Sequence Optimization

How Automating the Optimization of a Sequence of Processes Reduces Cost and Cycle Time

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Executive Summary

This paper describes a process and software tool (Sequence Optimizer) designed to reduce lead and launch time by eliminating or minimizing manual join and clamp sequence studies. Design gaps and part tolerances cause dimensional variation in assemblies using point-based attachment methods such as spot welding, riveting, or bolting. Sequence Optimizer finds the optimal join and clamp sequence from a candidate set resulting in manufactured assemblies as close to nominal as possible.

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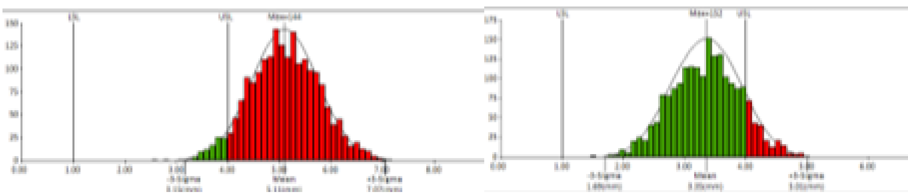
Problem Description

The sequence of joining parts using spot welding, riveting, or bolting can adversely affect the assembly's dimensional results. Additionally, design gaps and tolerances cause additional variation at the joining locations. Together, the joining operations cause internal stresses resulting in part and assembly deformation. Incorrect join and clamp sequences can cause large residual stresses and unwanted mean shifts in the assembly along with increased variation in the assembly dimensions. Both mean shifts and variation together can cause a significant increase in the percent of builds out-of-specification while adversely impacting process capability indices like Cp and Cpk.

As shown in Figure 1, the initial joining order produces a large mean shift and a negative Ppk. Reordering the joins will reduce the Mean, improve the Ppk, and reduce the variation.

Figure 1: Reordering the joining sequence can reduce variation and shift the mean



Current Solution Methodology

Join sequencing may be established as part of process planning. Otherwise, it is left up to the operator. The sequence can be set to minimize process time by minimizing tool travel path. In some cases, geometry set welds are done first to lock the part geometry. Usually, roughly equally spaced welds are distributed around the assembly, and in many cases, the resulting assembly meets the process capability requirements.

Unfortunately, the initial joining sequence results in mean shifts and excess variation. This condition is usually discovered at the start of normal production. Operators are then tasked in using their best judgment to modify the sequence to counteract the negative results and improve the process. If they are lucky, they can improve the out-of-specification condition. In many cases they cannot. If the problem cannot be solved quickly on the plant floor, process control experts need to be brought in that cause delays in reaching full capacity.

Because there were no software solutions previously for this problem, physical experimentation has traditionally been used to solve any problems. The Design of Experiments (DOE) methodology is the most commonly used and has been successfully applied to find better solutions. The DOE method calls for join sequences to be changed systematically, after which parts are produced, measured, and the measurement data analyzed. With each DOE and part run, incremental gains are realized.

Due to the time and cost of a physical DOE, only a fraction of the total solution space can be explored. Improvements can be found, but it is unlikely to find the global optimum sequence. In other words, a good enough answer can be found, but a great answer may prove to be elusive.

3DCS Sequence Optimization Methodology

The 3DCS Sequence Optimizer (SO) enables users to find the optimum joining and clamping sequence before start of production, ensuring smoother and faster startups. The following sections describe the software solution.

SO is part of the 3DCS Advanced Analyzer and Optimizer (AAO) add-on module for 3DCS Variation Analyst (Any CAD system), and uses compliant modeler FEA functionalities from the 3DCS FEA Compliant Modeler Add-on module. 3DCS Compliant Modeler combines traditional tolerance analysis with finite element analysis (FEA) to determine the impact of joining and clamping forces, gravity, and material stiffness on your parts' dimensional quality. SO joins and clamps compliant parts together, then measures the resulting assembly's dimensions given part stiffness and variation.

Assemblies may have many measures, and so Sequence Optimizer combines those measures to create an objective function for optimization.

Measures of Merit

3DCS Sequence Optimizer also allows you to choose your optimization criteria to maximize quality. All measures have been formulated so that smaller is better.

- Minimization from Average
- Minimization from Nominal
- Minimization of Force

Minimization from Average - the goal is to reduce total variation. As traditionally measured, variation is the second moment about the mean. There is no penalty for the mean being off target from the average...

$$\min\left\{\sqrt{\frac{\sum_i^M \sum_j^N \left(y_i^j - y_{Ave}\right)^2}{N}}\right\}$$

Minimization from Nominal - the goal is to reduce variation from nominal.

$$\min\left\{\sqrt{\frac{\sum_i^M \sum_j^N \left(y_i^j - y_{Nom}\right)^2}{N}}\right\}$$

Note, as the average drifts off target from nominal, the sequence will be penalized. The goal is to find the sequence that builds consistently close to the nominal design of the part.

Minimization of Force - the goal is to minimize the forces needed to join/clamp the parts.

$$\min\left\{\frac{\sum_i^M \sum_j^N \left|F_i^j\right|}{N}\right\}$$

where M is the number of total measurements, N is the number of simulations per trial, i is the i^{th} measurement, j is the j^{th} simulation, y_i^j is the i^{th} measurement value at j^{th} simulation. y_{Nom} is the design nominal value. y_{Ave} is the average value of N simulation at each trial. F_i^j is the i^{th} force measurement value at j^{th} simulation.

Given assembly deformation is proportional to and caused by strain energy due to joining, if we minimize the forces to join we equivalently minimize the strain energy. The force measure metric is a surrogate for total strain energy

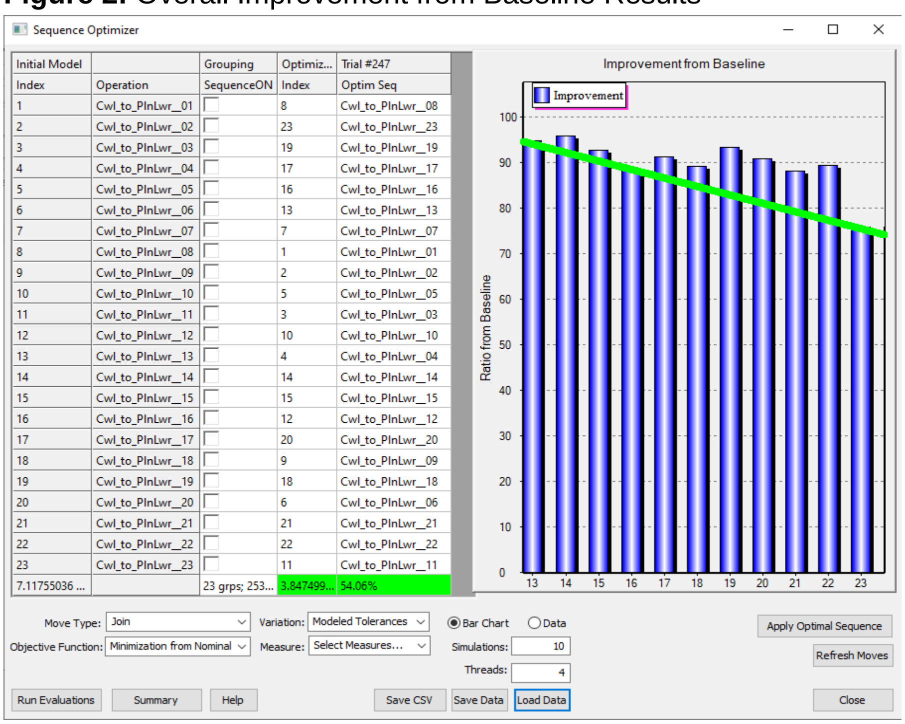
Search Methodology

The only method guaranteed to find the global optimal is to search all combinations of the join sequence. For any given sequence, there are n! number of sequence combinations. For 4 joining operations there are 4*3*2*1 = 24 combinations. For 5 there are 120 combinations, while 6 rises to 720 combinations. When the number of joining operations is large, the number of combinations explodes. There are over 3.6 million combinations at ten joints. For a small number of joining operations, full factorial is recommended. However as the number of joining operations grows, the number of combinations grows dramatically and becomes an infeasible feat in regard to computation time.

As mentioned by Tobar[1], the first joints have the largest effect on the final geometry. Therefore, the 3DCS Sequence Optimizer utilizes a greedy algorithm to find the optimal solution. SO searches the n possible operations for the best operation to perform first. The best is defined as the join operation that minimizes the Measure of Merit (discussed above). Given the first operation, the algorithm searches the remaining n-1 operations for the best second joining operation; then, given the best operations 1 and 2, SO searches the remaining n-2 operations to find the third. This continues until all operations have been resequenced.

Results for each trial are displayed numerically and graphically as shown below in Figure 2. The size of each bar represents the ratio of the calculated objective value for each trial compared to the initial objective value. As Sequence Optimizer searches, it incrementally improves as each operation is selected, driving the measures lower and lower as shown by the green line.

Figure 2: Overall Improvement from Baseline Results



The SO finds its best solution in only n*(n-1)/2 +1 steps. As shown in the table below, this results in significant gains in computational and thus decision making time.

Number of Joints	Number of Combinations	Number of Combinations Using 3DCS Sequence Optimizer
5	120	11
10	3,628,800	46
15	1.3 x10E12	106
20	2.4x10E18	191

Note: Because it is a greedy algorithm, it is not guaranteed to find the global optimum every time it searches. It is only guaranteed to find a better answer after each trial. Internal tests at DCS show it more often than not finds the global optimal in the first optimization. Additionally, the results of one optimization analysis can be the start of the next search.

Business Problem of Throughput and Cycle Time

There are two key elements to successful manufacturing: quality and throughput. We have shown dimensional quality can be improved by resequencing joining and clamping operations, but we also want to ensure throughput is high to maximize profits. It is possible that the optimal sequence results in the operator having to move from one end of the workpiece to the other and back, greatly increasing travel distance. Increasing operator travel distance increases process time, decreasing throughput and therefore profits.

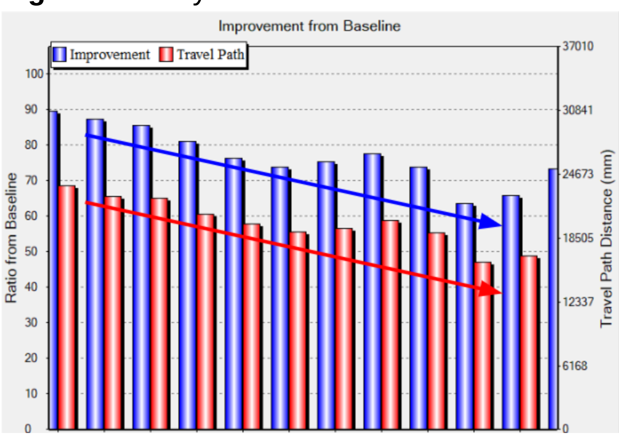
Fortunately, Sequence Optimizer is not restricted to a binary solution set of either maximizing quality while minimizing throughput or, alternately, maximizing throughput while minimizing dimensional quality.

The best solution is a combination of these two factors, providing an optimal travel path that creates the lowest amount of variation. 3DCS Sequence Optimizer provides analysis of both travel path and quality simultaneously. As shown in Figure 3 below, SO calculates the point-to-point travel distance for each sequence studied as well as the total joint-to-joint distance. In the graph, the blue bar represents the measure of dimensional quality as discussed above, while the red bar represents the travel path for that sequence of joints.

The user can now search for solutions that have both good dimensional quality and high throughput. In the analysis, dimensional quality measurements have been formulated to read smaller is better. Throughput has been measured based on the travel path times that also read smaller as better. As shown in Figure 3, solutions with small bars give you optimal scenarios for both factors.

Note, by calculating the point-to-point travel path, 3DCS is calculating a surrogate for travel time and throughput. The operator may have additional motion traversing normal to part or around part geometry. However, that motion will be relatively constant from sequence to sequence. The point-to-point travel distance is what will change from sequence to sequence. Therefore, it is sufficient to represent production throughput without including these additional inputs.\

Figure 3: Analysis of Travel Path and Variation



Multidisciplinary Optimization

3DCS Sequence Optimizer allows you to simultaneously optimize quality and throughput using the MultiDisciplinary Optimization (MDO) operator. The user can weight quality and throughput. 3DCS will solve for the best business solution across both metrics simultaneously.

To use MDO, the user must select one of the dimensional metrics discussed above:

- Minimization from Nominal
- Minimization from Average

- Minimization of Force

Then, the user must weigh the travel path 0<weight<1.

The system will create a combined MDO objective function: minimize f = weight*travel path +(1-weight)*dimensional metric.

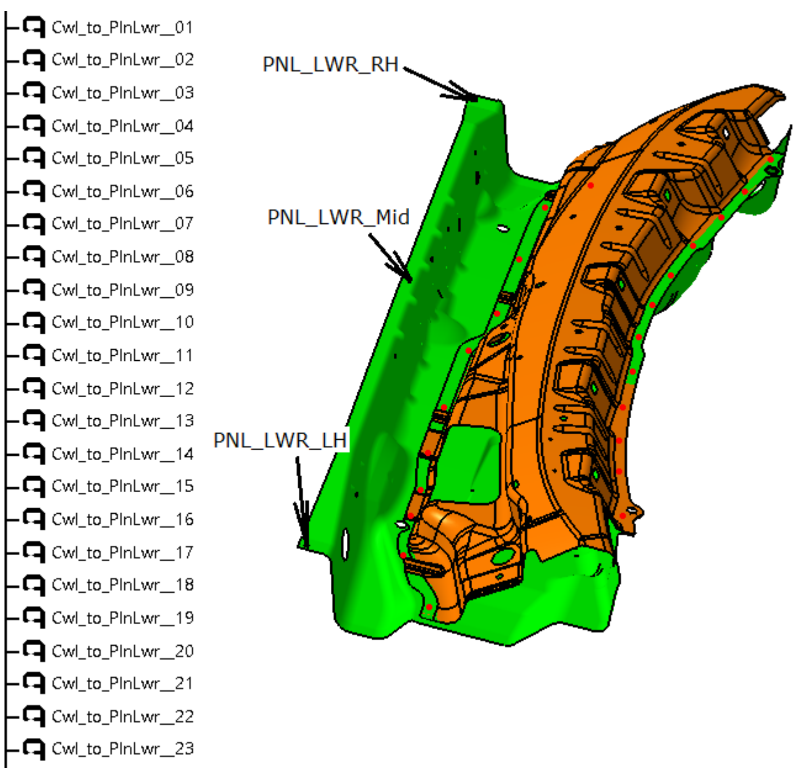
For example, if the user selects minimum Force and MDO with a weight of 0.4 then the objective function would be:

Minimize f = 0.4*(travel path/ original travel path) + 0.6*(sum of force / original sum)

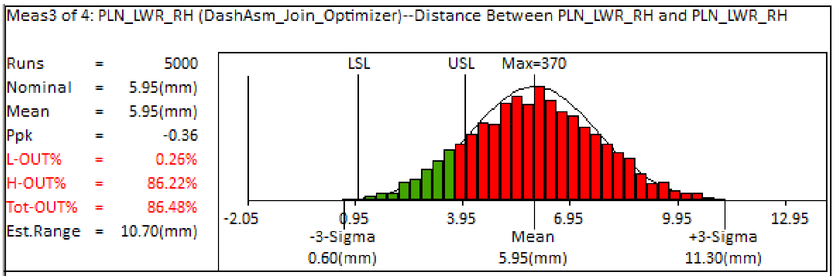
It is worth noting that 3DCS Sequence Optimizer uses the normalized values, instead of absolute values, to keep the objective function from being dominated by either aspect. It is important to note that the initial value for MDO objective function is always one.

Example Case

A Plenum cowl assembly, the structure that locates the lower windshield and rear of the hood in automotive vehicles, was analyzed using 3DCS Sequence Optimizer. It consisted of two parts with 23 joins and 3 output measurements. Minimization from Nominal was used as the Measure of Merit.



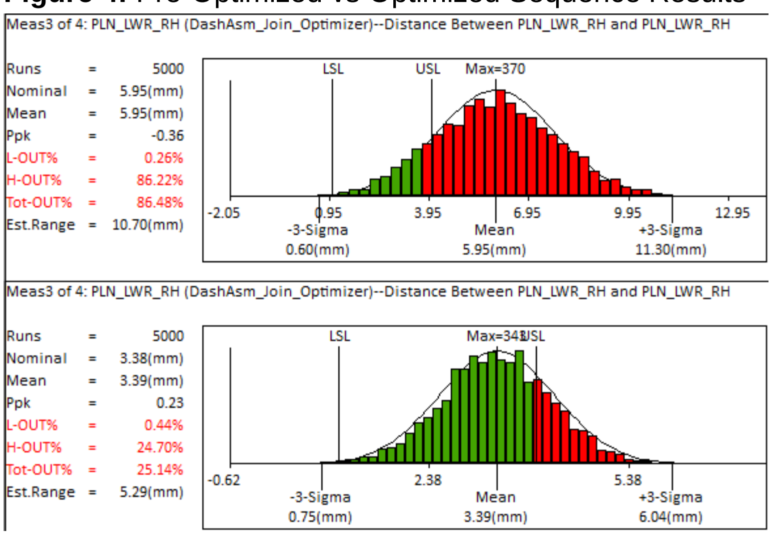
The initial sequence chosen using best practices resulted in significant dimensional problems. As shown below, the outboard right hand measurement point had a large mean shift and large variation.



3DCS Sequence Optimizer was run on the assembly. It took approximately 10 minutes to run the 253 trials necessary to find the optimal sequence.

Then, the sequence was reordered and 5000 Monte Carlo simulations were run (2 minute run time). As shown below, the optimal sequence significantly reduced the mean shift and reduced variation.

Figure 4: Pre-Optimized vs Optimized Sequence Results



As this solution is the global optimal for this problem, further improvements cannot be made by resequencing. The team would need to change other design parameters (design gaps, tolerances, stiffness) to improve the process any farther.

Conclusion

3DCS Sequence Optimizer is a large step forward in integrating engineering and manufacturing to produce dimensionally correct products. It uses a greedy algorithm to optimize for both travel distance and variation using a far lower number of runs than a full factorial analysis. This provides the most efficient pathing for the process. If used early in the product development cycle, faster and better product launches can be realized by releasing a robust join sequence before physical parts are made.

References

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[2] Bean JC. Genetic Algorithms and Random Keys for Sequencing and Optimization. ORSA Journal on Computing. 1994;6.p. 154-60.

[3] Carlson JS, Spensieri D, Wärmefjord K, Segeborn J, Söderberg R. Minimizing Dimensional Variation and Robot Traveling Time in Welding Stations. Procedia CIRP; 2014/01/01/. 2014. p. 77-82.

[4] Held, M., and Karp, R.M. A dynamic programming approach to sequencing problems, in Proceedings of the 1961 16th ACM National Meeting, p. 71.201-71.204, New York, NY, USA.

About DCS

DCS is a software developer providing tolerance analysis and quality SPC solutions to the automotive, aerospace, medical device, electronics, and energy industries. With more than 20 years' experience, DCS has grown to include clients from every region of the globe including companies like Airbus, BMW, GM, LG, Jaguar Land Rover, Phillips, Sony, Textron Aviation, and Volkswagen. As a quality solution provider, DCS prides itself on providing clients with not just software, but services, staffing, and dedicated support to guarantee the success of their quality initiatives.

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