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A SYSTEM DYNAMICS APPROACH TO MODELING AIRCRAFT SYSTEM PRODUCTION BREAK COSTS

THESIS

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AFIT/GAQ/ENV/02M-06

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A SYSTEM DYNAMICS APPROACH TO MODELING AIRCRAFT SYSTEM PRODUCTION BREAK COSTS

THESIS

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Abstract

This research effort employs a System Dynamics methodology to model Air Force aircraft production break costs. The Air Force currently used the Anderlohr, Modified Anderlohr, and Retrograde methods for the estimation of aircraft production breaks. These methods offer little insight into the dynamic behavior of an aircraft production break. System Dynamics offers a unique way of capturing expert opinions in this area and dynamically presenting behaviors of an Air Force aircraft production line during a production break. Development of this model followed a four-step process of conceptualization, formulation, testing, and implementation. Five Air Force aircraft production break experts in were interviewed to formulate and validate the model. This research identified manpower turbulence and parts disruptions as the main cost drivers during the initial shutdown of an aircraft production line. During the break, there were minimal costs and no main costs drivers. During the restart of production, new requirements and the reconstitution of the workforce were found to be key cost drivers. Expert feedback indicates the System Dynamics model developed during this research will prove most valuable in policy formulation and in training of cost analysts.

A SYSTEM DYNAMICS APPROACH TO MODELING AIRCRAFT SYSTEM PRODUCTION BREAK COSTS

I. Introduction

Purpose

The United States Air Force is continually challenged to procure the most lethal, reliable, and high-tech weapons to defend our nation within the budget allocated by Congress. Between Fiscal Fear (FY) 1996 and 2001, the Department of Defense (DoD) spent over $599.1 billion on the procurement of weapon systems (15:67). The DoD will spend an additional $551.7 billion between FY 2001 through 2005; including a procurement budget for FY 2001 of $60.2 billion (15:67). The Air Force's share of these procurement funds for the same FY is $20.9 billion, with $9.5 billion alone allocated for aircraft procurement (17:15).

The staggering resources expended to procure weapon systems necessitates that decisions regarding the allocation and management of these resources are sound and cost effective. The General Accounting Office (GAO) has stated, "Although DoD has increased its procurement budget, it consistently pays more and takes longer than planned to develop [and procure] systems that do not perform as anticipated" (36:8). While many sources of cost overruns exist, this research focuses on the effects of production breaks. DoD manual 4245.7M states, "Shut-outs and production breaks increase both technical risk and cost" (16:Chap 9). DoD manual 4245.7M further describes the increased costs and resource waste involved.

> Factory space, tooling, and equipment are idled, and in the worst case, may be eliminated. Publications and handbooks lose currency. Production flow is interrupted and benefits from assembly improvements and automation are lost. Experienced manufacturing and engineering personnel are either reassigned or dismissed. Moral suffers, teamwork is less apparent, problem identification and resolution become much more difficult to reestablish, and production efficiency degrades noticeably. (16:Chap 9)

To shutdown, and later restart a production line, requires extensive resources. With constrained resources stressing the weapon system acquisition process, accuracy in the estimation of these costs is critical for decision makers to explore all relevant trade-offs regarding weapon system production options, including production breaks.

The DoD, and ultimately the Air Force, acquires its weapon systems through a comprehensive and complex acquisition process. The Defense Systems Management College (DSMC) defines the defense acquisition process as

> …a single uniform system whereby all equipment, facilities, and services are planned, developed, acquired, maintained, and disposed of by the Department of Defense (DoD). The system includes policies and practices that govern acquisition: identifying and prioritizing resource requirements and resources, directing and controlling the process, contracting, and reporting to Congress. (13:1)

Specifically, the prioritizing of resource requirements is accomplished through the biennial cycle of the Planning, Programming, and Budgeting System (PPBS). Each segment of the PPBS cycle focuses on war fighter needs and how to program and budget for the development and procurement of those systems to meet those needs (38:1).

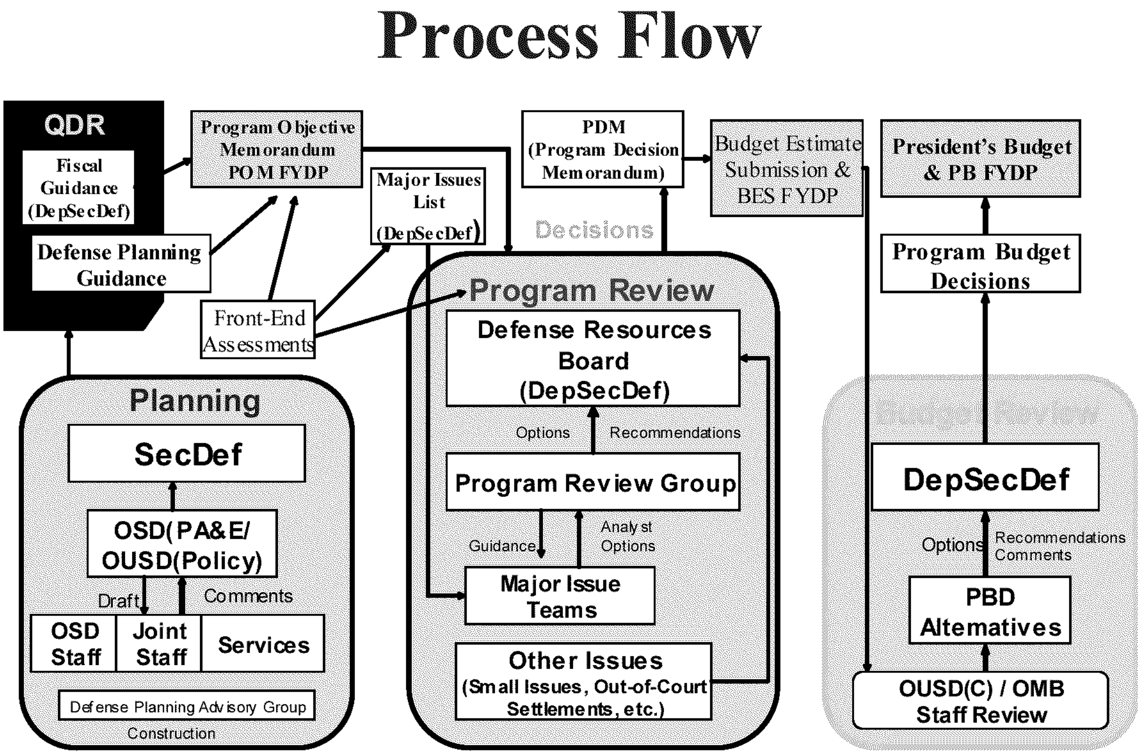


Figure 1. PPBS Cycle (14:6)

The PPBS has three different phases: Planning, Programming and Budgeting (Figure 1). The first phase of the PPBS is the Planning Phase. The Planning Phase identifies the basic threats and security needs of the United States and refines them into the Defense Planning Guidance (DPG). The next phase, the Programming Phase, uses the DPG to build the Program Objective Memorandum (POM). The POM begins by assigning defense resources, including funding, to programs identified in the DPG. The primary product of the Programming Phase is the Program Decision Memoranda (PDM). The PDM contains the initial program cost estimates and starts the Budgeting Phase. This phase further refines the resource allocations through several formal reviews and ends with the Presidents Budget (PB) (38:1-13). When completed, the PB goes to

Congress for debate. Congress ultimately votes on and passes the DoD Appropriations and Authorization Acts. These bills go to the President for signature and become law. The Appropriations and Authorization Acts become the financial blueprint of the DoD.

During the Programming Phase, the Budgeting Phases, and Congressional debates, questions arise regarding how to provide the best mix of defense forces within a constrained budget. Often, the question surfaces regarding what costs might be incurred if a program is halted during production and the resources allocated elsewhere. This thesis effort will focus on understanding, using System Dynamics modeling, the general cost drivers, and their interrelationship, associated with stopping, and restarting, an aircraft production operation.

Production Break

The Defense Acquisition University (DAU) defines production as, "The process of converting raw materials by fabrication into required material. It includes the functions of production scheduling, inspection, quality control, and related processes" (11:129). Webster's Dictionary defines a break as, "To make or become unusable or inoperative" (37:89). DoD manual 4245.7M, "Transition From Development to Production," defines a production break as "…[the] complete shutdown of the production line…" (16:Chapter 9). Max Lee offers another definition, "The production break is the lapse of time between the completion of a contract for the manufacture of certain units of equipment and commencement of a follow-on order for identical units" (26:73). For this research effort, production break is defined as the *temporary stoppage* of a production line.

Production breaks are common in the manufacturing process. George Anderlohr, a noted expert on production breaks states, "In the real world of Government procurement there is, almost always, a break in the production cycles" (3:1). Black states, "…production breaks and "follow on" production orders are common in [all] industry [ies]" (6:4). Parikh states, "Production breaks occur all the time. As defense contractors become fewer in number and size, their frequency of production breaks should increase" (27:1). Kugel writes,

> Production interruptions are a frequent occurrence in industry today. In the aerospace industry, contractors doing work for the government can be assured of having interruptions in their production processes. At the start of every government fiscal year, Congress is notorious for not having appropriated funds for the Department of Defense. Consequently, contracts for further production of aircraft and other weapon systems go unfunded and work ceases. (33:1)

There are several ways to estimate production breaks using non-descriptive techniques or models. Most estimating techniques use the calculation of man-hours, through the theory of learning curves, to determine the loss of learning that has taken place during a production break. The most popular of these methods is the Anderlohr Method (24:3). Several problems exist with these methods. First, only the number of man-hours for the first unit produced after the production break are calculated. Second, these methods are non-descriptive in nature and treat the dynamic nature of the production break as a *black box*. The analyst plugs-in the raw data into a scripted process and a point estimate is generated. Finally, with these methods, other miscellaneous costs are ignored and the assumption is made that labor hours is the most critical variable in calculating production break costs. This may not be the case since modern manufacturing has switched to more automation and an emphasis on imparting workers skills into the machine (27:19-20).

Research Questions

This research focuses on providing Air Force cost estimators, engineers and decision makers with a better understanding of the costs associated with aircraft production breaks. System Dynamics modeling will be used to build a production break model that will provide additional insight into the key issues driving cost during a production break. The following research questions will be explored in this thesis:

(1) What methodologies does the Air Force currently employ in estimating aircraft production breaks?

(2) Can the behavior of an aircraft manufacturing line undergoing a production break be explained using a System Dynamics methodology?

(3) Can this model identify policy combinations that contribute to and mitigate the costs associated with a production break?

(4) How can this model be used to improve the cost estimation of a production break?

Thesis Overview

This chapter has motivated the requirement for a more insightful approach to the estimation of production break costs. Because of the staggering defense budget and lack of explanatory production break models, decision makers may not be empowered to make sound decisions regarding the allocation of resources during the PPBS cycle. A System Dynamics model of a production break will give cost estimators, engineers, and decision makers a better understanding of the key issues that drive costs during a production break. In this research, four research questions will be addressed regarding production breaks and System Dynamics.

Chapter II begins with an explanation of the learning curve theory. The learning curve theory is at the foundation of the three most popular production break estimation techniques currently employed. These estimation techniques are the Anderlohr, Modified Anderlohr, and Retrograde Methods. Each technique is demonstrated with an example. The reminder of the chapter introduces System Dynamics, its terms, and validation tests.

Chapter III examines the methodology used to build and validate a production break model using a System Dynamics modeling approach. The construction of this model follows a four-stage process of conceptualization, formulation, testing, and implementation. The chapter concludes with a discussion of validation tests and interviewing techniques used to create a production break model.

Chapter IV presents how the System Dynamics aircraft production break model was developed using the conceptualization, formulation, testing, and implementation phases. The chapter also explores the overall impressions of the model by those interviewed.

Chapter V offers summaries of the four research questions explored in this thesis effort. The chapter also presents several future research opportunities.

II. Literature Review

Introduction

This chapter begins with a discussion on learning curve theory. This theory is the foundation of the three most common techniques in the estimation of Air Force aircraft production breaks. Those techniques are the Anderlohr, Modified Anderlohr, and Retrograde methods. These three methods are explained within the chapter and included an example of their calculation. The remainder of the chapter introduces System Dynamics, its terms, and its model validation tests.

Learning Curve Theory

The concepts behind learning curve theory were developed prior to World War II within the aircraft manufacturing industry. Managers found a quantitative relationship between the number of items produced and the time spent producing each of the items (4:17). Lee writes, "As more and more units of an item are produced in a given plant, the cost of producing a unit generally decreases" (25:9). Anderlohr summarizes learning curve theory as:

> The theoretical principle being that as the quantity doubles the labor hours required to manufacture the units decrease by a constant percentage. This percentage, referred to as a learning curve, can be graphically plotted a straight line on log-log paper. (3:1)

Additionally, Jordon states,

> The learning Curve theorem states that every time the production of a product double, the new cumulative average cost (hours or some similar

> unit of measurement) decline by a fixed percent of the previous cumulative average. This fixed percent identifies the learning achieved. (22:1-2)

The central idea behind learning curve theory is that workers learn through repetition of similar tasks. This brings about a reduction in per unit labor hours. No other factors are responsible for the reduction in hours. For example, Andress (4) discusses why productivity is not driving the per unit drop in labor hours. He offers the following example. If a production line stops producing the current design and switched to a different design, per unit labor hours for the first unit produced would be quite high. This first unit would need roughly the same number of labor hours as the first unit produced with the original design. The new production run would also follow the same trend of the reduction in per unit labor hours as units produced increased. These same results, a high labor hour requirement for the first unit and a constant reduction in per unit labor hour with lager quantities produced, would repeat with every new design change over. Andress states, "The phenomenon was referred to as learning because of this repetitive characteristic, rather than as productivity which implies some sort of sustained improvement" (4:18). During these transitions, the production line was stable and the workforce remained unchanged. The driving force behind the reduction in labor hours per unit is the consistent learning within the organization's work force.

The constant percentage of learning in a workforce is difficult to understand. Brewer states,

> In the learning theory, however, it is held that the proportional amount of learning (or percentage of increase in efficiency of performance) is <u>constant</u> for <u>proportional</u> numbers of repetitions. This means, of course, that learning is a continuous process and that no limit to learning is

> reached regardless of the number of repetitions. At first glance, this concept appears to be impossible; however, the key to rationality of the theory is the term proportional repetitions. (7:3)

The following simplified example illustrates this concept of proportionality. Workers require 100 hours of labor to complete the first unit of production. These workers achieve an average 10% learning rate. Using the doubling principle mentioned earlier, two units would only take an average of 90 hours each to finish (100 hrs * 90% = 90 hrs) or a total of 180 hours (90 hrs * 2 units = 180 hrs). Producing four units would average 81 labor hours each to complete (90hrs * 90% = 81 hrs) or a total of 324 hours (81 hrs * 4 units = 324). Table 1 shows the average projected hours of the cumulative production units out to unit 128. The proportionality is clearly portrayed in a graph of this data. Figure 2 illustrates the 90% learning curve when these points are graphed out with hours on the y-axis and cumulative production on the x-axis. Figure 2 clearly shows that as the production of units increases, the per unit learning decreases. Therefore, even though the average learning rate remains constant, there is a diminishing return of learning with each unit.

Table 1. 10% Learning Rate Example

Cum Production	Cum Average Hours Per Unit	Ratio to Previous Cum Average
1	100.0	-
2	90.0	90%
4	81.0	90%
8	72.9	90%
16	65.6	90%
32	59.0	90%
64	53.1	90%
128	47.8	90%

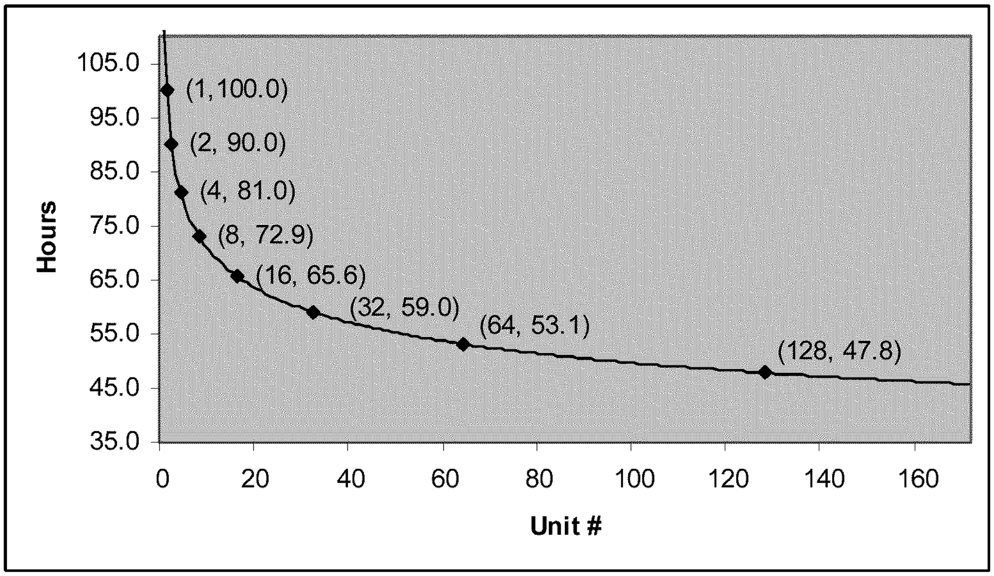


Figure 2. 10% Learning Curve Graph

There are two widely recognized mathematical models for describing and applying learning curve theory. The first is the cumulative average model, or Wright model. The second is the unit model, or Crawford model (25:11). The Wright model determines the average cost of a group, or lot, of production items and is formulated mathematically as:

$$A(Q) = A_1 Q^b, \qquad (1)$$

where A(Q) represents the average cost of the first Q units, and A_1 and b are constants (25:11). The Crawford model measures individual item costs and is formulated mathematically as:

$$C(Q) = T_1\, Q^b, \qquad (2)$$

where C(Q) is the cost of the Q^{th} unit, and T_1 and b are constants (25:11). Lee goes on to explain "The constants A_1 and T_1 are both known as the 'theoretical first-unit cost'" (25:11). The b constant is defined as:

$$b = \log \text{(Slope of learning curve)} / \log 2 \qquad (3)$$

The slope of the learning curve is defined as:

$$\text{Slope of learning curve} = 1 - \text{learning rate} \qquad (4)$$

For example, if there is a 15% percent learning rate, the slope is 85% (100%-15% = 85%). The b constant will always be negative, because the slope is theoretically negative. If the slope were positive, then the theory would indicate that as more units are produced, per-unit labor hours would increase. Because formulas (1) and (2) are log-linear, they are also written as:

$$A' = T_1' + Q' + b \qquad (5)$$

$$C' = T_1' + Q' + b \qquad (6)$$

where

$A' = \ln A(Q)$

$T_1' = \ln T_1'$

$Q' = \ln Q$

$C' = \ln C(Q)$

Plotting formulas (4) and (5) in log-log produces the characteristic straight line of the learning curve. Figure 3 below shows this behavior using the same 90% learning curve described in Figure 2.

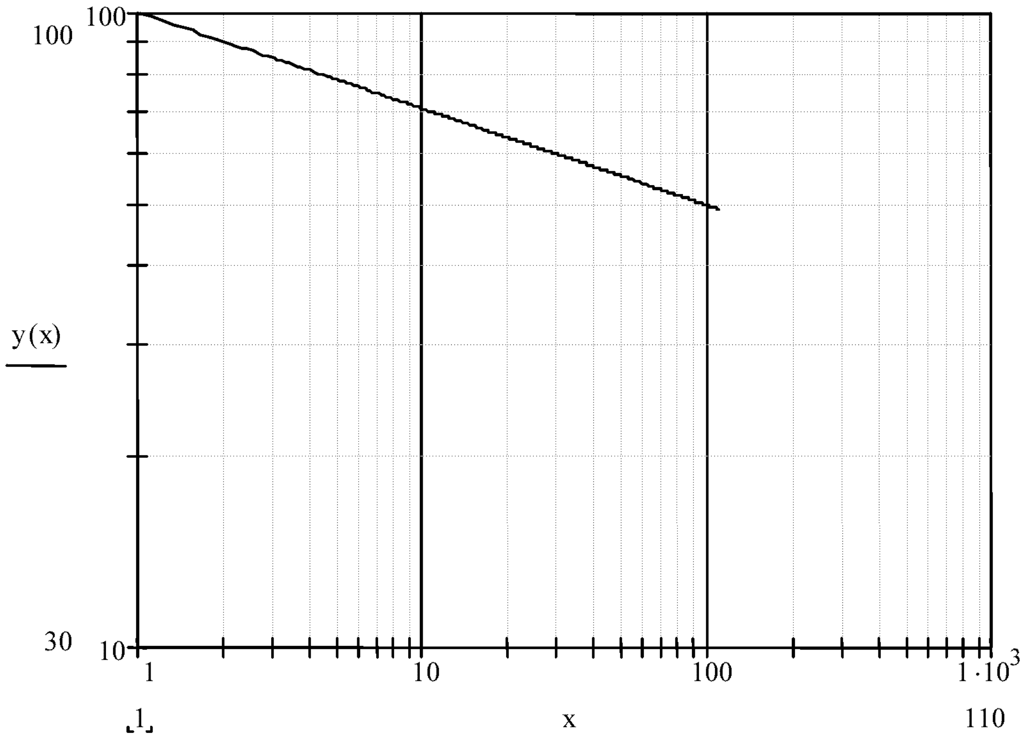


Figure 3. Log-Log Graph of a 90% Learning Curve

Production Breaks

There are several methods of calculating the costs associated with a production break. Methods include Cochran (27:18), DCCA method (27:18) (6:7), Pinchon-Richardson (27:18) (6:9), S Curve (27:18), Cubic Curve (27:18) (6:8), Delionback's Time Series (6:10), Anderlohr Method, the Modified Anderlohr, and Retrograde Method. The last three techniques are the most frequently used methods to calculate production breaks within the Air Force. Other methods have been theoretically proven but have not been fully embraced by industry or the DoD.

Anderlohr Method

In 1969, George Anderlohr, a DoD industrial engineer, proposed that the loss of learning during a production break could be calculated and used to estimate the number of labor hours required for the first unit produced following the break. He states,

> When plotting actual labor hours on a curve, it has been long noted that any interruption in the orderly and continuous flow of work from one workstation to another is accompanied by an increase of labor hours when production is resumed. This has been commonly referred to as start up costs which relates directly to loss of improvement. (3:1)

Anderlohr defines five categories of loss of learning during a production break. These categories include: personnel learning, supervisory learning, continuity of production, methods, and special tooling. His method of estimation involved evaluating the loss of learning from each category and then developing a Learning Loss Factor (LLF). Then, the Retrograde Method employs the LLF to estimate where the first unit labor hours will fall on the learning curve. Once the number of labor hours of the first unit of production is determined, the slope of the new learning curve can be applied.

The first of Anderlohr's five categories is personal learning. Personnel learning evaluates the knowledge of production employees involved with the startup of the production line and the assembly of the product. Anderlohr states, "In this area, it is required to determine the physical loss of personnel through attrition or lay-off" (3:2). Further, he states, "Personnel learning includes actual forgetting work procedures, hiring untrained replacement personnel, and rehire of personnel" (3:5). For example, a company shuts down a production line and lays off 3% of the employees working on that line. The production break lasts for several months and the employee's level of learning drops 5%. Both the 3% lay off rate and 5% employee learning loss is added to get a total of 8% loss of learning for the category personnel learning. The subjectiveness of this and the other four category calculations will be discussed later in this research.

Supervisory learning explores the level of lost learning experienced with management. Anderlohr states, "…the supervisory personnel retained will lose their overall how-to-do familiarity with the job so that the guidance they can furnish will be reduced" (3:3). Other areas for evaluation focus on the number of new hires and retention of management after the shutdown. For example, if 5% of the supervisors do not return and the break causes a 5% of a learning loss, then the learning loss for supervisory learning is 10%.

The third category is continuity of production. Black states," Continuity of production relates to the physical establishment of production lines, the position adjustments for optimal working conditions, and work in progress build-up" (6,5). Anderlohr states,

> This relates to the physical positioning of the product line, the relationship of one workstation to another, and the location of lighting, bins, parts, and tools within the workstation. It also includes the position adjustment to optimize the individual needs. In addition, a major factor affecting this are is the balanced line or the work-in-process buildup. (3:3)

For example, if 10% of the machines on the production line were moved or were sold during the production break, this would result in a loss of learning of 10% for this category.

The fourth category of lost learning is methods. This area examines how the plant is performing the actual manufacturing of the items. It addresses inventory, machine movement, and reassignment of personnel and policy issues. Also addressed is how the plant will convert the production line into producing the product again. Anderlohr states, “This area is least affected by a production break. As long as the method sheets are kept on file, learning can never be completely lost” (3:3). For example, if 98% of the documentation on producing the product were retained, then the loss of learning during the shutdown for the category of methods would be only 2%.

The last category is special tooling. This category consists of the non-standard tool and dies that produce the item. Anderlohr further defines special tooling,

> New and better tooling is a major contributor to learning. In considering loss in the tooling area related to learning, the major factors are wear, physical misplacement, and breakage. An additional consideration must be the comparison of short run, or so called soft tooling to long run, or hard tooling and the effect of the transition from soft to hard tooling. (3:3)

Special tooling can also be cannibalized or disposed of during the production break, leading to the loss of learning. For example, if only 85% of the special tooling is retained on the production line there would be a 15% loss of learning for special tooling.

The next step in the Anderlohr Method is to use a weighted averaging approach to calculate the overall loss of learning. Multiplying the five category’s percentages by a weight of twenty percent (100%/5=20%) gives the weighted average for each component. Twenty percent is a staring point in the calculation. Anderlohr states, “Refinement of the weights will be required for different industries as well as companies within the industries. In general, this refinement will be relative to the level of skill of the production personnel” (3:4). Adding together the weighted averages provides the overall

LLF. In the example, the LLF is 9% and represents a 9% learning loss during the production break (see table 2).

Table 2. Anderlohr Method Calculation

Anderlohr's Category	Level of Loss (%)	Weight Assigned (%)	Weighted Average of total learning loss (%)
Personnel Learning	8%	20%	1.6%
Supervisory Learning	10%	20%	2%
Continuity of Production	10%	20%	2%
Methods	2%	20%	.4%
Special Tooling	15%	20%	3%
		Learning Loss Factor	**9%**

Once the LLF is calculated, the next step is to apply the retrograde method to calculate the first unit labor hours following the production break.

Modified Anderlohr Method

The Directorate of Cost Analysis, Aeronautical Systems Division (now Aeronautical Systems Center) at Wright-Patterson Air Force Base, Ohio, developed the Modified Anderlohr Method. According to Kugel, this method:

- Adapts to existing learning theory.
- Adjusts the learning curve to the company situation by considering empirical data.
- Evaluates the break in production in terms of learning loss and as a percentage of the elapsed learning curve.
- Substitutes quantified information for pure subjective estimates. (24:9)

This method divides production into three elements. These elements include in-plant factors, availability, and retention of knowledge. The Modified Anderlohr Method can be mathematically formulated as:

$$R = F * AV * Kn \tag{7}$$

where:

F = Factor percentage
AV = Availability
Kn = Knowledge
R = Retained ability.

The in-plant factors include supervision, personnel, tooling, production continuity, methods, and configuration changes. This list includes the same production categories as the original Anderlohr method with the addition of the configuration changes category. Kugel defines configuration changes as new design changes or added capability (24:11). Each of these categories receives a weighting percentage corresponding to its relevance in the production break. This weighting represents the factor percentage F. Factors that are more influential receive higher percentage weights. The sum of the weights must equal to 100%.

The next step in the Modified Anderlohr Method is to analyze the contractor records for each category and develop composite availability curves. These curves show the percentage of availability or retention of the capability for the six categories. Likewise, the analyst will also have to develop knowledge curves for the six categories. These knowledge curves show the percentage of retained knowledge for each category. Kugel does not offer a precise method for developing either set of curves, presumably because every organization's situation is different. Once the percentages are calculated, formula (6) is used to determine the retained knowledge from each category. Summing each category's product, the overall level of retained knowledge is calculated (See Table 3). LLF is the total retained knowledge subtracted from one. In this case the LLF would be 44.9% (1- 0.551 = 0.449). The retrograde method then calculates the total labor hours for the first unit produced following the production break.

Table 3. Modified Anderlohr Calculations

In-Plant Categories	*Factors*	*Avail.*	*Kn*	*R*
Personnel	.25	.60	.56	.084
Supervision	.20	.54	.95	.103
Production Continuity	.20	.35		.070
Methods	.15	.95		.142
Tooling	.15	1.00		.150
Configuration Changes	.05	1.00	.05	.002
				.551

Retrograde Method

The retrograde method uses the LLF to calculate the labor hours of the first units after production. Calculating the LLF can be accomplished several ways. The Anderlohr Method (as previously addressed) and Modified Anderlohr are the most popular. According to the Department of Defense Systems Management College:

> The theory behind the retrograde method is that because you lose hours of learning, the percentage of learning lost (LLF) should be applied to the hours of learning that you achieved prior to the break. The result gives you the number of hours of learning lost. These hours can then be added on to the cost of the first unit after the break on the original curve to yield an estimate of that unit due to the break in production. Last, we can then back up the curve (retrograde) to the point where production costs were equal to our new estimate. (12:17-23)

To illustrate the concept, an example is developed to determine the cost of the first unit produced following a production break. Assume that the first unit produced costs $1,000. The break lasts six months with a LLF of 9%. The 9% matches the example used to previously illustrate the Anderlohr method. The learning curve slope is 90%. Twenty units are produced before the shut down of the production line and thirty more units are required. Implementing the retrograde method, the first step is to determine the learning achieved to date. This is accomplished by subtracting the production costs of the first unit from the costs of the last unit produced; the twentieth (see Figure 4).

$$T_1 := 1000 \qquad b := \frac{\log(.9)}{\log(2)}$$

$$Q_1 := 1 \qquad\qquad Q_{20} := 20$$

$$C_1 := T_1 \cdot Q_1^{\,b} \qquad\qquad C_{20} := T_1 \cdot Q_{20}^{\,b}$$

$$C_1 = 1000 \qquad\qquad C_{20} = 634.219$$

$$C_1 - C_{20} = 365.781$$

Figure 4. Retrograde Calculation Example

The next step is to calculate the Learning lost form the production break. This is done by multiplying the LLF of 9% by the lost learning cost of $365.80.

Lost Learning = Learning Achieved (LLF)

Lost Learning = 365.8 (.09) = 32.9

The third step is estimating the cost of the first unit after the break. This is accomplished by finding the projected cost of the twenty-first unit on the original learning curve and adding lost learning (See figure 5).

$$Q_{21} := 21$$

$$C_{21} := T_1 \cdot Q_{21}^{\,b}$$

$$C_{21} = 629.533$$

$$C_{21} + 32.9 = 662.433$$

Figure 5. Finding 21st Unit and Adding Lose of Learning

The estimate of the cost of the first unit off the reopened line is $662.4.

Concerns Regarding Current Production Break Methods

There are several concerns regarding current production break estimation techniques. They include the basic unknowns with the estimation of a new system, the use of learning curve theory, and issues with the Anderlohr method. Because of these problem areas, the estimation of production break estimates are called into question (1) (27).

A primary shortfall with current production break estimation techniques is the uniqueness of Air Force weapon systems. The Air Force procures aircraft that are on the cutting edge of technology and production techniques. Often, both the production lines and the production techniques are complex and employ state of the art processes. There is no historical data to predict the basic parameters such as the first unit cost or the slope of the learning curve. Parikh states, "Historical data from prior breaks can provide an insight; however, this data is seldom available" (27:18). With so few aircraft production breaks documented, it is difficult to calibrate models like Anderlohr or the retrograde methods. Cost estimators however, must predict the costs of production breaks on an annual basis.

Learning curve theory also has limitations. Because most models rely on this theory, it is important to focus on these issues. Ahmed (1) listed nine categories of limitations. They include:

- Influence of Causal Factors – learning curve models are developed using just two parameters; the first unit labor hours and the slope of the curve. These parameters can be easily influenced through the effort applied to preproduction and production activities. Generally, by applying more resources to preproduction activities causes the first unit's labor to be lower and the slope of the learning curve to become shallower. The opposite would be true by applying more resources to production activities. This mixture of resource applications will cause parameter estimation to differ greatly. (1:73-75)
- Measurement and Aggregation Problems – poor recordkeeping between direct and indirect accounts and raw material shortages could cause labor rates to be inaccurate. The lot sizes, varying lead times, and schedules make it hard to accurately calculate individual unit labor hours. The overall learning curve consists of several rates of learning for all the subassemblies involved. It would

be inaccurate to estimate an individual process with the overall aggregated learning curve. (1:75-77)

- Narrow Understanding of the Causes and Existence of the Learning Curve – "In general the contributions of engineers and indirect labor to the learning curve phenomenon has been ignored" (1:77). The initial learning gains come from the debugging process that these two groups, along with direct labor, perform.
- Uncertainty as to the Nature of the Learning Curve Model - Ahmed identifies seven different forms of the learning curve model. He emphasizes that it may be hard to find the one that most closely match the specific application under study. (1:77-78)
- Dubious Practices in the Estimation of Parameters - "One of the major deficiencies in the learning curve literature is the dubious practice in the estimation of the *b* parameter in the learning curve model" (1:78). This parameter is historically treated as a constant for a contractor's production line. No matter what products are produced or the stage, such as setup, full rate, low rate, or shutdown, at which they produced, the tendency is to use a constant for the *b* parameter.
- Separating the Wheat from the Chaff – "The learning curve may be used by management as an artificial device to secure contracts and justify their cost estimates. In other words management may estimate their labor requirements with a false learning curve presumably based on empirical performance" (1:79). The challenge is to identify the true learning curve from ones with questionable motives.

- Illusory Savings and Verification – Errors in calculation, implementation of automation, billing indirect labor, and hiring expensive better-trained workers may erode projected savings from learning. (1:80)
- Negative or Defeatist Attitudes of Employees –"Attitudes which ignore, belittle, or negate the presence of learning threaten the applicability of the learning phenomenon. … Some companies have been reported to obtain more progress when the workers are not informed of the target rate. This is possible because the target set does not become a self-fulfilling prophecy" (1:80).
- Anomalies in the Learning Curve Shape – A variety of situations such as shutdowns, new employee skill mixes and reaching a steady state, can cause the learning curve to deviate from its predicted shape. (1:80)

Finally, research has indicated that the Anderlohr method also has several shortcomings. Parikh (18) identifies nine of them. They include:

- "The method is hypothetical and unproven" (27:19).
- The weights for each of the five elements for the loss of learning are difficult to determine accurately. Supporting data tends not to be available. Anderlohr himself cautions users on the determination of weights in his works. (27:19)
- "The method assumes that improvement is related solely to direct supervision, direct labor, and related tooling" (27:19). The Anderlohr method does not cover areas such as management innovation, design, producibility, work simplification and new production equipment and techniques. These areas are usually permanent and directly affect the start up costs of reopening a closed production line. (27:19)

- Anderlohr applies the loss of learning to hours and not to units. The improvement curve theory is based on units produced not hours. Loss of learning is also applied uniformly regardless of the stage of the program. The improvements usually come in spurts, such as in debugging and process changes at the startup phase of a program. (27:19)
- The five elements of the theory focus on labor-intensive manufacturing of the 1960s. Modern manufacturing has switch to more automation and an emphasis on imparting workers skills into the machine. Computerization has captured more of the information that would be lost in a break. (27:19-20)
- "Mr. Anderlohr's inappropriate use of the term "learning" oversimplifies the complex improvement process. The more appropriate term is "improvement." Improvement curves measure the project not only the effects of manual dexterity, but also a brad group of management innovation and interaction between the two" (27:20).
- The gains in improvement since the break are not included in the method. For example, other factory lines at the contractors facility my have achieved improvements that the reopening line may benefit from. Advances in tooling and other production technology are accounted for. (27:20)
- The Anderlohr method does not distinguish between manual-based tasks and machine-based tasks. Less learning loss takes place with machine-based tasks. (27:20)
- "The method does not give any consideration to the accelerated rate at which lost improvement is regained. It is an accepted fact that the initial rate of

improvement at the restart of production is much greater than its historical rate" (27:20).

System Dynamics

The concepts of System Dynamics were developed in 1961 by Dr. Jay W. Forester and described in his book *Industrial Dynamics* (19). In this revolutionary book, Forester proposed scientifically modeling the complex behavior of the business world using a unique simulation strategy. The term Industrial Dynamics was renamed System Dynamics to emphasize the use of this methodology in other fields besides business. Coyle defines System Dynamics as:

> System dynamics deals with the time dependent behavior of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behavior, and designing robust information feedback structures and control policies through simulation and optimization. (10:10)

Clark states, "System Dynamics is the study of processes through the use of system and how they can be modeled, explored, and explained" (8:2). System Dynamics focuses on the feedback behavior of variables within the closed loop of the system. All the variables inside the system, and some exogenous ones, influence each other's behavior. The difficulty, and reason for using System Dynamics, is that it is difficult to predict the behavior of a system's key variables if the system is relatively complex. Clark states, "In their transient states, such systems are virtually impossible to solve mathematically, so they are usually simulated" (8:1). By analyzing the relationships and feedback behavior of the systems key elements, it is possible to understand the systems behavior and influence it.

The versatility of this methodology has allowed System Dynamics to be used in a variety of ways. Models such as those found in *Urban Dynamics* (20) have been used to explain how to implement policies to curb social problems. Examples found in business include *Industrial Dynamics*, which models the five main business variables of a company (19:1). The Navy has used system dynamic to model costs. Specifically, it was used to settle a lawsuit filed regarding a shipbuilding contract (9). The contractor and government then adopted the model for use in future contracts. A recent thesis effort by Purvis applied system dynamics to modeling of Operations and Support costs of the Air Force's C-17 aircraft fleet (28).

There are several ways to build a System Dynamics model. Coyle uses a five-step approach (10:11). Clark uses a less defined approach (8). This research effort will use a four-step process involving conceptualization, formulation, testing, and implementation. This process was originally developed by Randers (29) and adapted by Albin (2) though her work with Jay Forrester's *Road Maps* (18). A detailed explanation of this model building process is in Chapter III dealing with methodology.

System Dynamics Terms

System Dynamics, like s other disciplines, has unique terms. Some of the most common are:

- Reference Mode - a chart showing how key variables behave over time. The x-axis represents time and the y-axis represents the units of the variable. Albin states, “The reference mode captures mental models and historical data on paper, gives clues to appropriate model structure, and can check plausibility once the model is built” (2: 12).

- Influence Diagram - these diagrams show the cause and effect relationships of the variables. Coyle states, “[influence diagrams show] influences at work in the system, the interplay of which is the cause of its dynamic behavior” (10:18). This relationship can be either positive or negative. A positive relationship is defined as each variable having the same direction in the change in quantity. For example, if prices rise, the costs to consumers increase. If prices fall, the costs to consumers decrease. A negative relationship is one were the variables react oppositely when there is a change in a variable. The Influence Diagram is closed loop unless there are exogenous variables added.
- Causal loop Diagram - this diagram shows the interaction of different stock to one another. A closed pattern or loop in this diagram represents a feedback loop. Coyler states, “Influence diagrams are sometimes called ‘causal loop diagrams.’ There is little or no difference, but causal loop diagrams are best thought of as influence diagrams drawn at a very broad level, and not showing the fine detail which can be included in an influence diagram” (10:18).
- Flow Diagram - this diagram shows how variables transition through the system. Using commercially available software, such as STELLA (32), one can code the model in conjunction with development of the flow diagram.
- Stocks - the accumulators of the system. They are the nouns in the language of system dynamics. They can be tangible things like money, planes, and parts.

They can also be intangible concept like happiness, anger, burnout, and productivity.

- Flows - these are the regulators of the stocks. They are the verbs of the language of system dynamics. They regulate how much the stocks are filled up or depleted. They are always defined as a rate.
- Converters - these items transition variables of one type into variables of another type.

Validation

Validation of a System Dynamics model is a multi-step qualitative process. It is qualitative rather then quantitative because System Dynamics is not a traditional statistical modeling technique. Its overall purpose is to analyze the underlying trends of a system and advise on how different policies influence the system. Consequently, there are no mathematical tests that will prove or disprove conclusively validity as with other modeling validation techniques. Evidence of validity accumulates through passing several qualitative tests. Forrester and Senge define validation as the, "process of establishing confidence in the soundness and usefulness of a model" (21:210). Sterman states, "Validation is an inherently social process. It depends on the cultural context and background of the model builders and model users" (33:51). Forrester and Senge state, "There is no single test which serves to 'validate' a system dynamics model. Rather, confidence is a system dynamics model accumulates gradually as the model passes more tests and as new point of correspondence between the model and empirical reality are identified (21:209).

The qualitative nature of System Dynamics validation has created controversy with those familiar with other modeling techniques. Forrester and Senge state,

> The nature of system dynamics models permits may tests of model structure and behavior not possible with other types of models. Conversely, some widely used tests, such as standard statistical hypothesis test, are either inappropriate or, at best, supplementary for system dynamics models. (21: 209)

System Dynamics models are not intended to predict future values or match exactly the past system data. The modelers strive to create a dynamic understanding of how the system behaves now and into the future (21:218-219). There are no prediction or confidence intervals. There is general confusion over System Dynamics models because they are not stochastic in nature. Sterman states,

> System Dynamics modelers are often faulted for their reluctance to employ formal measures of goodness-of-fit when assessing the historical behavior of models. As a result, the validity of system dynamics models is often questioned even when their correspondence to historical behavior is quite good. (33: 51)

> …the single most common measure of validity in the social sciences, the historical fit of a model, is a weak test that contributes little if anything to confidence. (33: 52)

The tests of validation for a system dynamics models can be broken down into three main groups. The first group are the structure tests, which involve comparing the model's structure and parameters to the real system. The seconded group of tests are the behavioral tests. They involve matching the behaviors produced by the model to that of the real system. The final group of tests are the policy implications tests which focus on how policies affect the model and the real system. The relationships between these validation tests are shown in Figure 6.

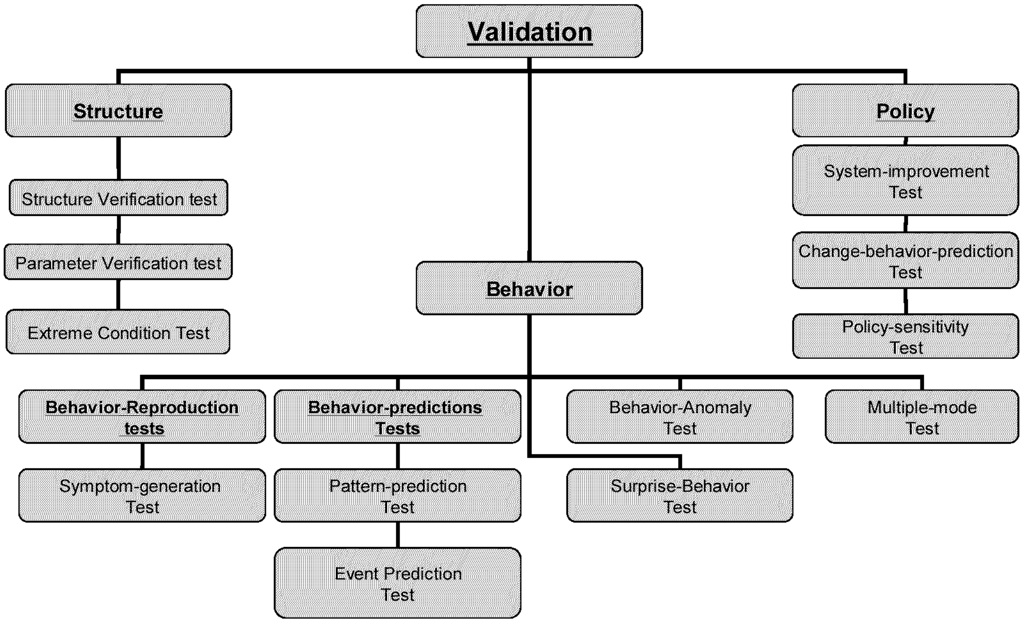


Figure 6. Validation Test Diagram

Structure Validation Tests

There are three main structure tests for system dynamics models. They include the structure verification test, parameter verification test, and the extreme condition test. Forrester and Senge state, "Verifying structure means comparing structure of a model with structure of the real system that the model represents. To pass the structure-verification test, the model structure must not contradict knowledge about the structure of the real system" (21: 212). The test is usually performed by explaining the structure of the model to someone that has a great deal of knowledge regarding the real system.

Validation is measured by how close the expert thinks the model's structure matches the real system's structure.

The parameter verification test analyzes the critical variables that comprise the model. Forrester and Senge state, "Model parameters (constants) can be verified against observations of real life, just as structure of a model can be compared to available knowledge" (21: 212). They go on to say, "Structure verification and parameter verification are interrelated. Both tests spring from the same basic objective – that system dynamics models should strive to describe real decision-making process" (21: 213).

The extreme condition test involves running the model at the parameter boundaries. The results are compared to the real system's behavior under the same conditions. This test becomes difficult to perform if the real system has not experienced the exaggerated behavior being modeled. In this case, the model's results should be compared to how the real system would most likely behave under these same extreme conditions. Forrester and Senge state,

> The extreme-conditions test is effective for two reasons. First, it is a powerful test for discovering flaws in model structure. Many proposed formulations look plausible until considered under extreme conditions. … The second reason for utilizing the extreme-conditions test is to enhance usefulness of a model for analyzing policies that may force a system to operate outside historical regions of behavior. (21: 214)

Behavior Validation Tests

Behavior tests for System Dynamics models are divided into four different categories. First are the behavior-reproduction tests that look at how well the system dynamics model coincides with real system performance. Second are the behavior-prediction tests. Forrester and Senge state, "Whereas behavior-reproduction tests focus on reproducing historical behavior, behavior-prediction tests focus on future behavior" (21: 219). Other tests include the behavior-anomaly and surprise behavior tests.

There are two common behavior reproduction tests for validation. They include symptom generation and multiple role tests. The symptom generalization test analyzes if the model is answering its true purpose. Forrester and Senge state, "The *symptom-generation* test examines whether or not a model recreates the symptoms of difficulty that motivated construction of the model. Presumably the model was made to show how a particular kind of undesirable situation arises, so it can be alleviated" (21:217). The multiple-mode test examines if the model will work in a variety of situations. Forrester and Segne state, "A model able to generate two distinctive periodicities of fluctuation observed in a real system provides the possibility for studying possible interactions of the modes and how policies differentially affect each mode" (21:218).

The two behavior-prediction tests include the pattern-prediction test and event-prediction test. The pattern-prediction test qualitatively analyzes the model's predicted behavior to determine whether its shape appears feasible and matches what is expected of the real system. This is not a formal goodness of fit test, but a generalized comparison of the model output to the real system. The event-prediction test focuses on the model's behavior at a critical moment in the time sequence of the model run. This could be a sharp increase or decrease in a variable at a specific time or the point in time that an exogenous variable is added. Forrester and Senge state, "…the event-prediction test should hinge on the dynamic nature of an event and identification of conditions leading to it rather than on the exact time when the event occurred" (21:220).

The behavior-anomaly test focuses on explaining unpredicted behaviors generated by the model because of a flaw in the assumption made to build the model. The behavior is traced back to its source in the model and the model corrected. Although this test is very useful in the model building stage, it also has value in explaining the finished model to the end-users. Forrester and Senge state, "For example, one can often defend particular model assumptions by showing how implausible behavior arises is the assumption is altered" (21:220).

The surprise-behavior test analyzes the unpredicted but apparently correct results of the model. Forrester and Senge state, "The better and more comprehensive a system dynamics model, the more likely it is to exhibit behavior that is present in the real system which has gone unrecognized" (21:221). The modeler must understand how the unexpected behavior is being generated and decide if this matches the real system. If the real system does indeed have this unrecognized behavior then the recognition of it adds to the validity of the model and more importantly the understanding of the real system.

Policy Implications Tests

The tests for policy implications include system improvement test, changed-behavior-prediction test, and boundary-adequacy test. Forrester and Senge state, "…tests of policy implication differ from other tests in their explicit focus on comparing policy changes in a model and in the corresponding reality" (21:224). These tests are the most difficult to run because they involve using the model's predictions to influence the policies that will change the real system. If the model has not been accepted and implemented, then it is very difficult to evaluate these types of tests.

The system improvement test analyzes how well policies developed from the system dynamics model improve the performance of the real system. This test has some drawbacks according to Forrester and Senge. The first is the model's end-users must have developed enough confidence in the model to use it for real world application. If they do not have this confidence then the model likely has been implemented. The second problem is determining if changes in the real system were actually caused by the policy or some other influence. The third problem is the long period required to see if the real system is influenced by the new policies (21:224).

The system improvement prediction test focuses on how well the model predicts behavior when there are changes to the real system. There are several alternatives to this test. The model can change its underlying policies and then analyze to see if the results are consistent with those of the real system. Another alternative is to repeat real system policy changes within the model and compare the results to the real system (21:224-225).

The policy-sensitivity test focuses on the how strongly certain policies will affect behavior of the variables in the model. The results of this test are very useful in explaining the risks involved with different policies. Forrester and Senge state, "Parameter sensitivity testing can, in addition to revealing the degree of robustness of model behavior, indicate the degree to which policy recommendation might be influenced by uncertainty in parameter values" (21:226).

III. Methodology

Introduction

This chapter examines the methodology used to build and validate a production break model using a System Dynamics modeling approach. The construction of this model follows a four-stage process of conceptualization, formulation, testing, and implementation. The chapter concludes with validation tests and interviewing techniques used to create the model.

Model Formulation

Albin states that the Systems Dynamics modeling process involves four stages: conceptualization, formulation, testing, and implementation (2:6). Conceptualization identifies the purpose of the model, the model boundaries, and key variables. The modeler also develops reference modes and feedback relationships during this stage. The formulation stage focuses on converting influence diagrams into flow diagrams and setting values for parameters. The testing stage begins the simulation process and analyzes how the model tracks to the dynamic behavior of the real system. The implementation stage examines how the models use will influence policies that affect the system and the new insights clients have on the system. The modeling process theoretically is never complete because as the model is used to influence the system, the model is updated to match the new behavior and again used to further influence the system.

Conceptualization

The first step in model creation is conceptualization. Albin writes, “During the conceptualization stage, a modeler must determine the purpose of the model, the model boundary, the shape of the reference modes, and the nature of the basic mechanisms” (2:8). She goes on to say, “The goal of the conceptualization stage is to arrive at a rough conceptual model capable of addressing the relevant problem in a system” (2:8).

In the building of a production break model for this research, the main purpose will be to simulate the causes and feedback relationships that influence incremental costs during a production break. The main problem addressed by this model is the lack of understanding of the costs associated with a production break. The goal of this model is to develop a greater understanding of the cause and effect relationship within production breaks. Primarily, the model will increase the ability of cost analysts to evaluate various policies that affect incremental costs and stimulate development of new and better ways to estimate the cost of production breaks. This model is not designed as an estimating tool for two reasons. The first is the model is too general to capture the specific influential relationships of a particulate production line. Extensive modification would be required to assure that the model’s structure and behavior match a specific aircraft production line. Second, there is incompatibility in using the methodology of System Dynamics as a point estimating tool. The value in using a System Dynamics modeling approach is in the analysis of feedback behaviors of a system. The output of a System Dynamics model cannot be assessed as to its quality prediction capability. This is not a stochastic tool, hence there exists no techniques for measuring the accuracy of a prediction value, such as R^2 or a prediction interval. The intended use of the model is to evaluate the general shape of the cost curve for a production break and model how that curve changes when different policies are implemented.

The audience for the production break model are the cost estimators, engineers, and decision makers. The model should be tailored to what the end user will be comfortable implementing. In this case, the production model will be a policy and learning device rather then a direct estimating tool.

The boundary of the production break model encompasses all the major variables influencing the costs on the production line during a production break. Albin states, “Every feedback system has a closed boundary within which the behavior of interest is generated” (2:9). Clark states, “The boundary is often not explicitly defined in the modeling process. It implicitly contains all variables that are defined as dependent on other variables, and excludes those only dependent on constants or exogenous variables” (8:33).

Each variable of the production break model is either endogenous or exogenous. Endogenous variables are those that are directly influenced by other variables in the model. Exogenous variables are those that are outside the boundary of the model, but affect some aspect of the model. Another way to look at these two terms is in how they are controlled. If the variable is controlled by other variables within the model, then it is endogenous. If a variables is controlled by forces outside the system then most likely it is exogenous. The production model should have as few exogenous variables as possible to explore the full range of the drivers of cost within the system.

Reference Modes are charts of the behavior of key variables over time. Albin states, “The reference mode captures mental models and historical data on paper, gives clues to appropriate model structure, and can check plausibility once the model is built" (2: 12). The vertical axis represents the variable while the horizontal axis represents time. When plotted, they are helpful in identifying the underlying structure of the model. They are also helpful in identifying feedback loops within the production line. Verbal descriptions and historical data are also useful and may serve the same purpose as a reference mode.

The conceptualization stage is complete when the causal and influence diagrams of the basic mechanisms of a production break are created. Albin states, "The basic mechanisms represent the smallest set of realistic cause-and-effect relations capable of generating a reference mode" (2:18).

Formulation

The formulation stage involves converting the influence diagrams into flow diagrams. Using a software package, such as STELLA (32), allows the modeler to create the flow diagram and code the model formulas as well. During this step, the modeler estimates and selects parameter values. Historical data, if available, is helpful for parameter estimations. If historical data is not available, the opinion of an expert is often used.

The flow diagram defines each of the production break variables as a stock, rate, or converter. Stocks are the accumulators of the model. They increase or decrease through the rates of the model. The converters transfer information or adapt information between other converters, stocks, and rates. The connecting arrows show how the three structures relate to one another. Figure 7 shows the symbols that STELLA (32) uses for rates, stocks, converters, and connectors.

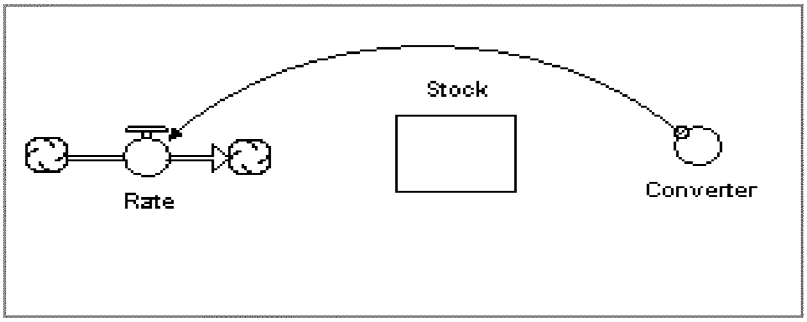


Figure 7. Flow Diagram Structures

The estimate of parameters involves assigning values to the constant variable of the model. The parameters should match what is observed on an actual production line. For example, the number of hours in a workweek is usually 40, so the model parameters should also use a 40-hour workweek. If the parameter, is unknown then either historical data should be used or the opinion of an expert should be used.

Testing

The testing stage involves simulating the model, testing the model's assumptions, and analyzing the overall behavior and sensitivity of the model. This stage uses several validation tests to assure the usefulness of the model. Important validation tests during this stage involve both structure, and behavioral tests.

The following questions are divided in order to adequately address both the structure and the behavior of the model. The production model should successfully pass each question in order to begin the validation process. By pass, it is meant that the production model should have a positive response to each of the subjective question asked. The structural questions include:

- Is the layout and workings of the production break model similar to that of a real production system?
- Are there the same elements of cost that you would see in an actual production process?
- Do the various connections between variables match those of an actual production line?
- Do the parameter values match those on an actual production line?
- Does the model duplicate a real production line when there is no brake in production?
- Does the model duplicate other extreme variables?

The behavior test will focus on how the model duplicates how an actual production line would react to a production break. The behavioral questions include:

- Does the model match the behaviors found in a real production line?
- Does the model's incremental costs match those of a real production line?
- Are there any surprising behaviors that match what the real production line would do?
- Does the model predict when the shutdown and startup times will be?

Implementation

The final stage is implementation. This stage involves simulating the model under a variety of different policies trying to gain insight as to what the actual system might do under similar polices. Once the new policies are implemented, the model's results should be checked against the real systems behavior. Modification should be made to the model if the model generates unexpected results compared to those of the actual production line. Unexpected results are usually caused by unknown structures that should then be added to the model.

Since full acceptance and use of this model may take several years, completion of the implementation stage is not feasible within this research. The model will be distributed to the experts identified in this research and to the ASC cost library. The model is a teaching tool and provides a way to test different policies concerning production breaks. The models teaching aptitude comes from its ability to show users the behaviors of the entire system during a production break because of the policies they enter into the model. With the Anderlohr, Modified Anderlohr, and Retrograde methods, the final product is a single one data point, which presents very little information and insight regarding the dynamics of the production break process. With this model, a diverse set of behaviors can be analyzed quickly, and a more robust understanding of the aircraft production line is realized not only at the startup of production but during the shutdown and actual break itself. The model also offers cost estimators, engineers and decision makers a quick way to test policies and see their long-term results.

Validation

Validation of the production break model is divided into structure, behavioral and policy of the tests. Forrester and Senge state, "There is no single test which serves to 'validate' a system dynamics model. Rather, confidence is a system dynamics model accumulates gradually as the model passes more tests and as new point of correspondence between the model and empirical reality are identified (21: 209). By passing more and more validation tests, more confidence in the production break model is generated.

The testing stage of the model building methodology previously discussed outlined several questions used to test the model in the areas of structure and behavior. The structure questions focused on the structure, parameter, and extreme conditions tests. The behavior questions focused on the symptom generation, frequency generation, relative phasing, pattern prediction, event prediction, behavior anomaly, and surprise behavior. The final implementation stage, although not within the scope of this research, would use the policy validations test of system improvement, change-behavior-prediction, and policy-sensitivity to further validate the model. A more detailed explanation of each of these tests is found in Chapter II of this thesis.

Interviews

One on One interviews were held with three experts in production breaks. The first interview gains insight about production breaks and begins to look for commonality between responses. Worksheets (Appendix A) were used to guide the discussion. These worksheets focus on the influences of costs during the shut down, production break, and eventual startup of production. They identified the most influential variables in the manufacturing system during the three phases of a production break.

A second interview was held to validate the production break model developed form the first set of interviews. Each expert reviews the structure of the model. The test phase questions were asked responses recorded for further modification of the model. Each interviewee was given an opportunity to run the model and become familiar with the generated results.

In addition to the three initial interviewees (30) (23) (35), two additional experts (34) (5), an industrial engineer and a former cost analyst, were interviewed to evaluate the production break model after its completion. These interviewees were shown the basic influence diagram and reference modes. The model was explained and demonstrated. Each expert was also be given an opportunity to run the model and become familiar with its operation. Validation questions were also asked and answers used to further refine the model.

IV. Findings

Introduction

This chapter will present how the production break model was built using the conceptualization, formulation, testing, and implementation phases. The chapter then explores the overall interviewee impressions of the model.

Model Conceptualization

The production break model was developed using a four-stage approach outlined by Albin (2). Those stages include conceptualization, formulation, testing, and implementation. The conceptualization phase involves determining the purpose of the production break model, its audience, boundaries and influence diagrams. The formulation stage transitions the influence diagrams into flow diagrams. The testing stage conducts various validation tests to determine soundness of the model. The implementation stage concerns the models use to change the behavior of the system modeled.

Conceptualization

The first step in building a model is to determine its purpose and the problems it is to solve. The purpose of the production break model is to simulate the causes and feedback relationships that influence incremental costs during a production break. The primary problem addressed by this model is the lack of understanding of the dynamics of costs associated with a production break. With this model, it is hoped that a greater understanding can be developed regarding the dynamics of production breaks. This model will increase the ability of cost analysts, engineers and possibly the decision makers themselves, to evaluate various policies that affect incremental costs and it is hoped, stimulate development of new and better ways to estimate the cost of production breaks. However, model is not an estimation tool however for two reasons. First, the model is much to general to apply to a specific program. The second is that underling methodology of System Dynamics does not support the models use as a point estimation tool. The focus of System Dynamics is to explore the general trends and behaviors of a system, not to find exact numeric output. System Dynamics models are based on expert opinion and do not have the stochastic foundation that is necessary for an accurate estimation tool. The intended use of the model is to evaluate the general shape of the cost curve of a production break and show how that curve changes with different policies.

The model was developed via interviews with several production break experts, both engineers and cost analysts. Specifically, three engineers and two cost analysts were interviewed (5) (30) (23) (35) (34). Each interviewee has over 20 years of government experience and has worked several programs experiencing production breaks. These experts have also been involved with the yearly estimation of a production break no their current programs. Tables 4, 5, and 6 identify the major variables that were initially developed interviewing two engineers and one cost analyst. The variables are divided into their relative influences during the three phases of a production break. Those three phases are the pre-shutdown, shutdown, and startup.

Table 4. Pre-Shutdown Variables

Interview 1	*Interview 2*	*Interview 3*
Bad Parts	Touch Labor	Manpower
Morale	Sustainment	Management
Manpower Turbulence	Quality Initiatives	Tool Storage
Cost of Errors	Management	Line Cannibalization
Compensation	Labor Union	

Table 5. Shutdown Variables

Interview 1	*Interview 2*	*Interview 3*
Length of Shutdown	Sustainment	Sustainment
		Level of Effort

Table 6. Startup Variables

Interview 1	*Interview 2*	*Interview 3*
Hiring	Loss of Learning	Line setup
Suppliers	Management	Loss of Learning
Tooling	Quality Initiatives	Training
Factory Support		Diminishing Manufacturing Sources
Training		Quantity
		Obsolesce

The key reference mode for the production break model is that of incremental costs. This variable represents all costs incurred through production over a specific time period. This reference mode was developed through interviews with the three initial production break experts (30) (23) (35). Looking at Figure 8, the shutdown phase shows a small decline, then a sharp increase in cost. The costs peak and then drop off quickly. During the production break phase, there are few, if any, incremental costs. Predominately, the production break phase requires a minimal level-of-effort to keep maintenance on the machines and storage of tooling costs. The startup phase begins with a large spike and then drops off to a constant state.

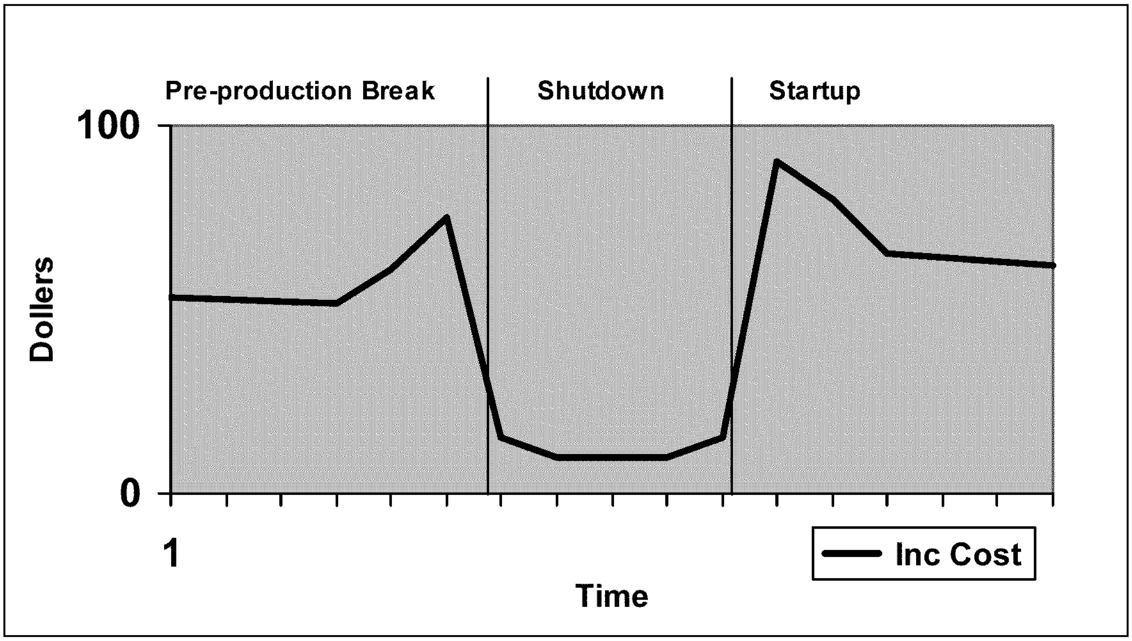


Figure 8. Incremental Cost Reference Mode

During the shutdown phase, the primary influences on cost are the use of bad parts and manpower turbulence. Figure 9 shows the influence of reconditioned parts on production. The term *bad part* represents the defective parts a contractor is forced to recondition or replace in order to complete the last units of production. Contractors will set defective parts aside and use others to avoid the reconditioning or purchasing costs at the time of discovery. For Example, a factory stocks 10 radar units for 10 aircraft in production. The third radar unit has a problem that will prevent instillation into the third aircraft. The contractor will likely set aside the defective radar unit and install the radar set assigned to plane four to keep the line moving and avoid incurring additional cost. During the pre-shutdown phase when the last plane is on the line, the radar unit originally slated for the third plane is finally reworked and installed in the last plane.

Unfortunately, this slows the line down, because of the time need to recondition or replace the defective parts and increases cost by requiring more materials and labor. The production rate decreases and slows the work completed. The contractor will likely try to make up for the lost time through overtime. Too much overtime can lead to low moral and eventually decrease efficiency even more.

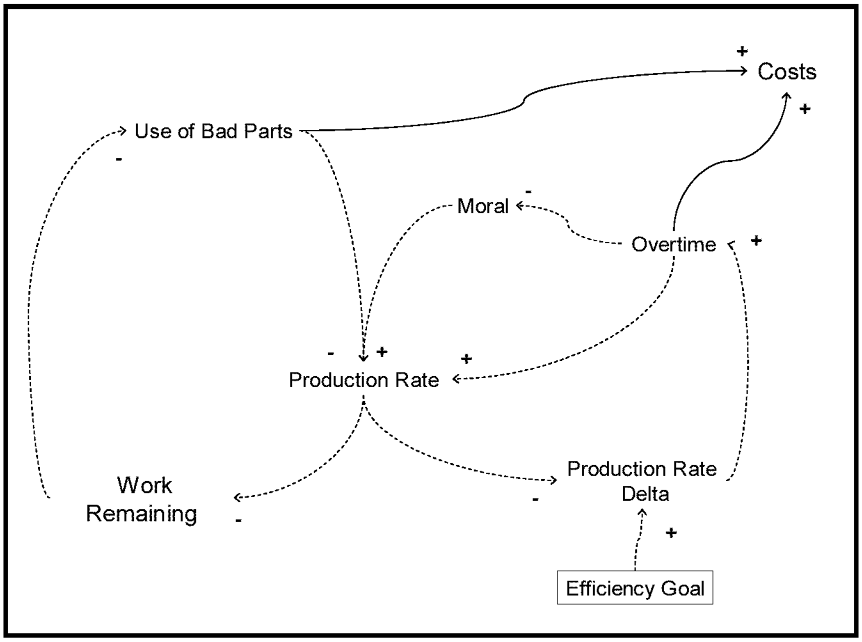


Figure 9. Bad Parts Influence Diagram

The second major driver of cost during the pre-production break phase is manpower turbulence (see figure 10). As workstations become idle as the last plane goes through the line, senior employees will take over jobs at the end of the line or move to a different program within the company. This creates what some of the interviewees term, manpower turbulence. Those senior employees moving to positions down the line must learn a new job, which decrease the job knowledge on those workstations. Those that move to another production line within the company usually move before the last plane has gone through their workstations, so a less experienced employees must learn and work the vacated position. As the employees learn new skills, errors will occur more frequently. These errors are particularly expensive during the shutdown phase because of the limited parts availability. The contractor keeps parts inventories at a minimum because of the shutdown. Suppliers may be no longer producing parts, causing substantial costs to remanufacture them. The wait for new parts will decrease the production rate and slow the amount of work being completed.

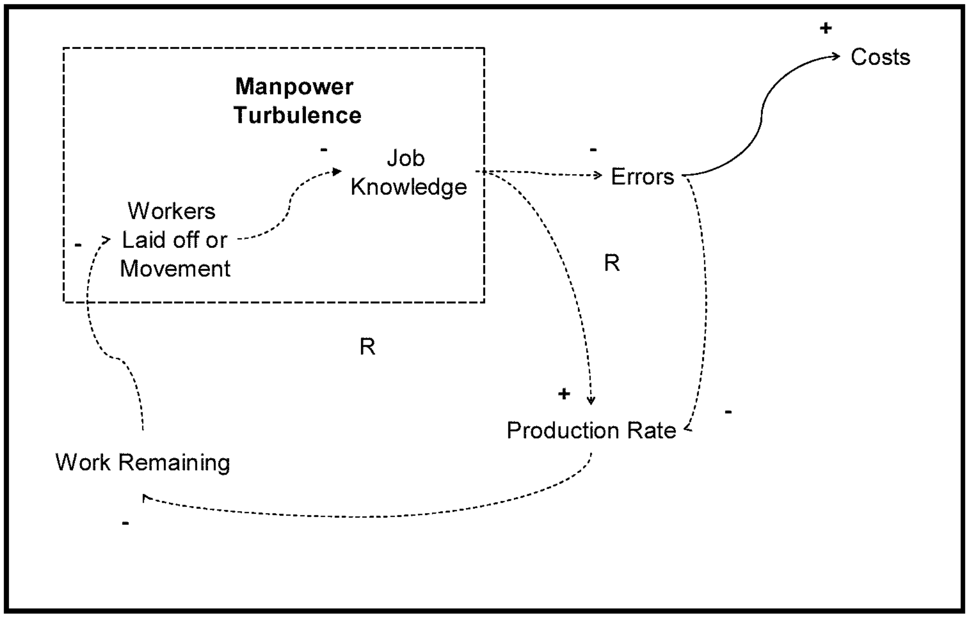


Figure 10. Manpower Turbulence Influence Diagram

During the production break phase, there is very little activity. Production has stopped and workers are laid off or moved to other production lines within the company. The costs are steady or fixed. The interviewees suggest that the main costs, not necessarily billed to the government include storage, tool maintenance, support, level of effort and *caretaker* operations.

The main drivers in the startup phase are requirements upgrades and the replenishment of the labor pool. The hiring of new employees is driven by the new plane orders generated at the startup of production. Figure 11 shows how new requirements will influence the addition of labor. New technology and added capability will drive up the goal for the labor pool. A difference in the labor pool and the labor pool goal will cause more employees to be hired. The personnel will need to be trained which will improve their job knowledge and the production rate. The production rate however will suffer from the hiring of new employees because of their lack of training.

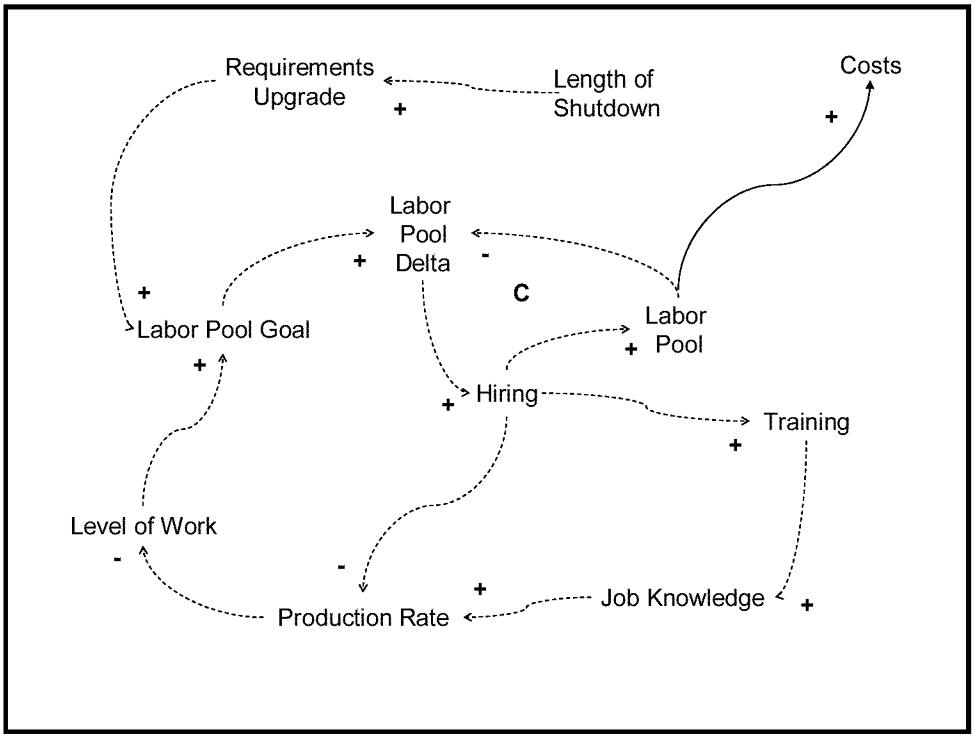


Figure 11. Startup Influence Diagram

This completes the conceptualization phase of the production break model development effort. The basic variables are identified and the general influence diagrams created. The influence diagrams show that costs will increase during the shutdown and startup phases of the production line. During the production break phase, cost will remain steady or fixed. This matched the overall incremental cost reference mode that was developed earlier in this chapter.

Formulation

The formulation of the model was divided down into in five areas. These areas include production, labor, materials, knowledge, and cost. The production area simulates the basic flow of planes through workstations in order to become finished aircraft at the end of the production line. The labor area simulates the amount of workers needed at different times during production. The materials area simulates the ordering and use of materials and parts during production. The knowledge section simulates the level of skills and job knowledge workers have during production. Finally, cost calculates the costs incurred on the production line over time.

Several assumptions are made to simplify the model and make it easier to understand. First, this model is a theoretical representation of a production line. Several production characteristics that exist on an actual production line are overlooked. For example, each workstation has four employees. On an actual production line, the number of employee in a workstation can vary greatly. The basic production scenario of this model is that the production line has 100 workstations. Four employees operate each workstation. A workstation completes its work with the assembly of 20 parts onto the plane. Each plane passes through all 100 workstations. The production line moves at an optimal rate of 10 planes per month or 10 planes move in and out of a workstation per month. The line is serial, meaning that the planes move in a set sequence from one workstation to the next.

The production area of the model is comprised of three main structures (Figure 12). They include the two rates of **New Plan Starts** and **Completion Rate** and one stock of **Active Workstations**. The **New Plane Starts** release planes at the start of the production line and fill the first workstation. As one workstation completes assembly, the plane is move to the next workstation. The stock **Active Workstations** shows the number of workstations that currently have a plane assigned them at any moment in time. As aircraft are completed, they are removed from the production line. The **Completion Rate** releases these planes from the production line.

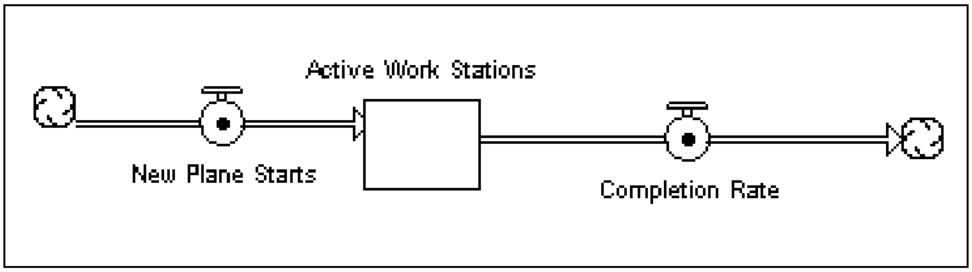


Figure 12. Flow Diagram of Production Area

The labor area has two stocks, **Touch Labor Pool** and **Support Labor Pool** (Figure 13**).** The **Touch Labor Pool** stock is the amount of assembly line workers employed at a specific time. The stock increases by the **Touch Labor Hiring Rate**, which is the rate of new assembly line workers hired to work. The stock depletes by the **Move or Layoff Rate** and the **Quit Rate**. The first rate represents management's involvement in reducing the labor pool by reassigning workers to other production lines or laying them off. The **Quit Rate** represents the more skilled employees that leave rather then waiting to be moved or laid off. The **Touch Labor Goal** converter calculates the amount of labor needed for the production line based on the **Active Workstations** and the amount of **Touch Labor Per Task**. The **Touch Labor Delta** converter calculates the difference between the **Touch Labor Goal** and the **Touch Labor Pool**. The **Touch Labor Delta** converter then influences the **Touch Labor Hiring Rate** or **Move or Layoff Rate** to achieve the **Touch Labor Goal**. The **Move or Layoff Rate** influences the **Quit Rate**.

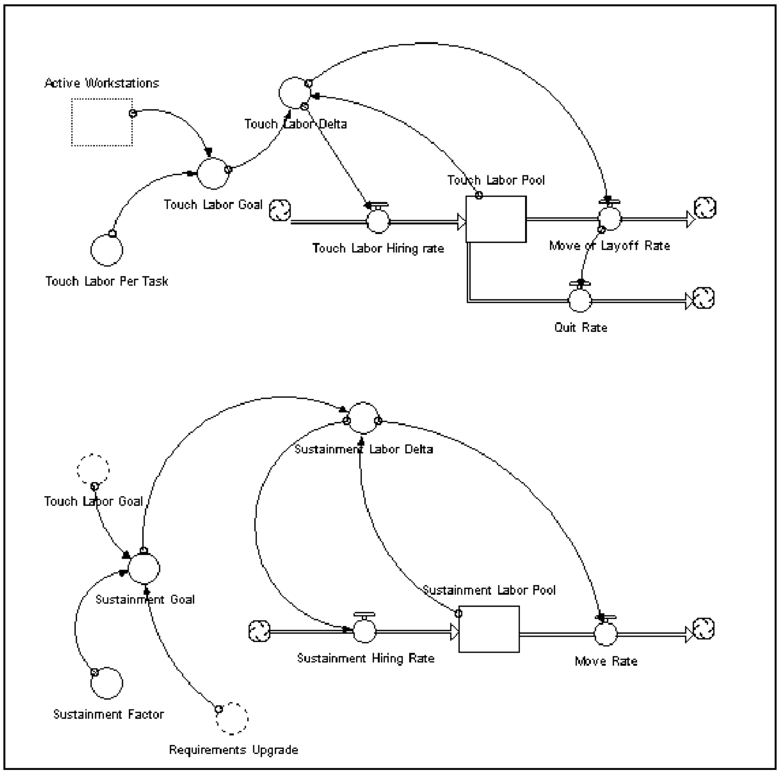


Figure 13. Flow Diagram of Labor Area

The **Support Labor Pool** stock operates similarly to the **Touch Labor Pool** stock. The term *support* refers to the technical experts, businesspersons, and engineers needed to keep the production line in operation. The **Support Labor Pool** stock is increased by the **Support Hiring Rate** and decreased by the **Move Rate**. The **Support Goal** converter is calculated by multiplying the **Touch Labor Goal** converter by the **Support Factor** converter and adding the **Requirements Upgrade** converters. The **Support Factor** is the percentage of touch labor that the **Support Labor Pool** should have. The **Requirements Upgrade** converter represents the increase in capabilities and upgrades that the aircraft design generally receives at the restarting of a production line.

The requirements upgrade causes an increase in the need for the support personnel to design the changes and prep the production line for those changes.

The materials area has the stock of **Inventory** (Figure 14). This stock increases through the **Parts Order Rate** and decreases through the **Parts Use Rate**. The **Parts Order Rate** is the number of parts ordered for the production line. The **Parts Gap** converter and the **Parts Use Rate** control the **Parts Order Rate**. The **Parts Use Rate** is the number of parts that are used on the production line and calculates by multiplying the **Active Workstations,** the **Parts per Workstation,** and the **Max Completion Rate** together. The level of **Inventory** is controlled by the **Parts Goal**, which calculates by multiplying **Active Workstations**, **Parts per Task**, and the **Workstation Completion Goal** converters together. The **Inventory** stock also depletes because of the **Defective Parts** rate. This rate calculates off the **Defective Parts Factor**, which is a percentage of parts that are defective in the inventory, and the **Refurbishment Factor**. The **Refurbishment Factor** represents the parts that are needed to be repaired or replaced when the **Active Workstations** are low. These bad parts were addressed in the conceptualization phase above.

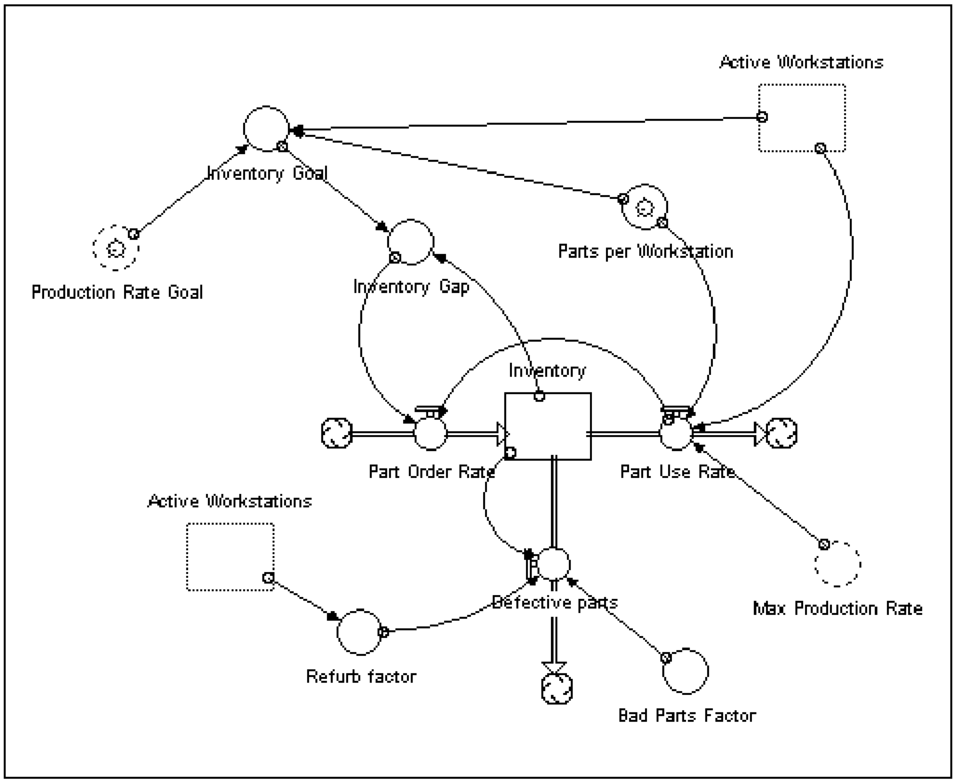


Figure 14. Flow Diagram for Materials

The knowledge area has the stock of **Job Knowledge** (Figure 15). This stock represents the amount of job skills and knowledge that employees have to complete their work. **Job Knowledge** is increased by the **Learning rate**. The **Learning rate** is a combination of on the job training represented by the **Max Completion Rate** and **Training** converters. The **Max Completion Rate** is the maximum rate of planes moving along the line per month. This converter uses the lowest rate of possible completion rates from the three areas of labor, materials, and job knowledge. The **Restart Switch** converter indicates when the restart of the production line will begin and trigger an increase in training. The **Production Switch** indicates when the production line is active and will turn off **Training** and **Learning** when there is no production activity. The

Learning Loss Rate is affected by the **Learning Loss Factor,** the **Touch Labor Hiring Rate**, and the **Move or Layoff** rate. As new employees are hired and other employees leave, there is a loss of job knowledge. The **Learning Loss Factor** is the amount of job knowledge that is lost through time. The **Knowledge Max** rate is an overflow valve for the **Job Knowledge** stock. In the model, **Job Knowledge** is expressed as a percentage and should not exceed 100 %.

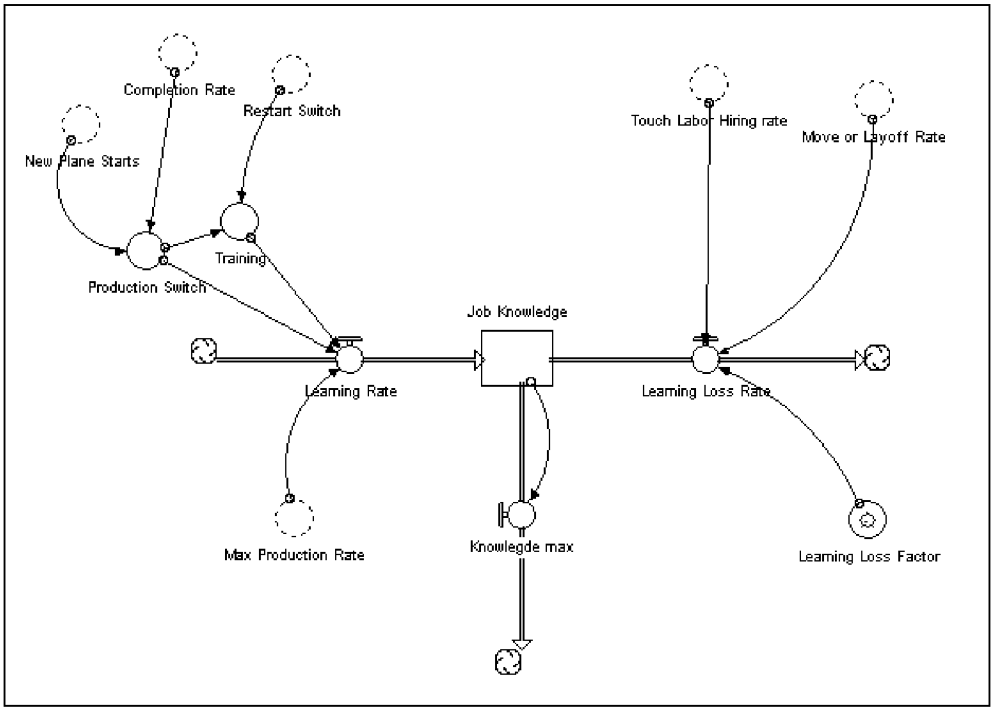


Figure 15. Flow Diagram of Knowledge

The last area of the model formulation phase is the cost area (Figure 16). This area brings together those stocks and rates that produce costs. Primarily each of the converters is multiplied by the other converters that are connected to the **Total Cost** converter. All labor costs are added together in the **Monthly Labor Cost** converter. The parts cost is calculated in the **Monthly Parts Cost** converter. These two converters are added together to get the **Total Cost** converter, which is the total incremental cost of production line within the production break model.

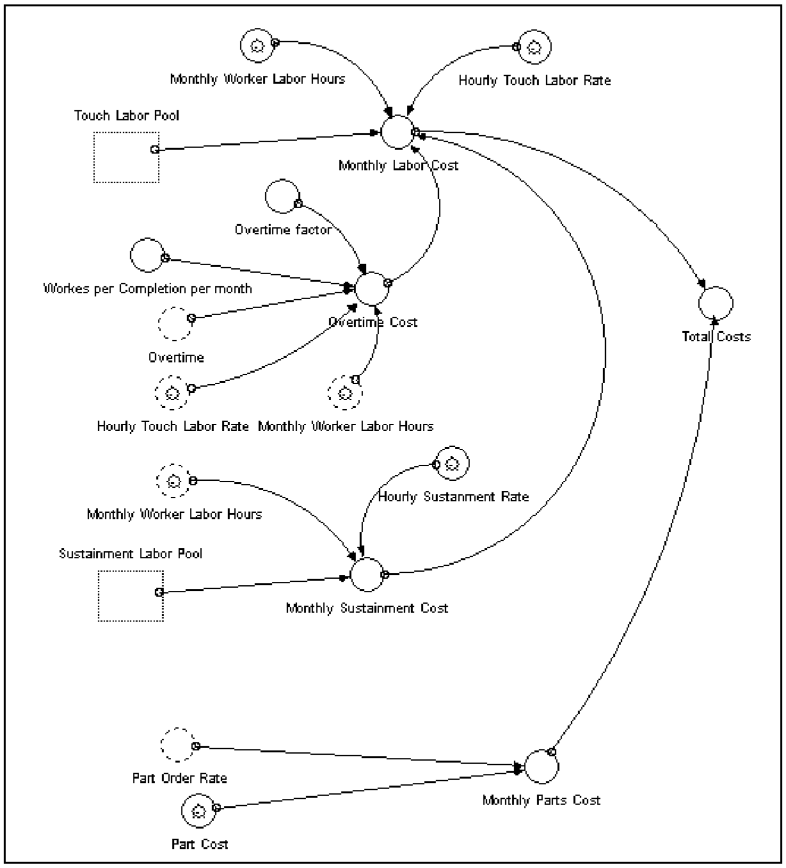


Figure 16. Flow Diagram of Cost

Testing

The testing phase of the model building process involved completing a variety of structural and behavioral validation tests on the production break model.

Structure Validations Tests

The structure of the model was compared to that of a typical aircraft production line. The experts interviewed agreed with the overall structure of the model. For example, they concur that the **Active workstations** stock would decrease as the line was shutdown and slowly increase as the line was restarted. The experts also agreed with how the **Touch Labor Pool** calculates the **Sustainment Labor Pools**. The use of the **Restart Time** variable verses the length of the production break was also consistent with a real production line. It is usually know when the factory will restart production, but it is mode difficult to estimate when the last unit will be finished in order, to calculate the length of the production break.

The different parameters of the production break model were compared to those in an actual production line. The experts agreed on the overall hourly rates and the **Worker Hours per Month**. However, there was some disagreement on the number of **Parts per Workstation** and the cost of those parts. The overall structure of incremental cost would change significantly if these parameters were changed. In addition, the calculation of the touch labor pool caused some debate because it is calculated by the number of workstations and the employees per task. In the real world, different tasks could take vastly different amounts of labor. Overall, the experts agreed that the perimeters were indicative of the same values in a real system. These types of disagreements are normal with any System Dynamics model. The overall purpose of the model is to simulate a majority of cost behaviors, and debate over structure and parameters helps to clarify the system under study. With any simulation, there will be areas of the system that are not explored or are oversimplified because of the difficulty in expressing them clearly. This is true particularly with a System Dynamics approach.

The extreme condition test was conducted on the **Restart Time** and the **WorkStation Completion Goal** variables. The **Restart Time** variable is the startup time of the production line after a production break. The model was run with a **Restart Time** of zero and shows a continuous production rate and cost. This represents the scenario of no production break and is consistent with an actual production line producing at a constant rate (Figure 17).

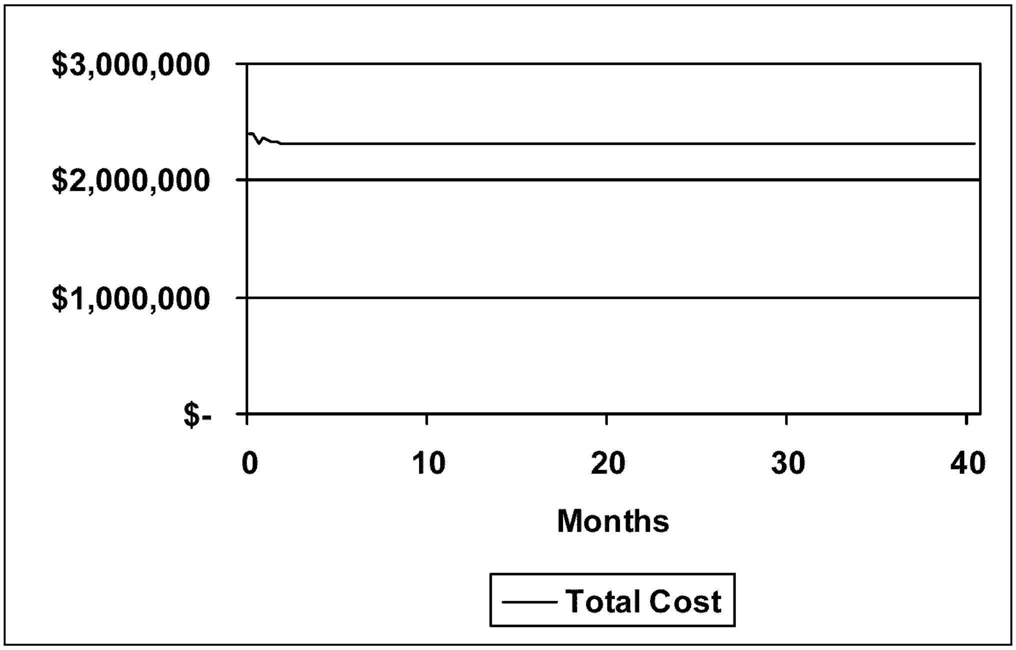


Figure 17. Production Model Output with no Production Break

The model was also run with the **Production Rate Goal** set to zero. This would indicate that the production line is fully functioning but not producing anything. As expected **Parts Order Rate** is zero. Only labor costs remain, and are constant. The

Active Workstation stock is also constant at 100 and the **Completion Rate** is zero. The employees are paid but there is no production.

Behavior Validations Tests

The model's behavior was demonstrated by setting the **Workstation Production Rate Goal** converter to 8, 10, and 12. This converter is a goal for the production rate at which the planes move along the line. The model simulates a production line working toward that goal. The graph in Figure 18 shows the three incremental cost curves for the three variations of the **Workstation Production Rate Goal**. During the shutdown phase with a goal of eight, the costs are lower, more spread out and exist longer then with the other two conditions. Feedback for the experts confirms that this makes sense because less parts and labor are used. During the startup phase, the peak is lower and more delayed. Again, the experts agreed that with a slower production rate, there are less part per month ordered and the labor would be less. When the goal is set to 12, the shutdown phase shows a peak in costs at the end of the phase. The experts (5) (30) (23) (35) (34) agreed that there would be more overtime, parts, and labor that would rise during the last units out of the factory. The increase in cost during the startup phase is also plausible to the experts.

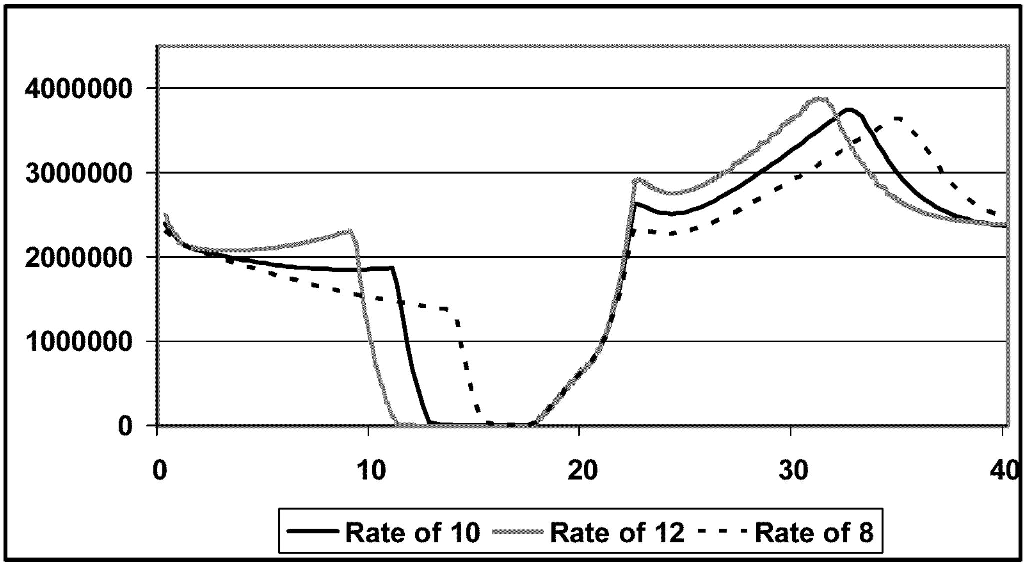


Figure 18. Incremental Costs with Production Rate Goal Changes

The symptom-generation test is used to determine if the model generates the similar conditions that the model was built to explore. Overall, the model was developed to analyze the incremental cost of an aircraft production during a production break. The model is duplicating those costs. Several of those interviewed stated that the model gives them a new perspective on costs during a production break. They also think that this model will help educate analyst and show then the cost relationships that exist during a production break. The experts interviewed also envision this tool as a way to test policies to mitigate cost to the government.

The multiple mode test is used to determine if the model will generate more than one set of behaviors. The demonstration of the three changes with **Production Rate Goal** shows the model will change the shape of the incremental cost curve. The model also demonstrates that if the **Production Rate Goal** is set to zero that the only cost would be labor. In addition, if the **Restart Time** is zero then there is no production break. These three groups of simulations demonstrate that the model is able to show multiple modes.

The pattern prediction test looks to see if the model produces the expected patterns of future behavior. For example, as the model starts, there are no new no new orders or aircraft stating production. The expected pattern would be a drop in the active workstations. Then when production restarts, the expected behavior is that active workstations would increase. During the production break, the expected pattern for incremental cost would be minimal and steady. The model demonstrated all of these predicted patterns.

The event prediction test looks at how the model forecasts a unique event. The model indicates that layoffs and overtime will happen at the same time during the end of the shutdown phase. The experts that were interviewed confirmed that this event does occur during a production line shutdown. The model then does predict the use of overtime at the end of the shutdown phase.

The behavior anomaly test looks at surprising behaviors of the model that when traced back through the model prove to be erroneously in the model. This test was used extensively with the formulation of the model. For example, a previous version of the model included the active workstations rise to full capacity immediately when the restart of production occurred. Several of the experts (30) (23) (34) interviewed found this to be surprising and inconsistent with an actual production line. Tracing though the structure of the model found that this was erroneously coded and the model update to show a steady build up of active workstations commensurate with the maximum production rate.

The surprising behavior test looks at unexpected behavior that is found to exist with an actual production line. For example, the model shows that layoffs and overtime occur at the same time during the shutdown phase. Experts (5) (30) (23) (31) (34) interviewed viewed this as a surprise but with further thought found to be accurate. The turnover in the labor pool could crate situations where too many employees are released and not enough labor exists with the proper skills to complete production tasks on time. Other surprising behavior can be seen in the two humps in the incremental cost curve at the start up of the production line. The model shows that most of this is parts and overtime for the first hump. This is accurate in that there will be a point in the restart that the production line will catch up with its goal and stop authorizing overtime. The labor pool continues to rise along with the support to a point were the factory is at full production and the extra support force to handle the requirements update is released. The model then has provided two new insights into the production break processes that were not noticed by the experts interviewed before.

Implementation

Implementation of the production break model will be accomplished with its distribution to cost and engineering communities. Specifically, each of those interviewed will be given an electronic copy of the model. Additionally, the model will become part of the ASC (Aeronautical System Center) cost library. Full implementation of the model will not be possible with this research because of the length of the implementation process.

Interviewee Impressions

The overall impressions of the model have been positive. The model has been accepted in its general structure and behavior. Several of those interviewed highlighted problems in initial models that were corrected with this final model. They all theorize that this model could function as a training aid and a tool to advise decision makers on the feasibility of a contractor proposal on production break costs.

V. Conclusions

Introduction

This chapter provides summaries of the four research questions explored in this thesis effort. The chapter also presents several future research opportunities.

Research Questions

This research focused on providing the Air Force with a better understanding of the costs associated with production breaks and their interrelationships. The following research questions were explored in this thesis:

(1) What methodologies does the Air Force currently employ in estimating aircraft production breaks?

A thorough review of the literature found that the Air Force primarily uses the Anderlohr, Modified Anderlohr, and Retrograde Methods for the estimation of production break costs. The Anderlohr Method analyzes five categories of learning loss. Those categories are personnel learning, supervisory learning, continuity of production, methods, and special tooling. Each of these categories is evaluated and a percentage of learning loss is determined. The five learning loss percentages are then multiplies by a weighted average to develop the Learning Loss Factor (LLF). The Retrograde Method is then used to calculate the number hours that the first unit after production should require to be completed.

The Modified Anderlohr Method breaks production into three elements. These elements include in-plant factors, availability, and retention of knowledge. The method is mathematically formulated as:

$$R = F * AV * Kn \qquad (8)$$

where:

F = Factor percentage

AV = Availability

Kn = Knowledge

R = Retained ability.

The in-plant factors include supervision, personnel, tooling, production continuity, methods, and configuration changes. Each of these categories is calculated using (8) above to find Retained Ability (R). LLF is the total retained knowledge subtracted from one.

The retrograde method uses the LLF to calculate the labor hours of the first units once production has re-started. The LLF from the Anderlohr, Modified Anderlohr, or one developed from other methods can be used. The following is a summery of the calculations involved:

> The theory behind the retrograde method is that because you lose hours of learning, the percentage of learning lost (LLF) should be applied to the hours of learning that you achieved prior to the break. The result gives you the number of hours of learning lost. These hours can then be added on to the cost of the first unit after the break on the original curve to yield an estimate of that unit due to the break in production. Last, we can then back up the curve (retrograde) to the point where production costs were equal to our new estimate. (12:17-23)

These three methods for estimating the costs associated with production breaks have several deficiencies. All three are based primarily on learning curve theory. Problems such as irregular shape (1: 77) and poor reporting of actual labor hours (1:75-77) call into the question the validity of an estimate based on this theory. Also, the Anderlohr Method suffers from a lack of validation of results (27:19), vagueness in the assessment of the loss of learning for each of its five categories (27:19), a lack of distinction between labor-intensive tasks and automated ones (27:20), and the subjectiveness of the assignment of the weighted average to determine the LLF (27:19). The method is also more then 30 years old and based on production techniques of the 1970s (27).

(2) Can the behavior of an aircraft manufacturing line undergoing a production break be explained using a System Dynamics methodology?

The development and validation of the production break model shows that a System Dynamics methodology can be applied to simulate the incremental costs incurred during an aircraft production break. The main theme of System Dynamics is that of exploring feedback loops and delays to evaluate policy changes on a system. This research has produced a wide variety of feedback structures and delay phenomena that occurs during a production break. For example, the model shows that the number of active workstation will influence the amount of labor needed. There is a delay in adjusting the amount of labor needed. The amount of labor influences the maximum production rate that influences the number of active workstations. The model combines this feedback loop with others to produce a more enlightened view of a production break and allows an analyst the opportunity to evaluate different policies pertaining to production breaks.

Validation of the model was accomplished with six experts in Air Force aircraft production breaks. Each expert has over 20 years civil service with the Air Force or DoD. Four of the experts were engineers and the other two were cost estimators. All six worked on at least one aircraft program that underwent a production break and five have been involved in the yearly estimates of production breaks. Validation of the model consisted showing these experts the results of structure and behavior test on the model. With System Dynamics there are no all-encompassing tests that prove validity, rather validation is achieved by a subjective incrementally process. The model is considered more valid with its ability to pass more tests of validity and in the comfort level of those using the model. Overall, the experts agreed with the results of the structural and behavioral test and found the model to be a good representation of an aircraft production line undergoing a production break. They also were comfortable in how the model duplicated the behaviors of an aircraft production break and looked forward to using the model.

(3) Can this model identify policy combinations that contribute to and mitigate the costs associated with a production break?

The System Dynamics production break model identifies policies that can be implemented to mitigate the costs associated with an aircraft production break. This research describes several examples of policies that can be implemented to reduce costs. For example, policies that minimize the amount of *bad parts* on hand before the shutdown of a production line could lead to lower costs associated with overtime and materials during the shutdown. The policies that affect the movement of workers during shutdown could be changed to minimize the manpower turbulence that is experienced. Decreasing the length of a production break could minimize startup costs. These are just a few of the scenarios that could lead to the mitigation of costs during a production break.

(4) How can this model be used to improve the cost estimation of a production break?

Primarily, the System Dynamics production break model provides a medium for gaining insight into the nature of a production break and explores policy decisions that affect costs during a break. However, because of the generalness of the model and the incompatibility of System Dynamics methodology to produce a point estimate, it is not intended to be a hard estimating tool. The value of this model is in its ability to simulate the general costs of an aircraft production line during a production break and identify areas of a cost estimate that should be more rigorously reviewed.

The model offers a valuable learning tool for engineers, cost estimators, and decision makers. They can to simulate several production line scenarios to see how costs can be mitigated and what the general trends of the incremental cost curve are. This type of simulation will be the most beneficial to those that are unfamiliar with production breaks and their costs. With this type of simulation, valuable insights will be created into how an aircraft production line undergoes a production break.

The System Dynamics model should also prove to be a very valuable tool for developing policies that will mitigate the costs of a production break. With the simulation, capability of the model a variety of different policies can be explored. The most promising of these policies can be implemented.

Future Research

The development of a System Dynamics production break model has lead to a variety of future research opportunities. The most important of these will be the study of the implementation of the model within the Air Force. This research should focus on how useful the model has been in developing policies to mitigate the costs of production breaks. Further refinement of the model is possible with further interviews with production break experts from other agencies and the business world. The model could also be tailored to specific program and check to see how the general results compare to the actual costs of the real program undergoing a production break. This model concentrated on the shutdown and restart of a production line. Differences may be incorporated into the model if the line is know it be completely shutdown and never restarted.

Another possible research area would be creating a System Dynamics model of other types of Air Force and DoD programs that experience production breaks. This could include missile, electronics, and space systems. In addition, System Dynamics models could be developed to explore the life cycle cost of a system, the causes of cost growth and any other acquisition cost problem faced by the Air Force and DoD.

Another possible research area is using System Dynamics Methodology with Monte Carlo simulation and the modeling Cost Estimation Relationships (CER). Monte

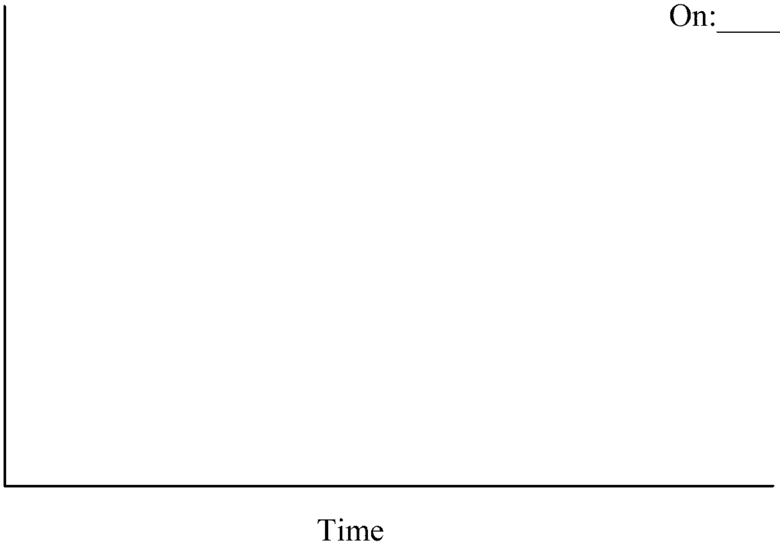
Carlo simulation depends on forming distributions of random variables for various model inputs and running the model several hundred times to get an overall distribution of the cost estimate. What if feedback loop and delays were incorporated in this process? CERs are commonly used in cost estimation. System Dynamics could be a useful way of exploring the methodologies and results of a CER. It is also probable that they could be used in a System Dynamics model.

One possible area of research out side the area of cost would be if there is a statistical difference in the maintenance or failure rate of the planes produced before a production break or the first ones produced after a break to the others produced on the same line. The model and interviews suggest that the work knowledge and reconditioning of parts is highest at these two points. How are these aircraft performing compared to other aircraft produced on the same production line?

Appendix A: Interview Worksheets

Reference Mode 1 Pre-break Variables Interview with:________________

On:________________



Major Variables Links

1.____________________________ ---------> ________________________

2.____________________________ ---------> ________________________

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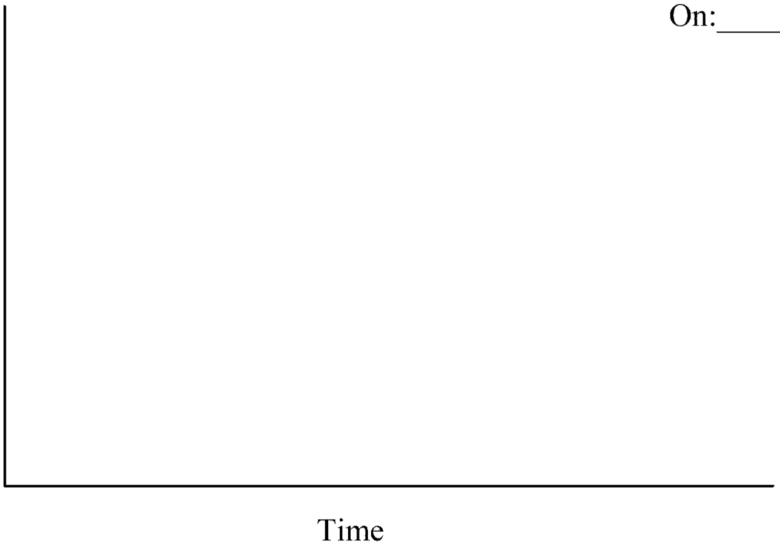
Causal diagrams

Reference Mode 2 Break Variables

Interview with:________________

On:________________



Major Variables Links

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Causal diagrams

Reference Mode 3 Post-break Variables Interview with:________________

On:________________

Major Variables Links

1.____________________ ---------> ________________

2.____________________ ---------> ________________

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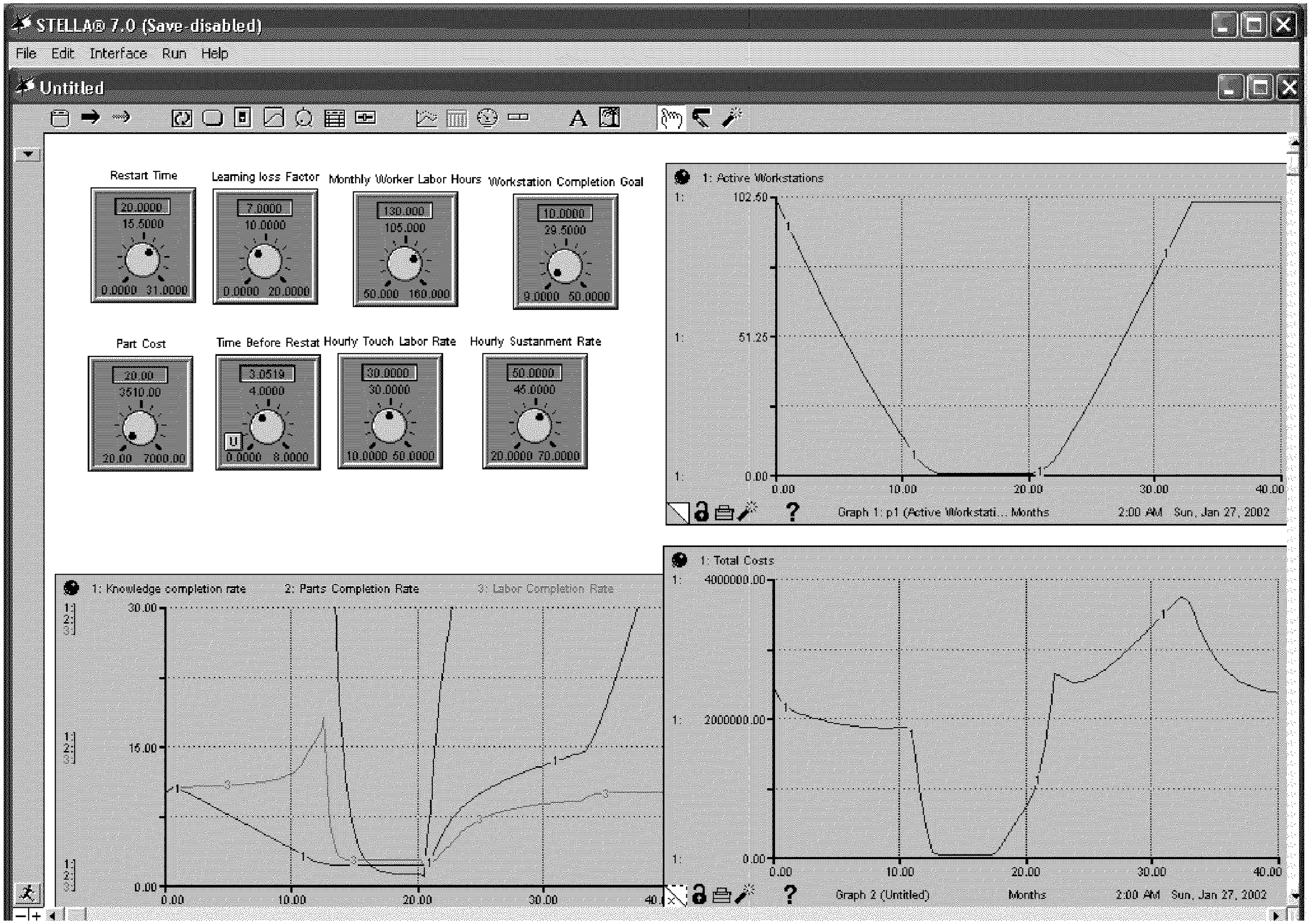
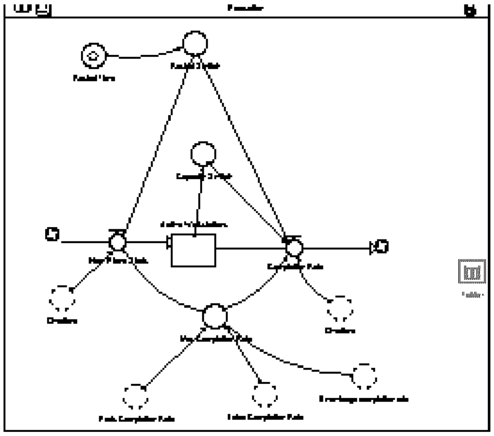
Causal diagrams

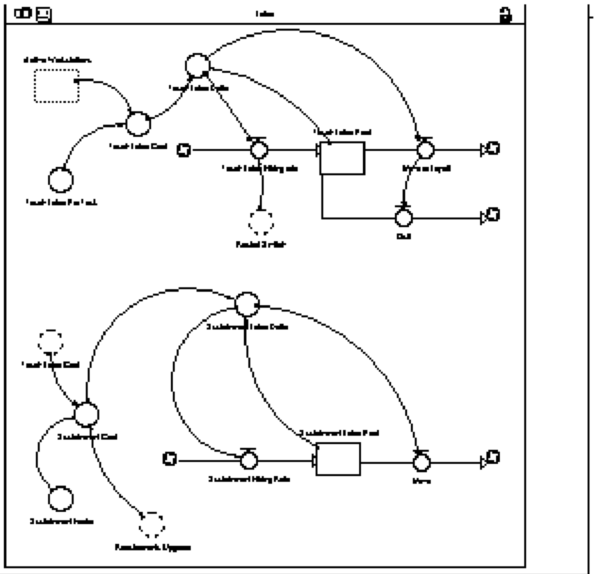
Appendix B: Production Break Model User Screen

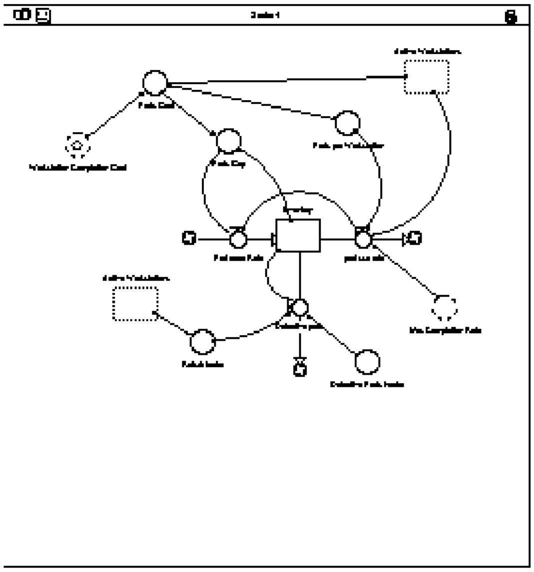


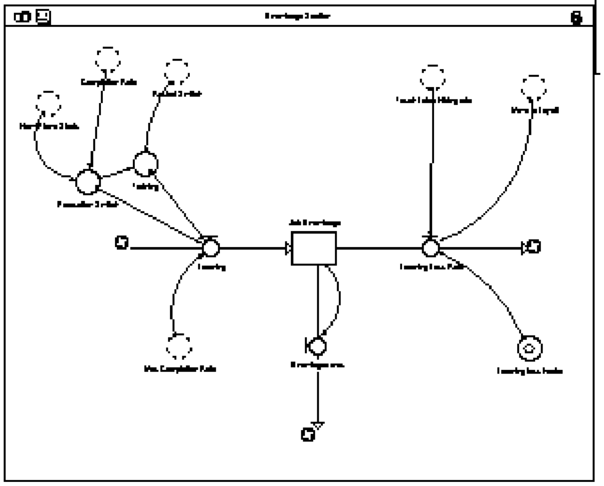
Restart Time: 20.0000 (15.5000; 0.0000 31.0000)
Learning loss Factor: 7.0000 (10.0000; 0.0000 20.0000)
Monthly Worker Labor Hours: 130.000 (105.000; 50.000 160.000)
Workstation Completion Goal: 10.0000 (29.5000; 9.0000 50.0000)
Part Cost: 20.00 (3510.00; 20.00 7000.00)
Time Before Restat: 3.0519 (4.0000; 0.0000 8.0000)
Hourly Touch Labor Rate: 30.0000 (30.0000; 10.0000 50.0000)
Hourly Sustanment Rate: 50.0000 (45.0000; 20.0000 70.0000)

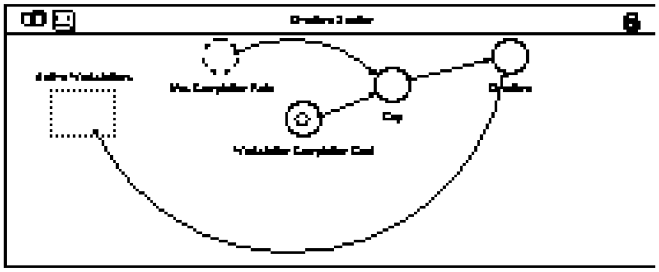
Appendix C: Production Break Model Flow Diagrams

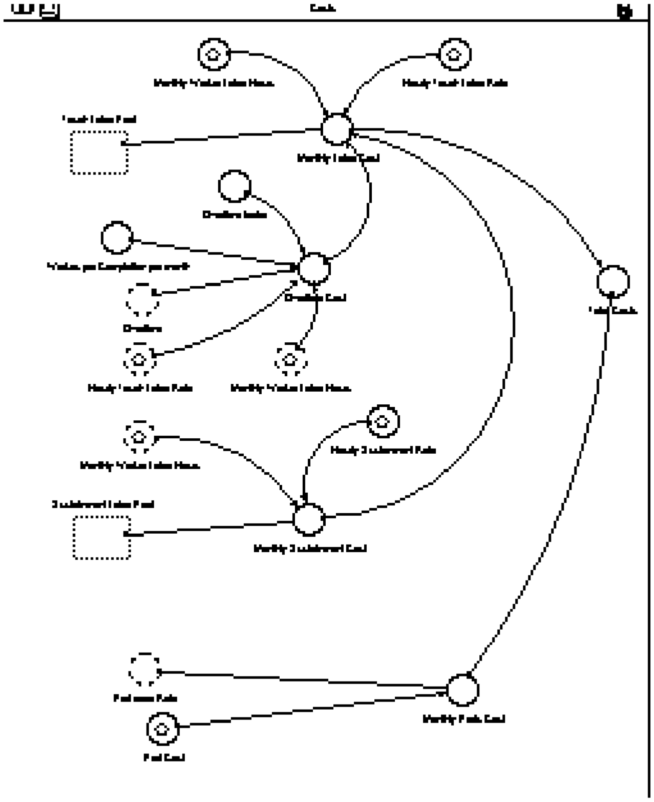


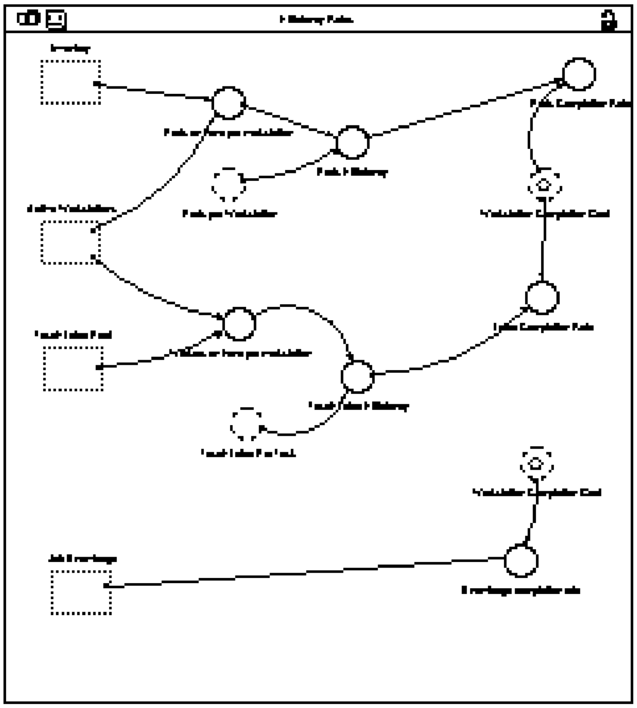


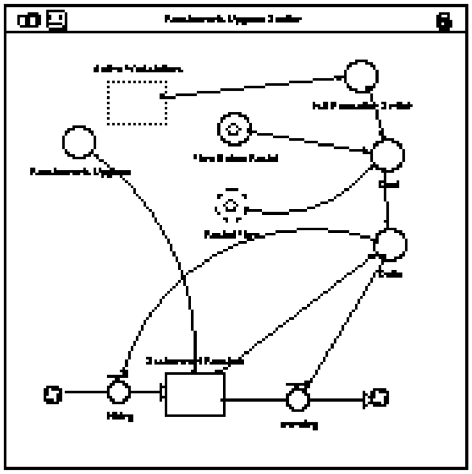




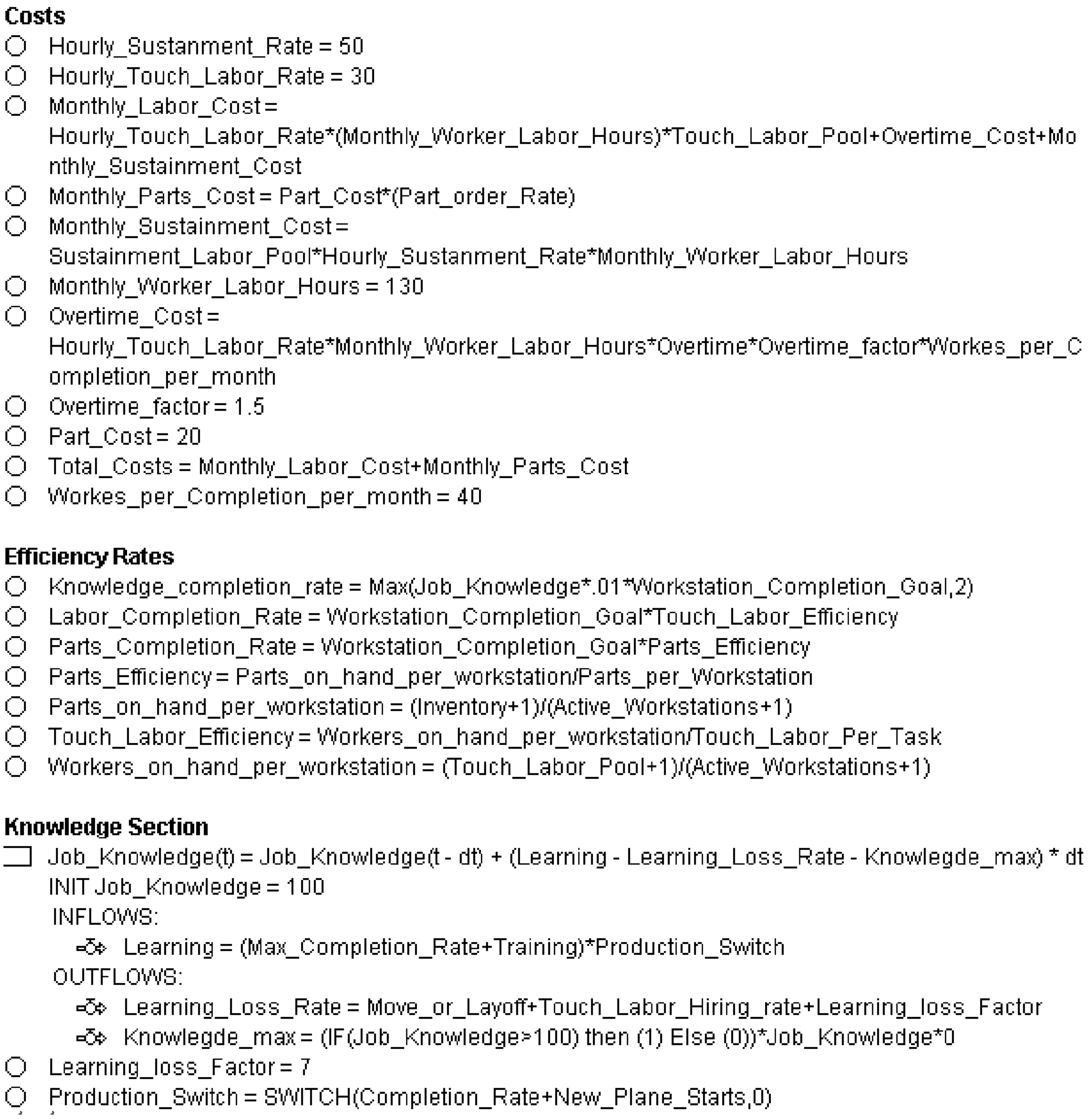








Appendix D: Production Break Model Equations



Costs

```
○ Hourly_Sustanment_Rate = 50
○ Hourly_Touch_Labor_Rate = 30
○ Monthly_Labor_Cost =
  Hourly_Touch_Labor_Rate*(Monthly_Worker_Labor_Hours)*Touch_Labor_Pool+Overtime_Cost+Mo
  nthly_Sustainment_Cost
○ Monthly_Parts_Cost = Part_Cost*(Part_order_Rate)
○ Monthly_Sustainment_Cost =
  Sustainment_Labor_Pool*Hourly_Sustanment_Rate*Monthly_Worker_Labor_Hours
○ Monthly_Worker_Labor_Hours = 130
○ Overtime_Cost =
  Hourly_Touch_Labor_Rate*Monthly_Worker_Labor_Hours*Overtime*Overtime_factor*Workes_per_C
  ompletion_per_month
○ Overtime_factor = 1.5
○ Part_Cost = 20
○ Total_Costs = Monthly_Labor_Cost+Monthly_Parts_Cost
○ Workes_per_Completion_per_month = 40
```

Efficiency Rates

```
○ Knowledge_completion_rate = Max(Job_Knowledge*.01*Workstation_Completion_Goal,2)
○ Labor_Completion_Rate = Workstation_Completion_Goal*Touch_Labor_Efficiency
○ Parts_Completion_Rate = Workstation_Completion_Goal*Parts_Efficiency
○ Parts_Efficiency = Parts_on_hand_per_workstation/Parts_per_Workstation
○ Parts_on_hand_per_workstation = (Inventory+1)/(Active_Workstations+1)
○ Touch_Labor_Efficiency = Workers_on_hand_per_workstation/Touch_Labor_Per_Task
○ Workers_on_hand_per_workstation = (Touch_Labor_Pool+1)/(Active_Workstations+1)
```

Knowledge Section

```
□ Job_Knowledge(t) = Job_Knowledge(t - dt) + (Learning - Learning_Loss_Rate - Knowlegde_max) * dt
  INIT Job_Knowledge = 100
  INFLOWS:
    ⇒ Learning = (Max_Completion_Rate+Training)*Production_Switch
  OUTFLOWS:
    ⇒ Learning_Loss_Rate = Move_or_Layoff+Touch_Labor_Hiring_rate+Learning_loss_Factor
    ⇒ Knowlegde_max = (IF(Job_Knowledge>100) then (1) Else (0))*Job_Knowledge*0
○ Learning_loss_Factor = 7
○ Production_Switch = SWITCH(Completion_Rate+New_Plane_Starts,0)
```

```
○ Learning_loss_Factor = 7
○ Production_Switch = SWITCH(Completion_Rate+New_Plane_Starts,0)
○ Training = 10*Production_Switch+30*Restart_Switch
```

Labor

```
☐ Sustainment_Labor_Pool(t) = Sustainment_Labor_Pool(t - dt) + (Sustainment_Hiring_Rate - Move) *
   dt
   INIT Sustainment_Labor_Pool = 80
   INFLOWS:
     ⇨ Sustainment_Hiring_Rate = Sustainment_Labor_Delta
   OUTFLOWS:
     ⇨ Move = -Sustainment_Labor_Delta
☐ Touch_Labor_Pool(t) = Touch_Labor_Pool(t - dt) + (Touch_Labor_Hiring_rate - Move_or_Layoff - Quit)
   * dt
   INIT Touch_Labor_Pool = 400
   INFLOWS:
     ⇨ Touch_Labor_Hiring_rate = Touch_Labor_Delta*Restart_Switch
   OUTFLOWS:
     ⇨ Move_or_Layoff = -Touch_Labor_Delta
     ⇨ Quit = Move_or_Layoff
○ Sustainment_Factor = .2
○ Sustainment_Goal = Touch_Labor_Goal*Sustainment_Factor+Requirements_Upgrade
○ Sustainment_Labor_Delta = Sustainment_Goal-Sustainment_Labor_Pool
○ Touch_Labor_Delta = Touch_Labor_Goal-Touch_Labor_Pool
○ Touch_Labor_Goal = Active_Workstations*Touch_Labor_Per_Task
○ Touch_Labor_Per_Task = 4
```

Overtime Section

```
○ Gap = MIN(Workstation_Completion_Goal-Max_Completion_Rate,Workstation_Completion_Goal*.7)
○ Overtime = MIN(Active_Workstations,Gap)
○ Workstation_Completion_Goal = 10
```

Production

```
☐ Active_Workstations(t) = Active_Workstations(t - dt) + (New_Plane_Starts - Completion_Rate) * dt
   INIT Active_Workstations = 100
   INFLOWS:
     ⇨ New_Plane_Starts = Restart_Switch*(Overtime*.5+Max_Completion_Rate)
   OUTFLOWS:
```

```
      ⇨ New_Plane_Starts = Restart_Switch*(Overtime*.5+Max_Completion_Rate)
   OUTFLOWS:
      ⇨ Completion_Rate =
         (Overtime*.5+Max_Completion_Rate)*(1-Restart_Switch+Capacity_Switch)
○  Capacity_Switch = SWITCH(Active_Workstations,100)
○  Max_Completion_Rate =
   MIN(Labor_Completion_Rate,Parts_Completion_Rate,Knowledge_completion_rate)
○  Restart_Switch = SWITCH(time,Restart_Time)
○  Restart_Time = 20
```

Requirements Upgrade Section

```
□  Sustamment_Required(t) = Sustamment_Required(t - dt) + (Hiring - moveing) * dt
   INIT Sustamment_Required = 0
   INFLOWS:
      ⇨ Hiring = Delta*.3
   OUTFLOWS:
      ⇨ moveing = -Delta*.5
○  Delta = Goal-Sustamment_Required
○  Full_Production_Switch = SWITCH(90,Active_Workstations)
○  Goal = (If (time>(Restart_Time-Time_Before_Restat) )then (Restart_Time*(15-Time_Before_Restat))
   else (0))*Full_Production_Switch
○  Requirements_Upgrade = Sustamment_Required
○  Time_Before_Restat = 4
```

Sector 4

```
□  Inventory(t) = Inventory(t - dt) + (Part_order_Rate - part_use_rate - Defective_parts) * dt
   INIT Inventory = 5000
   INFLOWS:
      ⇨ Part_order_Rate = Parts_Gap+part_use_rate
   OUTFLOWS:
      ⇨ part_use_rate = Active_Workstations*Max_Completion_Rate*Parts_per_Workstation
      ⇨ Defective_parts = Inventory*(Defective_Parts_Factor+Refurb_factor)
○  Defective_Parts_Factor = .05
○  Parts_Gap = Parts_Goal-Inventory
○  Parts_Goal = Active_Workstations*Parts_per_Workstation*Workstation_Completion_Goal
○  Parts_per_Workstation = 10
○  Refurb_factor = Max((100-Active_Workstations)*.01,0)
```

○ Defective_Parts_Factor = .05
○ Parts_Gap = Parts_Goal-Inventory
○ Parts_Goal = Active_Workstations*Parts_per_Workstation*Workstation_Completion_Goal
○ Parts_per_Workstation = 10
○ Refurb_factor = Max((100-Active_Workstations)*.01,0)

Not in a sector

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14. ABSTRACT

This research effort employs a System Dynamics methodology to model Air Force aircraft production break costs. The Air Force currently used the Anderlohr, Modified Anderlohr, and Retrograde methods for the estimation of aircraft production breaks. These methods offer little insight into the dynamic behavior of an aircraft production break. System Dynamics offers a unique way of capturing expert opinions in this area and dynamically presenting behaviors of an Air Force aircraft production line during a production break. Development of this model followed a four-step process of conceptualization, formulation, testing, and implementation. Five Air Force aircraft production break experts in were interviewed to formulate and validate the model. This research identified manpower turbulence and parts disruptions as the main cost drivers during the initial shutdown of an aircraft production line. During the break, there were minimal costs and no main costs drivers. During the restart of production, new requirements and the reconstitution of the workforce were found to be key cost drivers. Expert feedback indicates the System Dynamics model developed during this research will prove most valuable in policy formulation and in training of cost analysts.

15. SUBJECT TERMS

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