensive and difficult to change. In fact, much of the literature about manufacturing system design – especially in regards to lean systems – presumes that there is already a manufacturing system in place that is being redesigned, rather than designed from scratch.

Part of the reason for this may be that objective design tools are not available, or not used, for production system design as they are for product design. There very well may be better tools out there that can be used for production system design. There may be separate tools for simulation, layout, and cost analysis; or perhaps there is a program that can do all of those functions. It was not the intent of this work to evaluate the different products on the market for that. This project, however, did show one possible combination of analysis tools that can be used for this kind of objective, iterative design. The process used here allowed for continuous improvement. The components of the process – simulation, cost analysis, and layout design, will be discussed in more detail in subsequent sections.

5.1.2. The Value of Simulation

The simulation package ProcessModel was the centerpiece of the production system design process. The reasons ProcessModel was chosen rather than a different simulation package were discussed in section 3.3.2; they were more practical than technical. This section will discuss the benefits of simulation as a design tool in general, rather than the virtues of the specific package ProcessModel itself.

A user of simulation should be skeptical of the model she creates. Just because a simulation tool shows that a manufacturing system provides the desired throughput, cost, and cycle time, it does not assure that the system will operate that well in real life. There are a wealth of factors to consider, such as workers' ability to perform work consistently, variation from operator to operator, parts shortages, part tolerance problems, and unclear or inconsistent work rules. The simulation, however, provides a valuable reality check. If the simulated system does not meet the required output, a manager can be certain that the real system also will not do so. Thus, the simulation provides a way to identify problems and their root causes prior to any equipment purchases, floor layouts, or early production runs.

This idea of using simulation as a "reality check" came across from the work at Raytheon. Simulation was not intended to be part of the design process at the outset of this project. Basic analysis on an Excel spreadsheet was going to be translated directly into a physical design. The shortfalls of that approach rapidly became apparent. It was difficult to quickly change the design and try different scenarios. More importantly, a deterministic spreadsheet model could not easily be made to account for all the sources of variability that would be present. There was no certainty that the output from the spreadsheet at all reflected reality. The third shortfall was that it was hard to show a spreadsheet to a manager or engineer and describe what it meant in terms of a production system – an animation would prove to be much easier and more effective.

The simulation's value as a communication tool came as a bit of a pleasant surprise. It was remarkable how easy it was to discuss issues like bottlenecks, backflows, and queue sizes while displaying an animation, and how quickly the audience understood. In hindsight maybe this should have been expected. The cell designer may have a good sense in his head about how the system will operate, but it is difficult to express the ideas in words, numbers, spreadsheets, or inanimate diagrams. Nwoke and Nelson sum up the value of simulation for manufacturing system design by stating that it "render[s] the information meaningful to a larger group of decision makers often accustomed to viewing reams of unintelligible statistics and paperwork (Nwoke and Nelson 1993, 33-34)." They conclude that simulation is gaining wider acceptance in this role because of a "growing realization that people process information more effectively when it is presented through sight, sound and touch instead of just text or numbers." The experience at Raytheon certainly supports that assessment.

At a more analytical level, simulation allows a system designer to evaluate changes to buffers, material flow rules, or standard work definition. If variation is added or removed, its effect can be easily seen. If work is reallocated to different resources, the change in throughput and cycle time can be measured and understood almost immediately. Parameters can be changed in seconds, allowing trial-and-error design for parameters that cannot be easily calculated through deterministic means. The "updatability" of the model proved to be one of its greatest benefits in the Raytheon project.

The one shortfall to simulation in the antenna subassembly project, particularly during the product redesign, was a shortage of verifiable data to be used as input. If the input is unreliable, there are obviously limits to the value of the simulation output. Nonetheless, simulation allowed the team to assess the performance of the system given a set of reasonable assumptions, then test the robustness of the work cell design to changes in those assumptions.

5.1.3. Performing Cost Analysis

The cost analysis spreadsheets created for this project were not fancy, nor was there much in the way of complex math. They did, however, account for many of the components of cost. Part cost included parts that were scrapped. Labor cost included rework labor, and accounted for labor on parts that were eventually scrapped. Labor efficiency was included. The spreadsheet allowed for sensitivity analysis on all of those variables. Undoubtedly, a more complex spreadsheet could have been created to account for such things as support costs (there was no good data for this), fixed costs, and the time value of money.

Raytheon had been using a cost model that proved to be fairly accurate, but did not account for things like yield. Thus, the cost benefit of improving yield by 5% could not be computed easily and used for decision making. In the cost calculation comparing the manufacturing cost under the new production process to the old shown in Chapter 4, this component made a critical difference in showing that the new process will be cheaper. Raytheon's computation would not have captured that.

5.1.4. Layout Design

As in cost analysis, nothing unusual or innovative was tried in the layout design step. AutoCAD was used, as is standard procedure at the Raytheon plant. Later, for faster drawings, a package known as ClarisDraw was used. ClarisDraw provided a capability to quickly drag around components such as workstations to modify the design, which made it a simple design palette. It also provided an easy means to export drawings into presentation material (Figure 4.2 was created in ClarisDraw).

The point is that any suitable drawing tool may be used for this step. The lesson from this project is that it should be easy to update, and be able to create diagrams that are easy to read and clearly depict what the production cell will look like. It is necessary to have a drawing for communication purposes, and one that can easily be updated as design iterations continue. Nothing more.

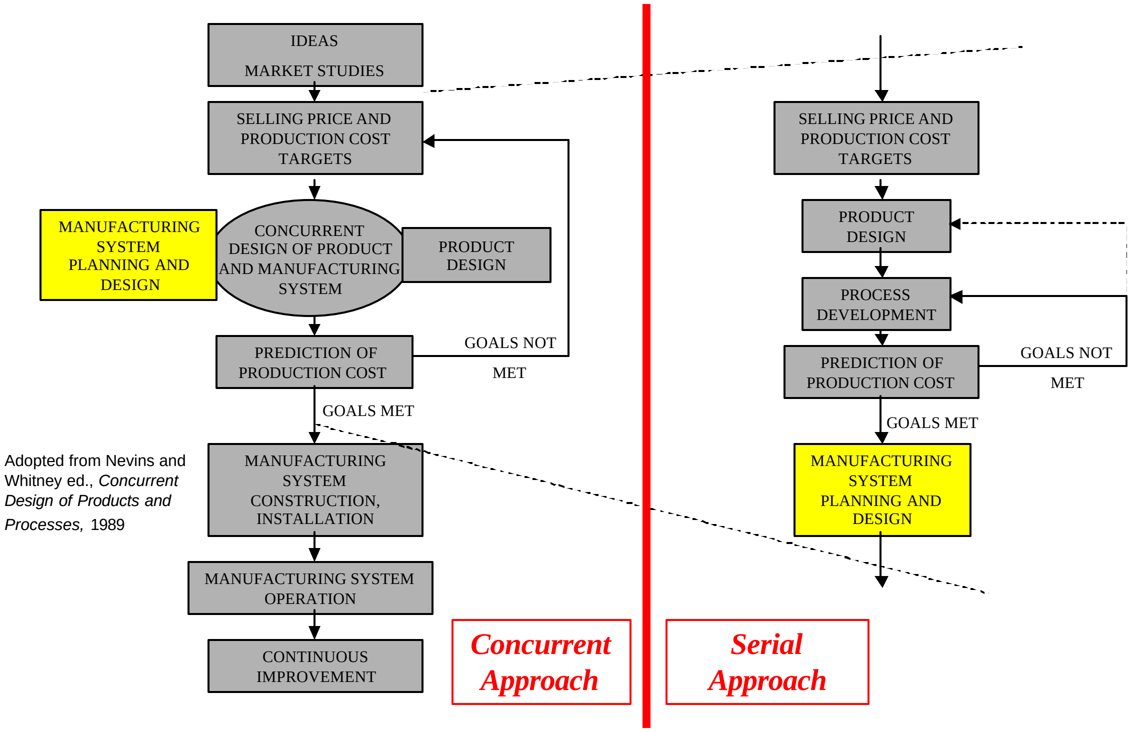
5.2. Incorporating Production System Design with the Concurrent Engineering Process

5.2.1. <u>The Timing of Manufacturing System Design</u>

Section 5.1 dealt with a process for manufacturing system design, or, more specifically, assembly system design. It did not, however, discuss the timing of that process relative to entire product development program. This section explores the value of using this process concurrently with product engineering, rather than afterward.

The concept is shown in Figure 5-1. On the left is a concurrent engineering approach (adapted from Nevins and Whitney, et. al. 1989), in which manufacturing system design is performed at the same time as product design. On the right is more of a serial approach, in which manufacturing system design follows only when the design is complete. It is important to note that even in the serial approach, it is possible to incorporate concurrent engineering processes, as Raytheon has. For the antenna subassembly project, process development was proceeding in parallel with product design. The difference is that manufacturing system design did not commence until product design and process development were deemed complete. The feedback arrows in the diagrams are the important distinction. On the left, the design is only considered complete after manufacturing system design is complete. If the manufacturing system design does not meet goals (cost is shown here, but other factors may apply), then all design activities are open to change. On the right, the product and process design are deemed acceptable – generally in a formal design review - without knowing the design of the production system.

Should some unforeseen problem be uncovered during production system design, there is no feedback to design.



Adopted from Nevins and Whitney ed., *Concurrent Design of Products and Processes,* 1989

Figure 5-1: Comparing a concurrent approach to production system design to a serial one.

It may be easier to use a serial approach. There would certainly be less iteration. But there are clear benefits to designing a production system concurrently. These benefits were observed during the antenna subassembly project, and will be discussed in the pages that follow.

5.2.2. <u>The Unintentional Concurrency of the Antenna Subassembly Design</u>

This was not originally meant to be a project in concurrent engineering, but that is what it became – by default – once the antenna subassembly redesign was launched. A tiger team was put into place that included product designers, process engineers, structures analysts, and manufacturing engineers, all working together on the redesign process. It became a perfect example of concurrent engineering. All that was learned from the first iteration of this production system design study was available for feedback into the product design, and production system design activities were to continue while the tiger team was in place. It was this production system design activity that was somewhat unique – it had always been an activity performed *after* product design, not during.

From a producibility standpoint, the environmental test failure was a blessing. No redesign would have been launched had the part not failed. Although this project had begun to document a pretty strong case that the antenna subassembly was not very producible, the program manager would not have been able to justify a costly redesign effort because at that point, manufacturing cost savings might not even offset the cost of the redesign. Process and manufacturing engineers would have shouldered the complete burden of solving the producibility challenges outlined in Chapter 3. It is impossible to know for certain how this ultimately would have turned out, but it surely had potential to become a long-term management headache due to low yields and unpredictable output.

Once the redesign was launched, it presented a clear opportunity to make design changes based on producibility concerns as well as to fix the structural problem. Some of these concerns were raised well before the initial design was complete, but were not incorporated into the original antenna subassembly design because they could not be justified. Partly this was from a lack of data – prior to the pilot build, nobody knew for certain what the yield would be or how generally difficult it would be to build antennas. But also, there was no quantifiable assessment of what those yield and labor problems would cost. Designers, on the other hand, knew exactly what those changes would cost in terms of both development effort and, more importantly, technical performance.

When the pilot build came around, however, there was a clearer understanding of the design trade space. In one notable example, process engineers suggested that the designers reduce the diameter of the RF cables, which would enable a new assembly process that would improve yield and reduce labor time. They could not quantify the improvements, though. The designers contended that the change would diminish a critical measure of electrical performance by a small degree, and were unwilling to make the change. By the time the tiger team was in place, though, the producibility benefit was more evident. The pilot build had provided actual yield data, and the simulation and cost study from the assembly system design process provided an objective analysis of what would be saved. At that point the design/process tradeoff was clear, and the change was made.

The other benefit of concurrent assembly system design that came about was earlier integration with equipment suppliers. The system design clarified exactly what components of the assembly cell still needed to be developed, or improved, before production was to start seven months later. This information was taken to makers of automated machines, manual equipment, and fixturing. Specifications, such as cycle time, maintenance down time, and labor input were known from the baseline work cell design. Because of the lead time necessary to design and build some of this equipment, it was necessary to begin as early as possible to avoid delays in production. Had production system design work not been started concurrently with the tiger team redesign, one of two things would have happened: 1) the equipment procurement process would have started months later, delaying the start of production, or 2) equipment would have been procured without knowing the necessary specifications, which inevitably would lead to disruptions of smooth production flow and inefficiency in the cell.

5.2.3. Benefits of Concurrent Assembly System Design

Some of the benefits of concurrent assembly system design were apparent in the Raytheon project. There are others that are worth discussing. Here are the main benefits that can generally be expected when production system design is performed as part of concurrent engineering.

- **Objective evaluation of the design space.** In order to make design trades, engineers and managers must be confident in the data. Concurrent production system design helps quantify producibility benefits, so process changes can be assessed against other characteristics like technical performance.
- **Better understanding of cost drivers.** Similarly, designers and managers need to understand the producibility impact of certain design features. They should know, for example, not just what the impact of a design change is in terms of yield, but how that

yield change translates to production cost. The same is true of labor time, variances, or other characteristics that may be driven by the design.

- **Earlier integration with equipment suppliers.** The earlier manufacturing engineers begin integrating with suppliers of equipment, the more options they will have. Some equipment may need many months of design or customization effort to bring online. Thus, concurrent system design should shorten the transition-to-production lead time. It may be possible to begin integration with suppliers before working on production system design, but then one runs the risk of not providing detailed, or correct, specifications.
- **Design for lean production.** For lean manufacturing to work, variability must be reduced. This variability often is caused by design and process issues such as ease and repeatability of assembly steps. Designers must be cognizant of the variability they have introduced to the system, understand its impact on the production system, and work to reduce it. This requires them to work closely with manufacturing personnel to identify the sources of variability and find ways to mitigate them. Doing this after the design is released is expensive and time consuming, but addressing these issues early in the design cycle is much less so.
- **Continuous improvement.** This is perhaps the most important idea behind concurrent production system design. The idea was discussed in Section 5.1.1 – production system design should proceed in a similar fashion to part design. Objective tools make the process inherently iterative. Concurrent engineering carries that logic one step further. Instead of having a product design proceed iteratively, followed by an iterative production system design, both designs proceed together, iteratively. In an ideal case, when a product designer makes a design change, she would not only know how that change effects product characteristics such as weight, material cost, or strength, but would also gain rapid feedback about production cost and other production characteristics such as floor space or lead time.

5.2.4. Challenges of Implementation

Although this concurrent approach worked well during the Raytheon tiger team, there are reasons that it may not be practical all the time. The main reason is data. In order to perform a realistic design of an assembly system, one must have reasonable estimates of yield and labor time, as well as some variability estimates. This data was available for the antenna subassembly only because of the pilot build several months before. Once design changes were underway, this data was no longer reliable, and the production system design had to be based on estimates of yield, labor time, and variability from prior experience. Getting this data is a critical step to full implementation of concurrent production system design.

In fact, Raytheon has a software tool that provides this data for some types of hardware, such as circuit boards and cable assemblies. The tool is called PCAT – for Production Capability Analysis Tool – and has been verified with experience. The shortfall is that this tool cannot help with unique assemblies such as the antenna.

There may be other barriers as well. Cultural barriers may make it difficult for designers and manufacturing people to work well together. If those people are not co-located, communication tools must be in place so it is easy to share and transfer data. There may also be programmatic pressure, such as a desire to hold a design review by a certain date, that hinders concurrent engineering. Thus, adopting a concurrent production system design strategy is not trivial.

5.3. The Role of Product Design in Lean and Six Sigma Production

Aside from presenting a concurrent approach for production system design, this project provided a case study about the difficulties of implementing lean manufacturing techniques. This project started out with a goal of introducing lean concepts into an assembly cell design. In practice, few were included in the initial design.

As implied by the discussion in section 2.3.1, lean manufacturing relies on low variability. Because large time and inventory buffers do not exist in a lean system, any disruption caused by variable operating times, unreliable resource availability, or inconsistent material flow will likely impact the production plan. In fact, that is the primary concern of most six sigma programs. Variability and lean do not mix well, so to design a good lean system variability must be rooted out of the assembly process. The antenna subassembly design was the cause of a great deal of variability, much of which has already been discussed.

The most critical sources of variability were quality, which resulted in massive amounts of rework, and the lack of standard work processes . The parts that will require rework cannot be expected to arrive in standard, consistent intervals, nor will each reworked part require the same amount of labor input. Rework will be a highly variable operation, with an uncertain input queue and an uncertain requirement for labor. Once parts come out of rework, they are sent to an upstream operation, which also is receiving new parts coming through the system. Thus, this operation must have an input queue of variable size to handle the parts that are intermittently passed to it. The effect of non-standard work is similar. Because it will take an operator a different length of time to do his job on each part, part arrivals downstream will be erratic.

The variability caused by rework and non-standard work must be accommodated with some combination of buffers and spare capacity. Spare capacity usually means underutilization, which was seen in the simulation iterations. Some of the workstations served as bottlenecks, but others were highly underutilized. As work was added to these underutilized stations to balance the line better, output got worse, unless buffers were added to account for the variable part movement. Buffers increased work-in-process and lead time. So much for a lean system.

The problem was that the antenna subassembly was never designed for lean manufacture; rather, it was designed primarily for electrical performance. Any hope to assemble the antenna according to lean principles came out of manufacturing personnel, not designers, well after the design was mostly determined. Lean manufacturing literature (see Chapter 3 for a review) is fairly clear in stating that repeatable, high-yield processes are a prerequisite to the implementation of a lean production system. The first chance to ensure that a product can be made with repeatable, high-yield processes is during the product’s design. The antenna subassembly provides a good example of the difficulties that may arise if an organization places the burden of implementing lean manufacturing principles solely on the shoulders of manufacturing personnel, without ensuring the product designs are appropriate for such an implementation. As stated in the previous section, this realization presents another benefit of concurrent engineering. In an ideal CE process, manufacturing personnel wishing to implement lean manufacturing processes could work with designers early on to make design choices that would lead to the repeatable, high-yield assembly steps necessary to do so.

6.0 FUTURE WORK

There is much work to be done (as of the writing of this thesis) if Raytheon wishes to implement the process changes discussed in Chapter 5. This chapter presents short recommendations for future work related to this project, in terms of both the simulation-based production system design process and concurrent engineering.

6.1. Validation of Simulation-based Design Process

Validation of the simulation-based design process is the obvious next step for this project. The timing of the internship was such that production system design work preceded actual implementation and production by seven to nine months. Thus, this thesis was written before the actual results and benefits could be measured.

The simulation-based approach to work cell design is unproven for this application. If Raytheon is to adopt this approach, there would be tremendous benefit to continuing this work while antenna production is ramping up. As more yield and labor data is available for the antenna subassembly, the model can be revised and updated to more accurately reflect production needs. The actual work cell layout would be based on the final model. Real production data should be taken, and compared to model output.

This would serve the dual benefit of verifying the model and getting a better handle on production concerns. Often the source of problems on the factory floor are not obvious. By matching the model inputs to actual factory data, then running and observing the simulation and studying the data, a manager or engineer can gain insights otherwise not available. “What if?” scenarios can be run. In this way, the simulation will provide a tool for continuous improvement.

6.2. Adoption of ProcessModel Software

Once the design process (and especially the software) is verified, the next step is to ensure it is adopted by the appropriate people within Raytheon. In this case, those people would be the product development engineers (sometimes called concurrent engineers) and manufacturing engineers, who are responsible for production system design.

Shortly after the internship was complete, Raytheon purchased about a dozen copies of ProcessModel for both production system design and unrelated process improvement efforts under their six sigma program. This financial commitment shows that management is serious about adopting the package. Having a sizeable user base, rather than just a few users, will make the long-term use of ProcessModel more probable, as users can rely on each other to help learn the program and apply it to different situations. Hopefully, the continued use of the tool will naturally lead to its institutionalization as part of the product and production system development process. As more managers become familiar with the output of the simulations, more will demand it as part of future development efforts.

This is not a difficult change to make. The few managers who have already purchased the program have the power to adopt it as a normal part of operating procedure. Little in the way of senior management buy-in is required, and a large consensus need not be built.

6.3. Integration with Other Corporate Tools and Methods

The more ambitious goal of integrating this work cell design process with concurrent engineering requires quite a bit more effort, well beyond that of a six-month internship. To get the full benefit of this process, Raytheon should consider integrating it with other tools and processes already in place. Fortunately, the company already has a fairly good concurrent engineering process in place, along with some nice tools to support it – but manufacturing system design is not part of it.

A representation of how the concurrent engineering process worked for the antenna subassembly is shown in Figure 6-1. In this system, a task labeled "process engineering" is done concurrently with product design, and manufacturing system design follows. Process engineering includes tasks such as characterization of individual assembly steps, lab experiments related to processes, drafting of process sheets, and investigation and design of automation and fixturing. The distinction with manufacturing system design is that in process engineering, nobody is looking at the system as a whole; rather, the focus generally remains on individual pieces.

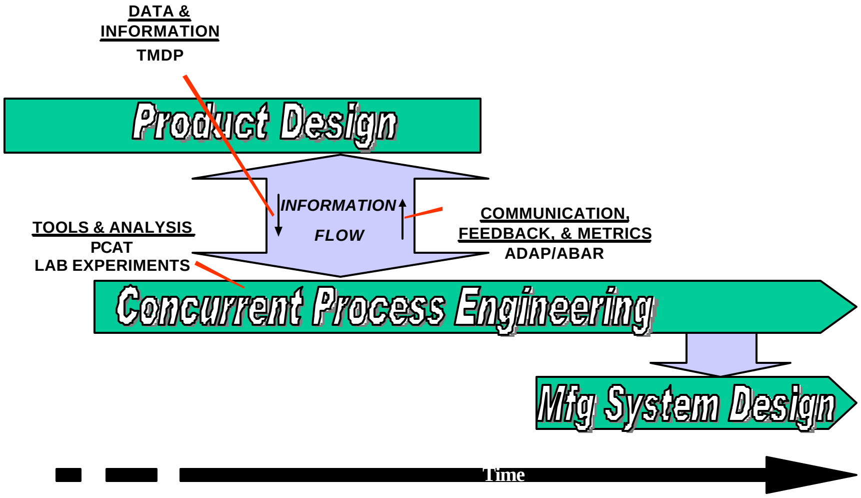


Figure 6-1: Current flow of concurrent engineering process at Raytheon

There are some tools in place, though, that support the concurrent engineering effort. A toolset known as the Technical Management Data Package (TMDP), currently under development and partially deployed, makes design drawings and other data easily accessible to manufacturing and other functions early in the design process. Prior to TMDP, process and manufacturing engineers could not get complete access to engineering data until drawings were released, hindering efforts to work concurrently. Thus, TMDP is potentially an important enabler of concurrent engineering. PCAT, a computer process analysis tool described earlier, allows process engineering to analyze designs for producibility for some product lines. This tool can provide important information to engineers and managers about the production issues of the product well before test hardware is built and tested. This tool increases the benefit of concurrent engineering. A process for tracking metrics known as “ADAP” (As Designed/As Proposed) was put in place last year to continuously track product cost during product development. Managers have made ADAP an integral part of program management. In doing so, they strengthened the role of process and manufacturing engineers – who are responsible for the ADAP cost estimates – by giving them a louder voice. Together, TMDP, PCAT, and ADAP provide a nice foundation on which the concurrent engineering process is based.

This foundation will make it easier to integrate manufacturing system design activities into concurrent engineering. A depiction of how this would work is provided as Figure 6-2. In this process, manufacturing system design would begin shortly after process engineering begins, while the design is still in its early stages. Thus, all three activities occur simultaneously. Information flows both ways between tasks, rather than being passed one way from design to process engineering to manufacturing system design. ADAP and TMDP become even more important as more people are working concurrently.

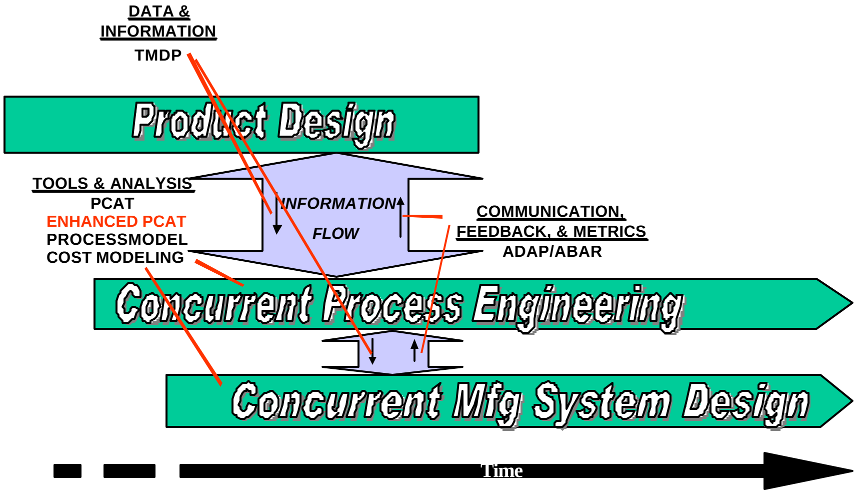


Figure 6-2: Potential future state of concurrent engineering with new tools

Figure 6-2 also notes a few differences from the current state. ProcessModel and perhaps enhanced cost modeling are part of the toolset. Also, there is a need for what is dubbed in the diagram as “enhanced PCAT.” PCAT, as it exists now, is not capable of analyzing components like the antenna subassembly; rather, it is made for standard components such as circuit cards and cable assemblies. This represents a hindrance to early manufacturing system design, because it is difficult to design a manufacturing system if process parameters such as yield and labor time are not known. Thus, to adopt fully the concurrent process shown in the figure, Raytheon must work on enhancing PCAT or figuring out a substitute. And, as stated above, better cost modeling wouldn't hurt.

This is a vision that must be fleshed out before being implemented. This project showed some of the benefits of doing these activities concurrently, but the practicality, difficulty, and costs of changing the product development process must be fully understood before these changes are adopted. Then, if it is adopted, it must be documented and inserted into their standard operating procedures.

7.0 CONCLUSIONS

Three main conclusions are draws from this project: 1) the simulation-based approach is effective for the design of an assembly cell; 2) this approach can be even more effective if it is included as part of a concurrent engineering process; and 3) variability in design hinders adoption of lean techniques, but the concurrent approach can help. Each is described in kind.

1. A simulation-based approach to production system design is effective. A primary goal at the beginning of this project was to propose and follow a step-by-step process for assembly system design. That process was presented in section 3.3.1, with simulation using the software package ProcessModel as a primary feature. Chapter 3 described the details of the process, as well as the actual use of the process for the antenna assembly cell.

The main benefit of this approach is that it is structured and iterative. Prior to this effort, the design of the work cell was progressing at a somewhat ad-hoc basis. Only a few people understood what the end system would look like, and how it would perform. The new design approach gave the team a baseline that everyone could see and understand, and from which improvements could be recommended. Thus, the approach provided a basis for continuous improvement.

2. A concurrent engineering approach for assembly cell design would provide added benefit. The second conclusion is that the simulation-based production system design approach is best used in a concurrent engineering system. This realization was almost reached by accident. Halfway through the project, a redesign of the antenna subassembly was launched, and the production system design proceeded concurrently with the component redesign. Lessons learned from manufacturing system design activities were fed back into product design.

One of the benefits of the simulation-based approach is that it allows for quick modifications to the production system design, and allows the designer to run numerous "what-if?" scenarios. If there is data available and good communication between the product design team and the production system designers, this work can be done much earlier in the product development process. Design of the production system provides information about the product cost and lead time that is not available before the production system is designed. This information can be used by product designers and program managers to optimize the tradeoff between product performance and production cost. The entire design space is made clearer. The concurrent approach allows for the entire product-process-production system design to be considered simultaneously and iteratively, maximizing the ability of the design team to incorporate production enhancements early in development cycle, when it is most cost effective and practical.

3. Implementing lean production requires variability control from designers. The third conclusion is that variability in the design and production process must be controlled before a lean production system can be put in place. The antenna subassembly production cell was originally going to be designed using lean practices, but the low yield and high labor variability would have greatly reduced the performance of a lean cell.

This variability is largely inherent in the product design. Part of the problem came from the fact that product designers had no reason to believe that this cell would be lean, and thus did not try to design variability out of the assembly. By the time the design was "thrown over the wall" to the production system designers, it was too late to implement the design changes necessary to reduce variability. Had the goal of designing a lean production system been specified earlier and communicated to designers, and a concurrent approach to production system design been in place, this problem could have been avoided.

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9.0 APPENDIX 1: PROCESSMODEL OUTPUT

```
--------------------------------------------------------------------------------
General Report
Output from C:\My Documents\thesis\ProcessModel\Radiator_Assembly2.mod
Date: Jan/16/2002   Time: 10:15:11 AM
--------------------------------------------------------------------------------
Scenario        : Normal Run
Replication     : 1 of 1
Warmup Time     : 120 hr
Simulation Time : 128 hr
--------------------------------------------------------------------------------

ACTIVITIES
                                      Average
                                      Minutes
Activity          Sched.       Total    Per    Average  Maximum  Current
Name              Hours  Cap. Entries  Entry   Contents Contents Contents  % Util
-------------- --------- ---- ------- -------- -------- -------- --------  ------
Build Stage1 inQ       8  999      60   89.84    11.23       29       29    1.12
Build Stage1           8    1      31   12.06     0.77        1        1   77.94
Stg1Cure inQ           8   15      38   96.71     7.65       13       12   51.04
Stg1Cure               8    1       2  150.00     0.62        1        0   62.50
Stg1Cool               8    1       2   15.00     0.06        1        0    6.25
MaskDisks inQ          8   15      35   56.93     4.15       12        5   27.68
MaskDisks              8    1      31    2.34     0.15        1        0   15.18
Apply Preforms inQ     8   20      32   10.02     0.66        1        1    3.34
Apply Preforms         8    3      32   21.16     1.41        2        2   47.03
Inject Epoxy inQ       8  999      30   14.60     0.91        3        1    0.09
Inject Epoxy           8    1      30    6.29     0.39        1        0   39.32
Insert Cables inQ      8  999      30    0.00        0        1        0    0.00
Insert Cables          8    1      30    5.99     0.37        1        1   37.45
Stg2Cure inQ           8  999      66   56.07     7.71       18       12    0.77
Stg2Cure               8    1       4  101.72     0.84        1        1   84.77
Stg2Cool inQ           8  999       3    0.00        0        1        0    0.00
Stg2Cool               8    1       3   15.00     0.09        1        0    9.38
Stage2 Test inQ        8  999       3  129.94     0.81        1        0    0.08
Stage2 Test            8    2      54   11.00     1.23        2        0   61.88
Stage2 Test outQ       8   11      54    0.00        0        1        0    0.00
Install Windows inQ    8   30      34   27.58     1.95        5        4    6.51
Install Windows        8    1       6    9.83     0.12        1        0   12.30
Stage3 Test inQ        8   10      35   47.72     3.48        9        7   34.80
Stage3 Test            8    1      29   10.64     0.64        1        1   64.34
Rework inQ             8  999      25   21.23     1.10        6        5    0.11
Rework                 8    3      22   37.75     1.73        2        2   57.68
Stg3Cure inQ           8  999       6    8.55     0.10        1        0    0.01
Stg3Cure               8    1       6   60.00     0.75        1        0   75.00
Stg3Cool inQ           8  999       6    0.00        0        1        0    0.00
Stg3Cool               8    1       6    1.00     0.01        1        0    1.25
SolderCR inQ           8  999      32    9.19     0.61        1        1    0.06
SolderCR               8    1      32   14.99     0.99        1        1   99.95
CircuitCure inQ        8  999       6    0.00        0        1        0    0.00
CircuitCure            8    1       7   51.42     0.75        1        1   75.00
CircuitCool inQ        8  999       6    0.00        0        1        0    0.00
CircuitCool            8    1       6   15.00     0.18        1        0   18.75
Cable  Sets            8  999      38   92.00     7.28       11        8    0.73
Apply sub and cir inQ  8  999     480   90.00       90      200      200    9.01
Apply sub and circuit  8    1       7   61.71      0.9        1        1   90.00
Clean and Inspect inQ  8  999     296   83.43    51.45       80       48    5.15
Clean and Inspect      8    1      31    5.00     0.32        1        0   32.29
```

```
ACTIVITY STATES BY PERCENTAGE (Multiple Capacity)

                                                           %
Activity                        Scheduled       %  Partially      %
Name                                Hours   Empty   Occupied   Full
------------------------------  ---------  ------  ---------  -----
Build Stage1 inQ                        8   25.08      74.92   0.00
Stg1Cure inQ                            8    5.46      94.54   0.00
MaskDisks inQ                           8   32.10      67.90   0.00
Apply Preforms inQ                      8   33.14      66.86   0.00
Apply Preforms                          8   20.80      79.20   0.00
Inject Epoxy inQ                        8   38.76      61.24   0.00
Insert Cables inQ                       8  100.00       0.00   0.00
Stg2Cure inQ                            8    3.96      96.04   0.00
Stg2Cool inQ                            8  100.00       0.00   0.00
Stage2 Test inQ                         8   18.78      81.22   0.00
Stage2 Test                             8   11.91      52.44  35.66
Stage2 Test outQ                        8  100.00       0.00   0.00
Install Windows inQ                     8   26.68      73.32   0.00
Stage3 Test inQ                         8   15.78      84.22   0.00
Rework inQ                              8   50.89      49.11   0.00
Rework                                  8    0.86      99.14   0.00
Stg3Cure inQ                            8   89.30      10.70   0.00
Stg3Cool inQ                            8  100.00       0.00   0.00
SolderCR inQ                            8   38.70      61.30   0.00
CircuitCure inQ                         8  100.00       0.00   0.00
CircuitCool inQ                         8  100.00       0.00   0.00
Cable  Sets                             8    0.00     100.00   0.00
Apply substrate and circuit inQ         8   25.00      75.00   0.00
Clean and Inspect inQ                   8    0.00     100.00   0.00


ACTIVITY STATES BY PERCENTAGE (Single Capacity)

Activity                     Scheduled          %      %        %        %
Name                             Hours  Operation   Idle  Waiting  Blocked
---------------------------  ---------  ---------  -----  -------  -------
Build Stage1                         8      77.94  22.06     0.00     0.00
Stg1Cure                             8      62.50  37.50     0.00     0.00
Stg1Cool                             8       6.25  93.75     0.00     0.00
MaskDisks                            8      15.18  84.82     0.00     0.00
Inject Epoxy                         8      39.32  60.68     0.00     0.00
Insert Cables                        8      37.45  62.55     0.00     0.00
Stg2Cure                             8      84.77  15.23     0.00     0.00
Stg2Cool                             8       9.38  90.62     0.00     0.00
Install Windows                      8      12.30  87.70     0.00     0.00
Stage3 Test                          8      64.34  35.66     0.00     0.00
Stg3Cure                             8      75.00  25.00     0.00     0.00
Stg3Cool                             8       1.25  98.75     0.00     0.00
SolderCR                             8      99.95   0.05     0.00     0.00
CircuitCure                          8      75.00  25.00     0.00     0.00
CircuitCool                          8      18.75  81.25     0.00     0.00
Apply substrate and circuit          8      90.00  10.00     0.00     0.00
Clean and Inspect                    8      32.29  67.71     0.00     0.00
```

```
RESOURCES
                                                      Average
                                              Number  Minutes
Resource                        Scheduled   Of Times      Per
Name                   Units        Hours       Used    Usage  % Util
-------------------   -----   ---------   --------  -------  ------
MaskDisksPreforms.1        1            8         30    12.48   78.02
MaskDisksPreforms.2        1            8         33    11.37   78.23
MaskDisksPreforms          2           16         63    11.90   78.13
Stg1                       1            8         31    12.06   77.94
EpoxyCables                1            8         30    13.28   83.02
Windows                    1            8          6     9.83   12.30
Tester1.1                  1            8         42    10.75   94.14
Tester1.2                  1            8         41    11.00   93.96
Tester1                    2           16         83    10.87   94.05
ReworkSpecialist.1         1            8         11    33.48   76.73
ReworkSpecialist.2         1            8         11    42.02   96.31
ReworkSpecialist           2           16         22    37.75   86.52
Solderer.1                 1            8         16    30.00  100.00
Solderer.2                 1            8         17    28.23  100.00
Solderer                   2           16         33    29.09  100.00
SubstrateCircuit           1            8          7    61.71   90.00


RESOURCE STATES BY PERCENTAGE

Resource              Scheduled       %       %      %
Name                      Hours  In Use    Idle   Down
-------------------   ---------  ------   -----   ----
MaskDisksPreforms.1           8   78.02   21.98   0.00
MaskDisksPreforms.2           8   78.23   21.77   0.00
MaskDisksPreforms            16   78.13   21.87   0.00
Stg1                          8   77.94   22.06   0.00
EpoxyCables                   8   83.02   16.98   0.00
Windows                       8   12.30   87.70   0.00
Tester1.1                     8   94.14    5.86   0.00
Tester1.2                     8   93.96    6.04   0.00
Tester1                      16   94.05    5.95   0.00
ReworkSpecialist.1            8   76.73   23.27   0.00
ReworkSpecialist.2            8   96.31    3.69   0.00
ReworkSpecialist             16   86.52   13.48   0.00
Solderer.1                    8  100.00    0.00   0.00
Solderer.2                    8  100.00    0.00   0.00
Solderer                     16  100.00    0.00   0.00
SubstrateCircuit              8   90.00   10.00   0.00


ENTITY SUMMARY  (Times in Scoreboard time units)

                        Average    Average
                          Cycle         VA
Entity          Qty        Time       Time  Average
Name      Processed   (Minutes)  (Minutes)     Cost
---------  ---------  ---------  ---------  -------
Parts Kit          0          0       0.00     0.00
Cable Set          0          0       0.00     0.00
Antenna           27    1412.07     625.87    53.23
```

```
VARIABLES

                                           Average
Variable                        Total      Minutes  Minimum  Maximum  Current  Average
Name                          Changes   Per Change    Value    Value    Value    Value
----------------------  -------  ----------  -------  -------  -------  -------
Avg BVA Time Entity                 1         0.00        0        0        0        0
Avg BVA Time Parts Kit              1         0.00        0        0        0        0
Avg BVA Time Cable Set              1         0.00        0        0        0        0
Avg BVA Time Antenna               28        16.54        0        0        0        0
```