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USE OF MONTE CARLO SIMULATION AT LOCKHEED MARTIN

Jorge Pica, Research Engineer, Lockheed Martin Dallas MFC
Jerry Hamilton, Lean Six Sigma Coordinator - Black Belt, Lockheed Martin Dallas MFC
Randy Burch, Manager Production Contracts PAC-3 Program, Lockheed Martin Dallas MFC
Sean Elliot, Graduate Student, Florida A&M University

ABSTRACT

This paper contains a high level overview of the Design for Six Sigma process at Lockheed Martin Missiles and Fire Control. Tolerance analysis is highlighted as an example of how Crystal Ball® software is utilized within Design for Six Sigma Process. This paper also contains a case study comparison between Monte Carlo and Discrete Event Simulation (DES) for Manufacturing Cell and Facility layout. Time and complexity metrics for the two simulation methods are also contained.

The case study reveals that Monte Carlo Simulation is a superior method for cell layout. The method is easily understood and involves little training for manufacturing engineering staff. For large facility layouts DES is determined to be the optimal solution. This is primarily due to the built in functions that are included within DES packages. Some of these built in functions include: automatic costing data collection, utilization percentage calculation, process time recording, etc. These functions would be custom creations if Monte Carlo simulation was utilized, normally created in visual basic macros. ProModel DES software was used in our study.

1 INTRODUCTION

Lockheed Martin MFC uses Crystal Ball for numerous applications, some of which are listed below:

- Tolerance Analysis
- Constrained Optimization
- Robust Design
- Frontier Analysis
- Low to Medium Complexity Manufacturing Cell Design
- Cost, Performance and Schedule Analysis
- Financial NPV and IRR calculations
- Sales Forecasting

By using Crystal Ball software, Lockheed Martin gains a better understanding of engineering system performance, financial models, sales projections and many other areas of the Defense business. Crystal Ball is a key tool in changing a culture that is accustomed to dealing with deterministic models and fixed point solutions. Lockheed Martin is beginning to better understand that variability exists in every task of a project. Understanding the probability of dangerous variation levels and its resultant impact to business outcomes creates a competitive advantage for Lockheed Martin in the aerospace and defense industries.

2 ROBUST DESIGN

Conventional experience and history demonstrate that it's much easier, cheaper and less risky to fix design problems early in the design cycle compared to when a product has entered into full scale volume production. Please see the chart below as a graphical illustration of the design cycle (Figure 1).

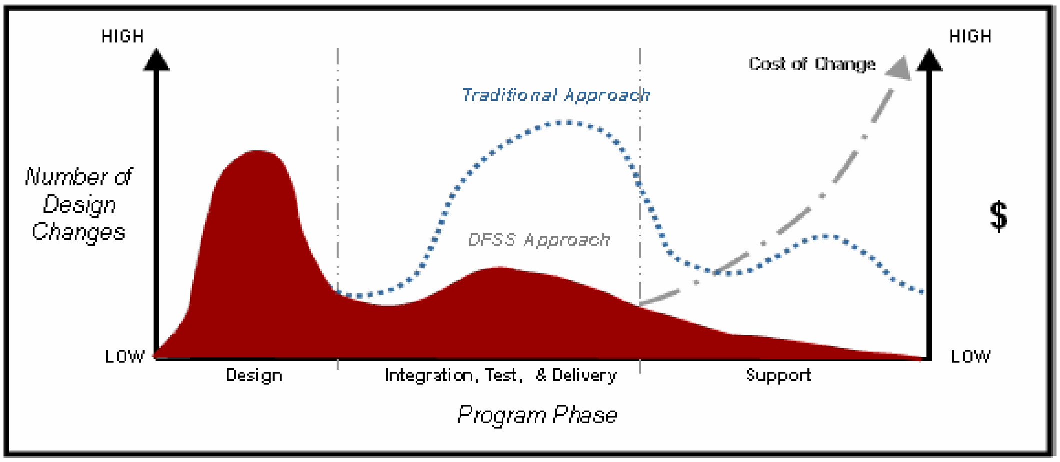

Figure 1: DFSS Impact

Traditionally within Aerospace and Defense industries, the many of design changes occur during the integration, test and delivery phases. Through the use of Crystal Ball in DFSS techniques, designs are finalized earlier in the design phase. The use of DFSS techniques also results in a decreased number of design changes during the integration, test, delivery and support phases of the product life cycle.

Robust design is deeply rooted in the DFSS (Design for Six Sigma) methodology. At Lockheed Martin MFC, a robust design is one which is insensitive to manufacturing variations, and operating conditions. From a manufacturing standpoint, our goal is to build a quality product, regardless of which operators are involved in assembling the product on the factory floor. Crystal Ball aids Lockheed Martin MFC in the identification of variation drivers in our key processes and helps LM MFC understand how manufacturing processes affect our designs. By understanding this variation, robust designs which are resistant to that variation can be developed. Figure 2 is a sample roadmap used for developing Robust Designs and the practice of DFSS techniques at Lockheed Martin Missiles & Fire Control (Lockheed Martin MFC):

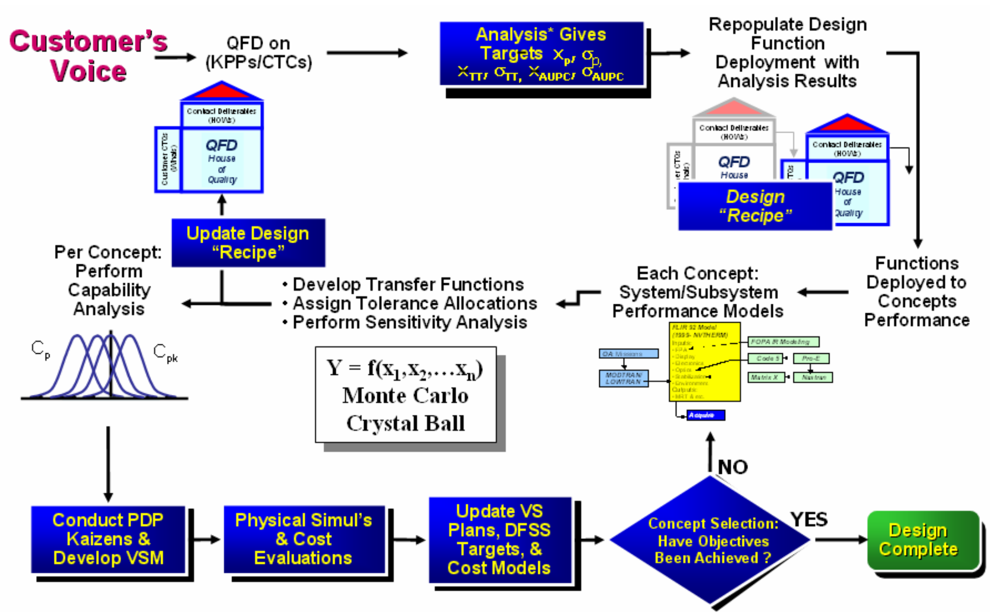

Figure 2: DFSS Roadmap

Our DFSS strategy all begins with the voice of the customer. Our key customer characteristics are then captured with a QFD (Quality Function Deployment) matrix. The QFD highlights the key drivers of customer satisfaction. Several iterations of a QFD may be conducted to ensure that the essence of the voice of the customer has been captured. At a later stage, Monte

Carlo analysis is used to understand tolerance allocations and sensitivity analysis better. In addition, process capability studies can be performed as well. Lean tools are used in conjunction with these approaches to refine and optimize targets while balancing for cost. Ultimately, the design will be reviewed to determine if it satisfies measures of robustness from an assembly and operational/functional standpoint. In addition, the design process will be reviewed against design for manufacturability/assembly (DFM/DFA) guidelines to ensure that the design was developed concurrently with manufacturing feedback early in the development cycle. Once these questions are answered favorably, a sample design is released.

3 DFSS EXAMPLE: TOLERANCE ANALYSIS

Tolerance analysis is used frequently at Lockheed Martin MFC in conjunction with Crystal Ball. A tolerance is basically a range of acceptable manufacturing variation that is permitted in a design. For instance, in mechanical systems, the tolerances of individual parts stack up and may ultimately lead to gap interference or movement in mechanical sub-assemblies. In general, the tighter the tolerance, the higher the part cost.

At Lockheed Martin MFC, several tolerance techniques are employed. They are Worst Case Analysis, Root Sum Square, Modified Root Sum Square, and Monte Carlo (Crystal Ball). Each technique has its advantages and disadvantages and application areas. Worst Case analysis, for example, is a very conservative approach to understanding assembly conditions. Some of the governing equations for worst case analysis are shown in Figure 3.

For the one dimensional case: $$T = \sum_{i=1}^{n} (X_i \pm T_i)$$

For the multi dimensional case: $$T = \sum_{i=1}^{n} \left(\frac{\partial X_i \pm T_i}{\partial X}\right)$$

Where T is the condition of interest.

X_i = the nominal dimensions

T_i = the tolerances for the nominal dimensions

Figure 3: Multi-Dimensional Tolerance Analysis

Worst Case analysis is an older technique that is very simple and is very conservative in nature. Its key benefit is that parts manufactured with the method employed almost always fit and yield is near 100%. The negative aspect of the method is that parts and subassemblies have extremely tight tolerances. This additional precision often requires specialized machines and inspection resources, resulting in higher cost. Essentially, the parts and subassemblies become unnecessarily expensive, as confirmed by understanding tolerance variation with Crystal Ball. Through the use of Crystal Ball, tolerances are identified that can be relaxed without negatively impacting the system quality or reliability. As a result, system complexity and defect rates are reduced, while the probability of on time delivery is increased. Validation steps must occur in order to certify the model accurately represents the current manufacturing capability. Some additional benefits of using Crystal Ball in tolerance analysis include the following:

- No need to assume that processes are in statistical control.
- No need to assume that processes are normally distributed.
- No need to assume linear or one-dimensional subassemblies.
- Skewed distributions can be accounted for in Crystal Ball.

An example of how Crystal Ball can be applied to tolerance analysis is illustrated below. Suppose that 5 panels are to be assembled adjacent to each other. They are to fit in a female receptacle represented by the rectangular box beneath it (depicted in the figure below):

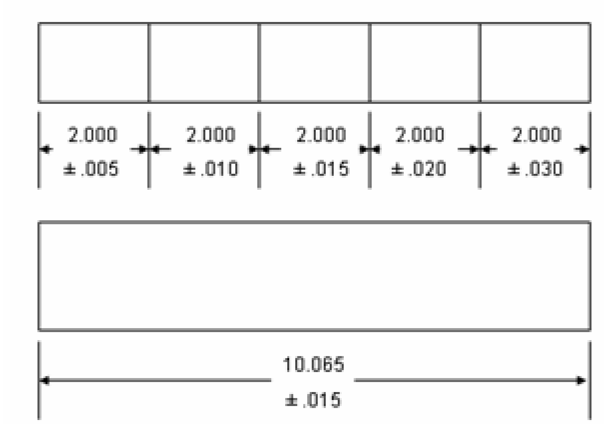

Figure 4: Solar Panel Exercise

Each panel and receptacle has its own characteristic tolerance. Crystal Ball can help identify where efforts should be focused to get the biggest tolerance impact by means of the sensitivity chart (Figure 5).

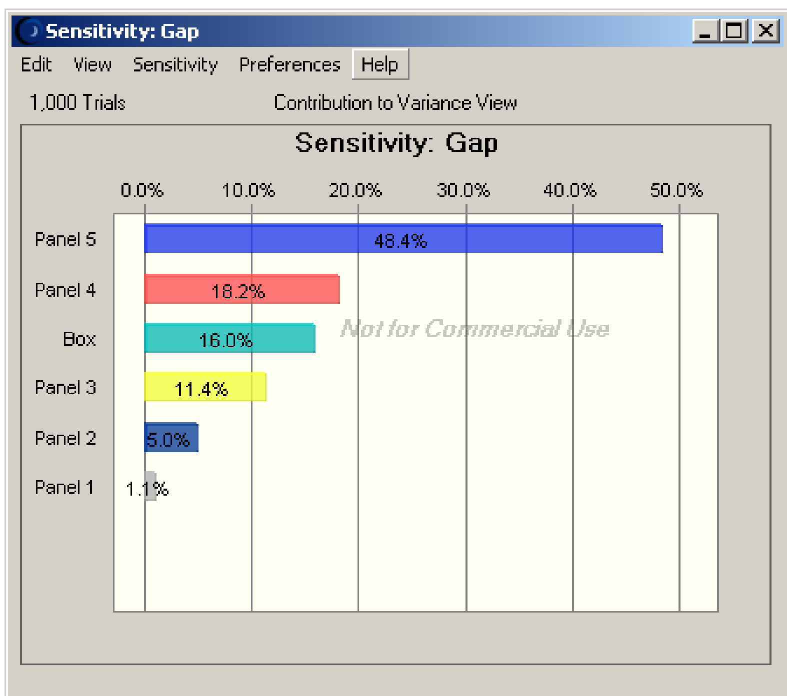

Figure 5: Sensitivity Analysis

Obviously, Panel 5 is driving the majority of the variation in the tolerance analysis. Therefore, efforts should be focused on Panel 5 to drive out variation in the tolerance gap.

4 MANUFACTURUING CASE STUDY

This case study involved the creation of four models: two for each manufacturing scenario (cell layout and manufacturing facility). Figure 6 and Figure 7 display process flow charts for each scenario.

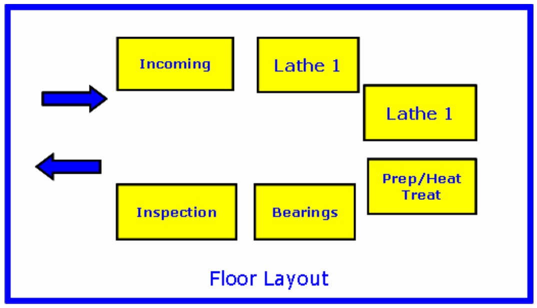

Figure 6: Cell Layout

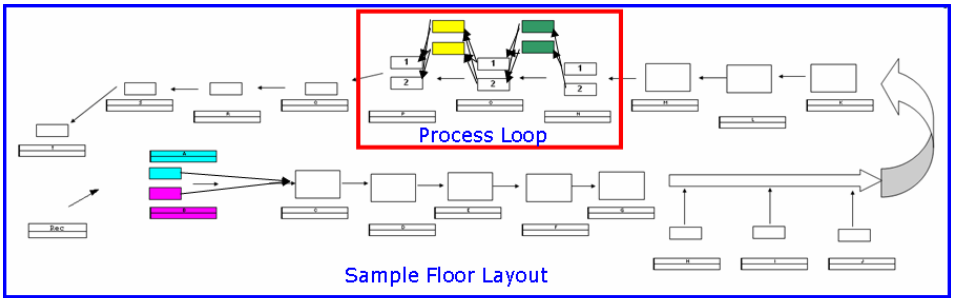

Figure 7: Facility Layout

The process flows for this case study have been drastically simplified in order to permit the presentation of this material. First, both DES and Monte Carlo simulations were created for the cell layout. Simulation output metrics were compared and creation time was measured. Figure 8 displays the difference in creation time in hours. Figure 9 has descriptive manufacturing statistics regarding the differing simulations.

The greatest difference in the manufacturing metrics was the cycle time. That was the only metric that was outside the 5% confidence interval for both the means. This was primarily due to the queuing effects inherent in a discreet event simulation model that can also be modeled easily within Crystal Ball. For this case study the Hidden Factory Model was used was used as the primary Monte Carlo. Figure 10 contains box plot comparison of the cycle time data in minutes.

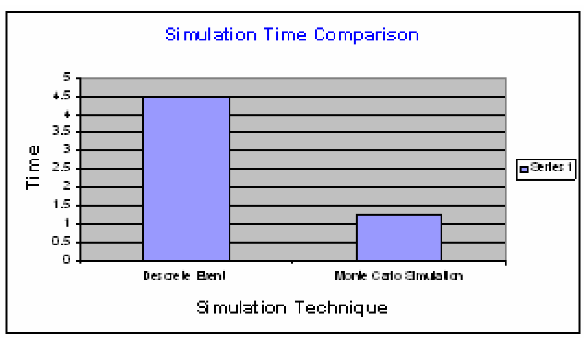

Figure 8: The difference in model creation time in hours

Metrics	Crystal Ball	ProModel	5% Confidence Interval
Total Cogs	109.9	107	5.35
Rejects	33.9	31	1.55
Cost Per Part	12.6	12.81	0.6405
Cycle Time	20.1	27.21	1.3605
WIP	Na	19	0.95
Total Process Cost	1555.061978	1577.213	78.86065

Figure 9: Descriptive manufacturing statistics regarding the differing simulations

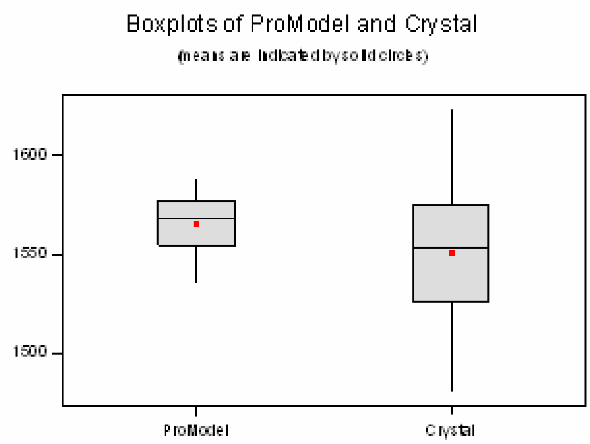

Figure 10: Box plot comparison of the cycle time data in minutes

The manufacturing facility models were then begun using the layout in Figure 7. Shortly after the Monte Carlo simulation construction began, certain difficulties were encountered that delayed model creation to extreme degrees. Complex manufacturing scenarios were very difficult to model and often custom visual basic code was needed in order to simulate the scenarios accurately. Examples of these scenarios are contained in Figure 11.

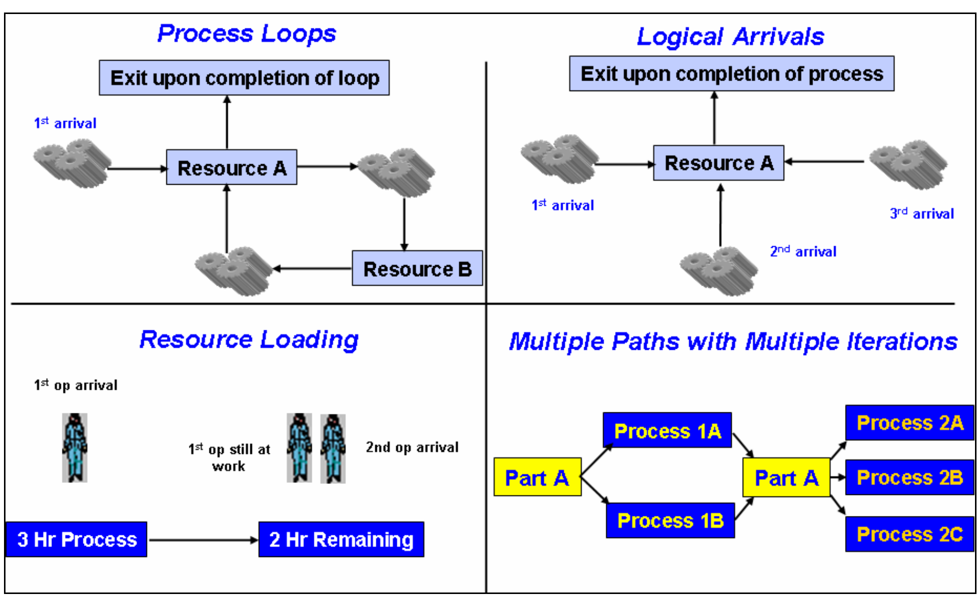

Figure 11: Examples of complex manufacturing scenarios

After the ProModel DES of the facility was completed the Crystal Ball simulation remained uncompleted for several days and after an additional week the effort was discontinued. The DES software selected contained templates that were ready to use that collected, displayed and analyzed relevant No metrics will be shared for the facility build due to the proprietary nature of the information.

5 CONCLUSION

Crystal Ball Monte Carlo simulation software has aided the change of culture within Lockheed Martin MFC. This change has focused more on DFSS techniques within the technical operations and simulation in production operations. Our case study proved that Monte Carlo simulation for cell layout was a low cost viable technique. Although means and standard deviations were statistically different, other queuing models were identified that would have eliminated the differences. Those models were equally easy to use when compared to the Hidden Factory Model (employed in this study). Crystal Ball was selected as a superior choice for cell layout based on ease of use, cost and build time required.

In the facility layout portion of the case study, the DES software utilized (ProModel) was chosen as the correct alternative. This was due to the build time associated between the two modeling methods and the amount of custom programming required to utilize the Monte Carlo software. Commercial DES software is ideally suited for large facility layouts and transactional processes across multiple organizations where many custom metrics need to be gathered. It is also best suited for large applications where resources are available for software purchase (average cost for DES software in 2005 9,800.00 dollars). This cost is restrictive for smaller projects where budgets are smaller.