Lean Supply Chain Management Techniques for Complex Aerospace Systems: Using Discrete Event Simulation to Mitigate Programmatic Cost and Schedule Risk

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Abstract— **Historically, major US aerospace programs have suffered from cost increases and schedule delays. While inaccurate basis of estimates can lead to discrepancies between planned and actual program performance, a well-planned, lean supply chain can still experience cost and schedule pressures. It is clear that all design changes lead to schedule delays and associated cost increases, and it is also clear that complex system development programs in the aerospace industry inevitably experience design changes. In this research a discrete event simulator was created for modeling aircraft production supply chains where the major variables of interest were the depth of supply chain, the rate of design change impacting the supply chain, and the allocation of design authority to each level of the supply chain. The simulations identified that mitigating schedule delays can be achieved by allocating design authority in the supply chain to speed up change incorporation, and result in first unit lead time being reduced by up to 50%, while increasing overall production system productivity. Additionally, staffing design change boards for concurrent change incorporation can also lead to significant productivity improvements. The optimal solution points to a dynamic plan for the change traffic that achieves the most efficient production schedule amongst suppliers. Further, an acquisition program trap is also shown to exist in government acquisition programs that can be avoided by understanding the impacts of the design change traffic identified with this simulation.**

I. INTRODUCTION

The design and integration of major aircraft programs, both manned and unmanned, remain focused at the Prime Contractor level in the US Aerospace and Defense Industry, while sub-tier suppliers account for an increasingly larger percentage of the program production content [39]. Growth in program cost and schedule risks continues to be of concern to the government [14], [15],[16]. Efforts have been made through many initiatives to employ new acquisition strategies [17],[18],[19],[20],[21] including Lean Sigma principles and practices, to managing the design, production, and supply chain processes, but the fact remains they have been largely optimized and managed in silos rather than as an integrated development and production system, and thus have missed a potential cause of major program cost and schedule risk [32], [33], [46], [7], [6].

Any change to aerospace systems traditionally takes time, costs money, and is affected by where the change is designed/validated, and where it is inserted/produced in the supply chain [29]. From a lean perspective, the focus on just in time (JIT) processes that remove inventory between process steps results in an extended supply chain that is highly interdependent [flow],[41],[26],[10],[8], and thus adversely susceptible to variations. Significant commentaries have been written on the mass customization perspective of this kind of supply chain problem [37], [43],[13],[23], as well as decades of JIT system modeling for the development of production system optimization heuristics [40], [30], [31], [4],[2]. Most of these discussions have focused on the problem from the perspective of set production times for different products, whereas the current problem discussed herein appears as one of estimated production times with unknown time variations due to design changes.

The increasing depth of the Aerospace and Defense supply chain, coupled with the design ownership remaining at the Prime Contractor level results in increasing steps in the design change process as perturbations of information, requirements, manufacturing issues, approvals, and payments must flow up and down the supply chain iteratively until a change is fully incorporated into the final product. These perturbations will affect many enterprise functions including contracts, purchasing, engineering, tooling, production, and materiel management. Managing and incorporating the changes takes resources and time, sometimes resulting in production stoppages. Depending on the extent of the changes, the outcome can be significant programmatic delays and cost overruns.

In evolutionary acquisition (spiral development) the risk to cost and schedule due to design changes is heightened by the fact that new system capabilities are being deployed after small numbers of systems have been fielded [3],[9],[5], [trimble 2003],[35] [38] [34]. Major structural design changes arising from the introduction of new technology further affect the production system due to the inherent interdependence of the structure with the other elements of the aircraft system [36], [42]. Key variables attributing to the cost and schedule impact of design changes in this environment include the production rate, the design change rate, the depth of supply chain, and the allocation of design authority to suppliers. Understanding the systemic effects of these variables on product lead time and cost can contribute to managing programs more effectively, and potentially lead to better models for new technology insertion (i.e. planned changes) and overall cost-effective acquisition strategies that manage the risk of unplanned changes.

II. GLOBAL HAWK PROGRAM

The Global Hawk program has been in ACTD and low rate production for over a decade [11],[DSBS 2004] resulting in the RQ-4A and RQ-4B variants of the aircraft, the latter of which has been in low rate production since 2004. While the performance capabilities of these ircraft have been phenomenal, the Air Force has been pursuing cost reduction strategies on the program amidst mounting criticism from the GAO about program cost increase, schedule delays, and the goal of introducing new technology-based capabilities [12],[DID 2006],[DD 2004],[GAO 2004]. Furthermore, the program surpassed Nunn-McCurdy limits for program cost growth requiring the program to certify all of the program costs. [12]. While evolving the Global Hawk Unmanned Aircraft program, the USAF Program Office and the prime contractor (Northrop Grumman) and have been working efforts for greater efficiencies from the Global Hawk supplier base in view of mitigating cost and schedule risks. [27],[25].

The Global Hawk is a prime example of a system undergoing development and rapidly evolving capabilities while in low rate production. Criticized for cost growth and schedule delays by the GAO and other sources, questions about cost and schedule risk mitigation have been raised to all levels of the DOD. From the aerostructures development and manufacturing perspective of the program, design changes to the UAV have been identified as a risk by the GAO, citing over 2000 structural changes to a baseline of 1400 engineering drawings. While considered a risk, no quantification of "how much of a risk," was determined.

From a supply chain perspective, the prime contractor subcontracts approximately 50% of the aerostructures for the vehicle. Data from a second tier subcontractor on the Global Hawk program, delivering major aerostructure subassemblies was the starting point for this research, as the effects of design changes on its portion of the program seemed to be significant. Over a 3 year period, the Global Hawk Program Office at the second tier supplier tracked over 2500 programmatic changes (Figure 1), of which somewhere in between 10%-30% were design or specification changes resulting in work stoppages in production. The majority of these stoppages were short term, while some were longer term taking several weeks to resolve.

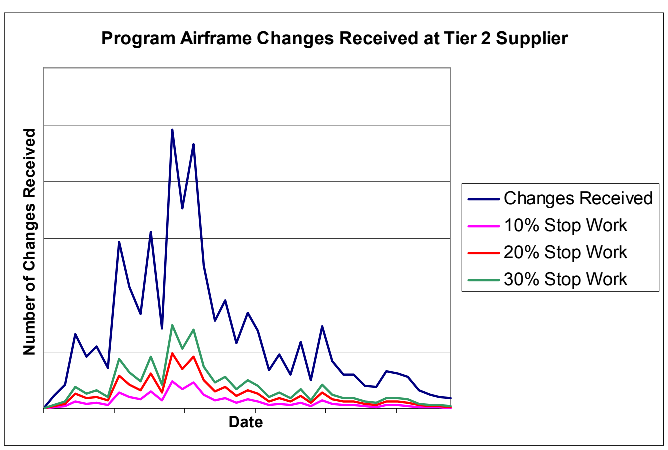

Figure 1 – Programmatic Change Rate at Second Tier Supplier

All changes were captured and recorded in a change management process at the second tier supplier. The types of Changes include Engineering Release Notice, Drawing Change Notice, Deviation, Engineering Order, Stop Work/ Lift Stop Work, Request for Change or Information, Direction, Manufacturing Plans, Planning, Specification. The mix of changes covered both prime contractor directed changes and supplier change requests/deviations necessary to make the product work (i.e. tolerances or specifications that were not achievable in standard production methods, relocation or resizing to make parts fit, etc.). Not all of the changes tracked were design changes and not all impacted production. Of all changes received, the program office estimated between 10% and 30% actually resulted in a measurable stop work in production. Figure 1 sows the estimated change profiles for the 10%, 20% and 30% distributions.

While the non-recurring engineering (NRE) activity for processing and incorporating the engineering changes were contracted into the first lots of RQ-4B production, the schedule delay and associated costs with the delays were not factored into the original contract, as it was handled as a traditional "build-to-print," outsourcing effort. Given this kind of program environment, it was apparent that cumulative delays throughout the supply chain might be a source of significant program cost and schedule risk. Understanding the magnitude of these risks and the potential mitigation strategies for acquisition programs became the focus of this research. Discrete event simulation was chosen to provide a means for modeling and animating the supply chain and testing variations in supply chain schemes. It was felt that the results of these experiments would provide insight into management strategies for optimization of the system by understanding the mechanisms of the schedule and cost creep, versus a traditional linear programming effort attempting to optimize a single problem.

III. SIMULATION

A. Generic Design

The generic production system input/output (I/O) block diagram fro the n^{th} tier of the supply chain is represented in Figure 2. At the core of every tier is a production block that is performing to the planned production time. The physical entities progressing through the simulation are Shipsets of parts. The informational entities progressing through the simulation are Changes. Shipsets progress from the $n^{th}+1$ tier, are transformed through the n^{th} tier production process, and then shipped to the n^{th}-1 tier. Without the addition of changes, the n+1 level production system operates at the standard production time (t_P), delivering product from tier to tier at the customer demand rate (i.e. takt time).

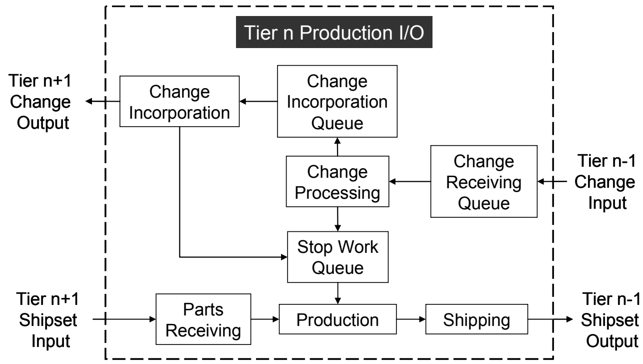

Figure 2 – Tier n Generic Production System I/O Block Diagram

As changes are input to tier n, they disrupt the standard production process and are modeled as a delay in production, where the effective production time (t_{Peff}) is now the standard production time (t_{Pn}) at tier n plus the delay time (t_{dn}) at tier n.

$$t_{Peff} = t_{Pn} + t_{dn} \quad (1)$$

The delay time can be modeled as a constant or as a distribution depending on the specific simulation data. The model is built to accept immediate stop works issued by the customer, as well as stop works resulting from the changes that are processed (i.e. specification change, design change, etc.). Changes requested by tier n are assumed to flow through the same process, triggering stop works for design problems that need to be rectified such as emergent problems of fit, function, or compliance to specification arising during the production process. As new layers of supply chain are added, a variable for the percent of changes that flow down to the next supplier is introduced (φ_n). The lowest level of the supply chain modeled has this variable set to zero.

With this generic model, the affect of altering the change rate and the production rate can be investigated. Additionally, two major systemic variables were addressed from the program management perspective, namely the capacity of processing changes (serial/concurrent) and the allocation of design authority in the production system (Boolean). The capacity for processing changes that stop work is modeled as either infinite capacity, which results in concurrent change implementation, or single capacity which results in serial implementation. While no company has infinite capacity for incorporating change, the best case scenario for this simulation is when all changes can be processed concurrently and thus no cumulative delays. The worst case is serial incorporation when all delays are cumulative. In actuality the tier n production capability for incorporating change lies somewhere in between these two extremes (serial vs. concurrent) based on a company's resources.

Finally, the allocation of design/contract authority to the suppliers is a Boolean variable in that they either do or do not have it. In the positive case of having authority, this represents a contracting mechanism in which the tier n supplier can proceed with incorporating changes without having to get the approval of the tier n-1 customer. This could represent something as simple as the right to disposition minor variations and repairs to get parts to meet specification, or more major changes to designs or specifications to ensure fit and functionality. It is understandable that there is a spectrum of types of changes and thus inherently a potential spectrum of contracting authority depending on the severity and impact of the change. What is important, however, is to understand the impact this variable has on the systemic performance for the program. Without the authority, every change must be reviewed for schedule and cost impact at tier n and approvals gained from the tier n-1 customer to proceed. With authority, the delays associated with gaining the tier n-1 approvals are eliminated, thus reducing the overall change incorporation time. From the perspective of the simulation, this variable is modeled as a short delay when there is authority, and a long delay when there is no authority. In the latter case, this accounts for the multiple levels of supply chain contracting having to review and disposition the contract implications of the change.

B. Global Hawk Simulation Configuration

Based on data from tier 2 suppliers, approximately 50% of the Global Hawk aerostructures are outsourced, with the tier 2 supplier studied in this research building approximately 40% of the outsourced parts (or 20% of the final airframe). This estimated percentage of outsourcing was derived from the overall aerostructures cost. The tier 2 supplier in turn outsourcers approximately 20% of its work to lower tier suppliers for material, parts, and services, again based on cost. For the purposes of simulation, it will be assumed that the same ratio applies to the Tier 3 suppliers and that the supply chain stops at Tier 4. Thus the tier 2 supplier provides 20% of the final aircraft aerostructures, and of this 20%, 4% is supplied by the Tier 3 suppliers and 0.8% by the Tier 4 suppliers. This outsourcing structure is then used as the basis for the change flow down variable (φ_n) as follows for a four tier simulation: φ_1 =40%; φ_2 =20%; φ_3 =20%; φ_4 =0%;

The simulations using the Aurora Global Hawk data are intended to provide insight into the effects design changes have on the production system with varying system parameters. The takt time for the program was 90 days, and is used as the baseline value for all tiers of the production system operating at consistent cycle time. Wait times for activities such as transportation between layers are kept to zero to investigate the primary variables, but can be modified later to tune the model further. The inventory is modeled as a JIT inventory with no excess stored between suppliers. The changes that stop work are modeled as a percentage of the total number of changes received, which is a time-dependent variable. Finally, the stop work time caused by a design change is modeled according to Table 1 below based on observations from the Tier 2 production program. The majority of changes that stopped work were on the order of half a day delay, with some causing significant delays of weeks. The average delay from this distribution is approximately 0.6 days of downtime per change.

TABLE 1 - PROBABILITY DISTRIBUTION OF STOP WORK TIME.

Stop Work Time	Probability
0.5 Day	99%
5 Days	0.5%
10 Days	0.25%
15 Days	0.25%

When modeling the design change rate (D_c) shown in Figure 1, a linear model is used for the portion of the program where changes are increasing with time (up to month 15), and an exponential decay is used for the portion when changes are decreasing with time (after month 15). As such, the profile of the function takes the form

$$D_c = m \cdot t \quad (2)$$

for $0 \le t \le 450$ days (15 months), and

$$D_c = \alpha \cdot e^{-\beta(t-450)} \text{ for } t > 450 \text{ days (15 months)} \quad (3)$$

for $t > 450$ days (15 months)

However, since the simulation program operates on the premise of days per change, or more precisely, mean time between design changes ($mtbD_c$), the above equations need to be inverted into days per change, and as such are modeled as follows in the simulation

$$mtbD_c = \frac{1}{D_c} = \frac{1}{m \cdot t} \quad (4)$$

for $0 \le t \le 450$ days (15 months), and

$$mtbD_c = \frac{1}{\alpha \cdot e^{-\beta(t-450)}} = \frac{e^{\beta(t-450)}}{\alpha} \quad (5)$$

for $t > 450$ days (15 months)

For each distribution of change arrivals (10%, 20%, and 30% of all changes causing stop work) values for m, α, and β are determined when fitting the model to the data. As this is a first order analysis, no probabilistic variation is added to the change profiles to model the higher and lower rates that occur on a smaller time scale and appear as variability from the smooth line of the model. For 20% of changes stopping production, the following math models represent the composite simulation model for changes

$$mtbD_c = \frac{1}{D_c} = \frac{1}{0.0030158 \cdot t} \quad (6)$$

for $0 \le t \le 450$ days (15 months), and

$$mtbD_c = \frac{1}{\alpha \cdot e^{-\beta(t-450)}} = \frac{e^{0.0035(t-450)}}{0.7333} \quad (7)$$

for $t > 450$ days (15 months)

Since this simulation uses a discrete event simulator, 10 runs of each model were used in each experiment in order to determine an average simulated lead time and cycle time for aircraft, along with their respective standard deviations.

IV. RESULTS

A. *First Unit Delivery*

The impact of the major variables on aircraft production can be seen in Figure 3, which represents a 4 tier Global Hawk supply chain where 20% of the incoming changes result in work stoppages. The data plotted shows the simulation runs associated with a four tier production system incorporating changes serially (solid line) versus concurrently (solid line). The simulations are also run to show the effect of being with design authority (WA) and without design authority (NA). The error bars provide the 3 sigma (95%) error bands on the average data plotted. The error is represented on the time of aircraft delivery.

In all cases, the move towards concurrent incorporation of design changes has a tremendous improvement in aircraft lead time. Furthermore, regardless of the incorporation method (serial or concurrent), the allocation of design authority can further improve the lead time on the aircraft. The worst case scenario for this model is that changes are incorporated in serial, with no design authority allocated, resulting in a lead time of approximately 1000 days from production program start. Incorporating changes concurrently, or providing design authority to the serial system have the same basic effect of reducing the first unit lead time to less than 600 days (40% reduction). The best case scenario employs both the concurrent implementation and the design authority, resulting in a first unit lead time of 300 days, a 70% reduction from the worst case baseline, and a tremendous improvement in program performance.

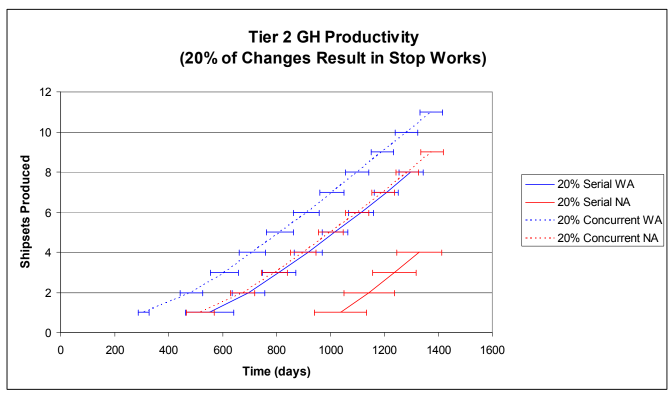

Figure 3 – Simulation Results for Global Hawk Supply Chain with 20% of Changes Stopping Work.

B. *Impact of Changes that Stop Work*

From the simulation it is apparent that first unit lead time is a major system outcome variable. Figure 4 shows the simulation results for a varying percentage of changes that stop work, and the impact this variable has on the first unit lead time, where a lower lead time is better. Data was plotted for concurrent (CO) and serial (SE) supply chains both with authority (WA) and without authority (WA). Based on data from ten simulation runs for each simulation set up, the error bars a plotted for the 3 sigma (95%) error band on first unit lead-time.

With no changes input to the system, all of the supply chains would perform equally. Thus as expected, each of the supply chain models performs relatively similarly at 10% or less of design changes that stop work. Above this value, the different models diverge in performance with the serial change incorporation model and no design authority going from a 350 day lead time at 10% to a 1000 day lead time at 20% (a 300% increase!), to being unable to deliver on this scale at 30%. The best case scenario, with concurrent change implementation and design authority allocation goes from 300 days at 10% to 350 days at 20% to 400 days at 30% (a 33% increase versus the 10% starting point). The main result to be seen is that the ability of the system to incorporate changes concurrently and with design authority lowers the slope of the lead time to change curve, which shows it is relatively inelastic to the changes. Conversely the serial incorporation with no authority is a fairly steep slope, and thus very elastic and adversely susceptible to incoming design changes.

In the event of no major difference in lead time, the cost of implementing concurrent design change incorporation and allocating design/contracting authority may exceed the savings from the minor improvement in productivity. However, as the change rate increases (and thus the number of changes that stop work), which is more representative of the Global Hawk program experience, the allocation of design authority and the staffing for managing concurrent change incorporation could see first unit lead times of less than half of what would occur without design authority and concurrent implementation. Even without concurrent implementation, and increasing change rates, the allocation of design authority has a major impact on accelerating first unit deliveries in half the time it would take without design authority allocation. Coupled with congressional budgetary oversight and first unit lead times as key measurable milestones, the results of Figure 4 have a profound affect on how program managers view their supply chains.

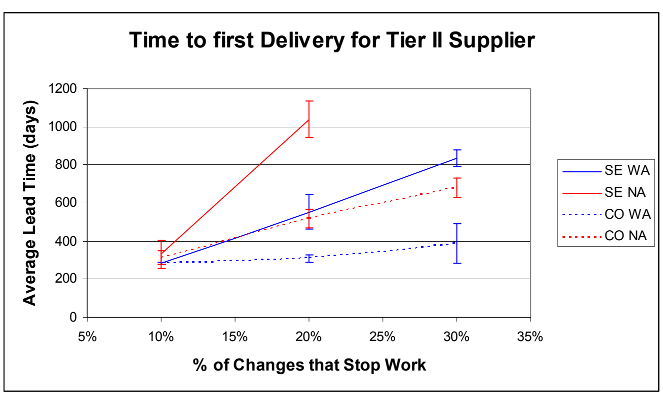

Figure 4 – Simulation Results for Global Hawk Supply Chain Lead Time with increasing Changes that Stop Work.

C. Risk Mitigation - Planed Lower Tier Cycle Time

The final simulation consists of a mitigation strategy for dealing with expected change traffic that stops production. In this analysis, the Planned Cycle Time (t_{cpn}) at each tier is investigated as a major variable that can affect delivery. In this series of simulations, the lower tier production time is set to a fraction of the Tier 1 Cycle Time (t_{cp1}). The scenario is intended to model a forward thinking program structure that anticipates design changes that stop production and thus accommodate a portion of them by planning to produce the shipsets in less time then they are needed by the customer at Tier 1, or more formally a strategy of

$$t_{cp1} > t_{cpn} \quad \text{where } n > 1 \qquad (8)$$

This means the upstream suppliers (Tiers 2, 3, & 4) create a production plan that is has a cycle time less than the customer takt time. The simulations were run with the lower tiers planned cycle times at 30%, 50%, 70%, 90%, and 100% of the t_{cp1} (90 days). Figure 5 shows the average results on aircraft first unit lead time based on a serial change incorporation supply chain with no design authority allocation. Ten (10) runs of each simulation set up were used to calculate the average values presented on this graph.

The curve in Figure 5 is S-shaped showing a region of steepest slope where the reduction in lower tier Cycle Time compared to the tier 1 Cycle time results in a significant decrease in first unit lead time. The simulation was not run a finer scale, say 1% decrements, and thus the inflection points are not precisely with this data set, but do appear somewhere in the 90% range and the 60% range. These values would change by program based on the distribution of the expected change rate, the percentage of changes that stop work, the average stop work time, and the other variables discussed previously in this paper.

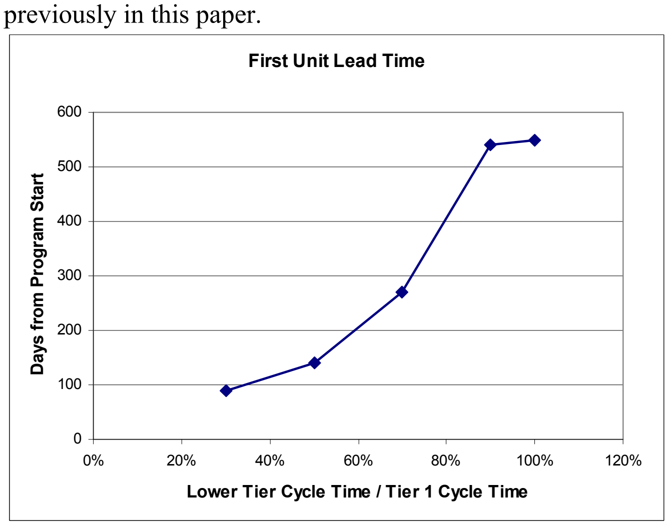

Figure 5 – Simulation Results with Varying planned Cycle Time by Supply Chain Level.

When looking at the first 8 aircraft in the program, which represented the first two lots of low rate initial production (LRIP), the data from the simulation indicates that planning for shorter cycle times at the lower tiers, in anticipation of changes that will impact production, can increase the overall program productivity. Figure 6 shows that planning for a 40% shorter cycle time at the lower tiers results in a 50% increase in productivity for aircraft deliveries in these two LRIP lots.

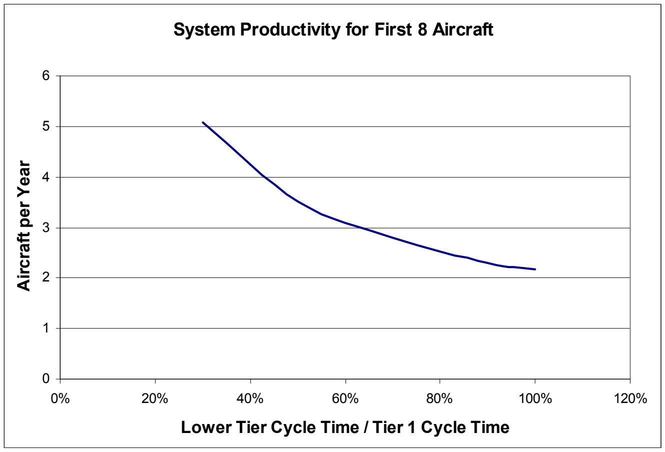

Figure 6 – Simulation Results with Varying planned Cycle Time by Supply Chain Level.

V. CONCLUSIONS

The discrete event production simulation model created in this research can be abstracted to n layers of supply chain. The simulation provides time series output of production, and thus the production time per unit (the inverse of productivity). From the simulation factor experiments it is evident that increasing design change rates have a substantial impact on the ability of a supply chain to produce aircraft. This is further compounded in a Lean Supply Chain where a just-in-time (JIT) strategy results in strong critical path dependence in the supply chain.

The amount of time the system stops work for design changes will also impact productivity. The allocation of design authority proves to be one mitigating factor in improving the supply chain productivity, and in fact has a much greater impact as the system becomes overwhelmed with design changes that stop work. The concurrent incorporation of changes can also mitigate delays compared to serial incorporation, but this has an affect on staffing sizes and may actually increase labor costs in the short term. The tradeoff between the carrying cost of delays and the cost of staffing for concurrent change implementation should be determined from a system level, as the total program cost is based on the sum of all the suppliers' costs, while a locally optimized cost analysis would ignore the impact of the cost delays at the other supply chain partners.

Finally, there appears to be an optimum supply chain strategy for increasing productivity and decreasing program schedule risk by planning for t_{cpn} based on the customer takt time and the expected value (EV) of the delay time (t_{dn})

$$t_{cpn} = \text{takt time} - EV(t_{dn}) \quad (9)$$

With a steady state distribution of $EV(t_{dn})$ derived from a constant change rate and constant delay time, this planning would be easy, as the results of the calculation would yield a single t_{cpn}. However, as shown from the Global Hawk case data, the distribution of the design changes in the program are time dependent and the resultant stop work time is also a distribution, rather than a constant. As such, the effective implementation of the optimum supply chain planning strategy is inherently dynamic. The staffing to incorporate changes must thus respond to the change rate in order to move towards concurrent implementation, and the t_{cpn} will change from shipset to shipset, thus affecting the allocation of resources to the program at each supplier. This type of dynamic pre-scheduling is not the norm in most of the aerospace industry and actually requires a forward looking estimate of the design change rate.

The forward looking design change rate can be composed of three types of changes, the known changes, the known unknowns, and the unknown unknowns. The known changes represent design elements that the program is aware must be changed, such as incomplete drawings, specifications, parts, etc., which can all be tracked and planned for as part of a successful change management process in the program. The known unknowns are design issues that the program knows will be encountered based on past experience, but does not have an explicit listing of the changes like the known changes (i.e problems with first build, fit, meeting specifications, finishes, etc.). These are best estimated by past experience on similar programs as a percentage of the overall changes. Finally, the unknown unknowns are problems no one has anticipated. They do arise, but there is no real prior knowledge. Again, these are best estimated based on historical program comparisons to create a forward looking distribution, or by including an additional estimating factor in the change rate distribution that may or may not have a time dependence (i.e. a random variable). Figure 7 shows a notional build up of these projections, which form the underlying basis for calculating the expected value of delays and thus dynamically managing and optimizing the supply chain performance.

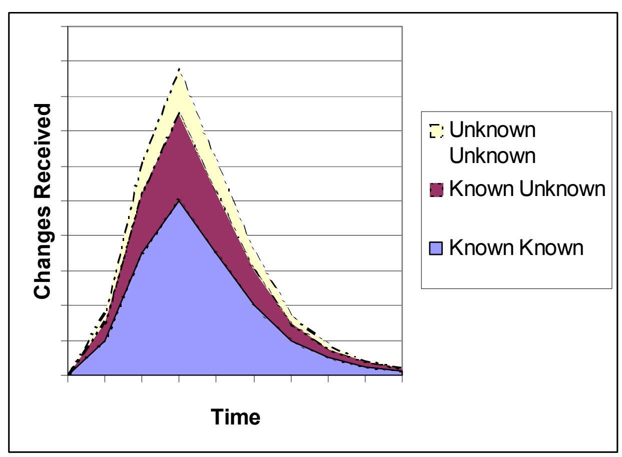

Figure 7 – Notional Distribution of Program Design Change Forecast.

In fact, the multitier supply chain dynamic planning model applies equally as well to block upgrades, which are essentially a planned set of changes to a program at some pre-determined point in time. The effects exhibited in this study would be the same in terms of schedule risk due to disruptions and having a forward looking estimate of all changes would help mitigate the program risk.

The case study of the Global Hawk program from the perspective of a Tier 2 Major Aerostructures supplier highlights the importance of understanding the supply chain structure and dynamics in a low production rate, high change rate environment. From the simulations and analyses it is evident that design change traffic is a major driver of cost and schedule. This conclusion should be self-evident in that all design changes from the norm have a schedule and thus cost impact on the program. It is also evident that this risk can be mitigated by the allocation of design authority to the lower tiers of the supply chain. Creating acquisition policy for supporting lower tier staffs to manage an incorporate these changes in a timely manner, and planning for shorter cycle times at the lower tiers, based on programmatic projections for change traffic, will also contribute to significant cost and schedule risk reductions. A simple simulation like the one contained herein could be used to produce probabilistic models of shipset arrival rates from multiple suppliers at Tier 1 as a means for structuring and managing cost and schedule risk on major defense programs.

VI. RECOMMENDATIONS

For an acquisition program like Global Hawk, where a large portion of the production is outsourced, and the supply chain is several layers deep, the analyses in this study have demonstrated the need for some clear policies aimed at reducing schedule delays and program costs as part of the program plan. Namely program offices should:

1. Plan for change up front: Develop a projected plan with time-based distributions for
   a. Known changes (planned)
   b. Known unknown changes (expected)
   c. Unknown unknown changes (unexpected)
2. Understand that the key program milestone of first shipset delivery is going to be more of a risk with increasing design change traffic, and the projected first unit delivery date needs to be analyzed based on the expected design change profiles developed in recommendation 1 and their resulting expected schedule impact.
3. Allocate design authority to the lower tiers of the supply chain to reduce the change incorporation process time for changes that stop work, as this will have an immediate improvement on productivity and lead time. The increasing levels of design authority allocation include
   a. Allocating manufacturing repair authority to bring out of specification parts within specification
   b. Allocating minor design modification authority for moving holes, trim lines, and internal features by limited amounts to accommodate form and fit of the subassemblies
   c. Allocating major design modification authority for modifying or altering flight critical component designs to meet manufacturability needs while still adhering to vehicle design specifications
   d. Outsource the subassembly design with the part, while managing interface control.
4. Support the lower tiers for staffing change incorporation in a manner that approaches concurrent implementation. These staffing levels will have to change over time, eventually diminishing as the program matures. This requires mapping the change process and establishing lower tier measures for the capacity for change incorporation.
5. Plan for cycle times that are shorter at the lower tiers in anticipation of the design changes that stop work, using measures of expected total change disruption from the distributions identified in recommendation 1. As the program matures, these cycle times can be extended to approach the Tier 1 customer cycle time, with some margin for change built in based on program expectations for long-term change rates. As the cycle times are extended, staffing will need to be reduced to maintain program costs since the work content per day will decrease.
6. For block upgrades, the design changes should be modeled for staffing, and for planning the production cycle time changes necessary to maintain DOD customer delivery schedules. Including a working supply chain simulation as part of the program office management plan will help establish a forward looking measure of potential cost and schedule risk impacts to the program and lead to more timely mitigation strategies.

VII. FURTHER RESEARCH

This research provides insight into the need to allocate design authority as programs outsource more and more of their aerostructures. This becomes critical as the rate of design change increases with respect to the production rate. From the perspective of the Tier 1 Prime Contractor and the DOD customer, the multiple suppliers will each have a probability distribution for shipset deliveries. Modeling this complete set of suppliers could be achieved by expanding the model used in this report to include parallel lower tier suppliers feeding the upper tier suppliers. Thus the aggregate probability distributions for Tier 1 Lead Times and productivity could be determined and investigated from the point of view of the end customer.

This effort is not greatly complex and would provide valuable insight to the Prime Contractor and the end customer on the potential effects of aerostructure design changes and new technology insertion *a priori* to making major changes. Mitigation strategies for these changes cold then be planned, and ultimately, the Prime Contractor and Customer would have a good understanding of the outcomes on the changes and be expecting the schedule and cost results, versus investigating them at a later date in hopes of determining the causes and assigning blame.

Another area of interest is the effect design-change related delays have on overall programmatic planning and forecasting using learning curves. Traditionally, learning curves represent gains in production efficiencies resulting from the learning effect associated with repeating production tasks. The learning curve is a model of the production hours per aircraft, where the percentage quoted represents the amount of labor hours are reduced every time the number of aircraft produced doubles. Thus, large gains in efficiency are seen through the first few shipsets of production and the subsequent gain reduces over time.

However, the addition of design changes causes two effects, especially in low rate production. First, the real learning curve will be flatter than on programs with no design changes, as each design change results in the local task being done for the first time each time a change is introduced, thus the learning on the specific task is delayed until later shipsets and not experienced as projected. Second, the overall tracking of labor hours on the program includes the delay hours, thus there are two combined curves representing total labor hours, a learning curve and a design-change delay curve. The problem arises that programs are aggressively bid based on learning curves without accounting for the effect of design change delays. Thus when the changes are incurred, the programs fail on cost and schedule against their baseline projections.

Finally, higher fidelity models could be created for programs by coupling detailed cost models to the simulation models, thus allowing for multivariate optimization of cost and schedule. This would permit trade offs between schedule and cost risk as a means to manage programs and meet funding agency and customer expectations.

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APPENDIX A- 4 TIER SUPPLY CHAIN SIMULATION MODEL STRUCTURE