Origami with Abaqus

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Tetra Pak Packaging Solutions

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Exemplar

Abstract: Origami is the art of paper folding. Our entire range of packages is formed from a flat web of packaging material using the origami technique. Virtual and reverse engineering are fundamental for the development of our technology. Complex simulations like extremely nonlinear dynamic events as well as design optimization are part of our daily activity. This paper describes how Simulia's software with the help of automated tools has been successfully used to simulate the fundamental phases of our forming process driving in some cases its design.

Keywords: Packages, Forming, Optimization, Customization

1. Introduction

Tetra Pak packages are formed inside our filling machines starting from a flat web of packaging material. The packaging material is a multilayered composite material that already contains the crease lines which can be considered the folding instructions of our packages. The crease lines are introduced by pushing a male die into a female channel as shown on Figure 1; this creates a delamination inside the board layer fibers.

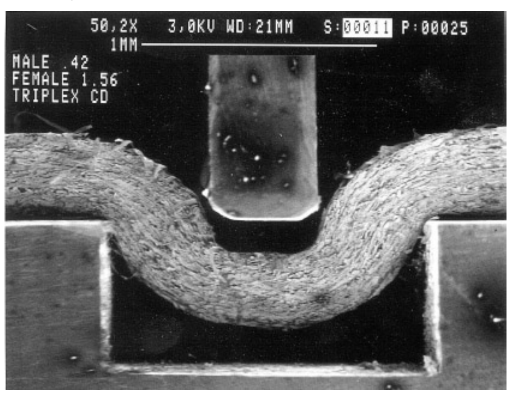

Figure 1. SEM image of the creasing procedure (Dunn, 2000).

If aseptic packages are to be formed, the web is sterilized inside the machine when it is still flat. The first stage of our forming process is to shape the web in the form of a tube that is then longitudinally sealed. A filling pipe fills the formed tube with the desired fluid. A section of the machine then forms the packages by folding the tube around the crease lines, sealing and cutting transversally. Figure 2 shows how the web is transformed into packages inside the filling machine.

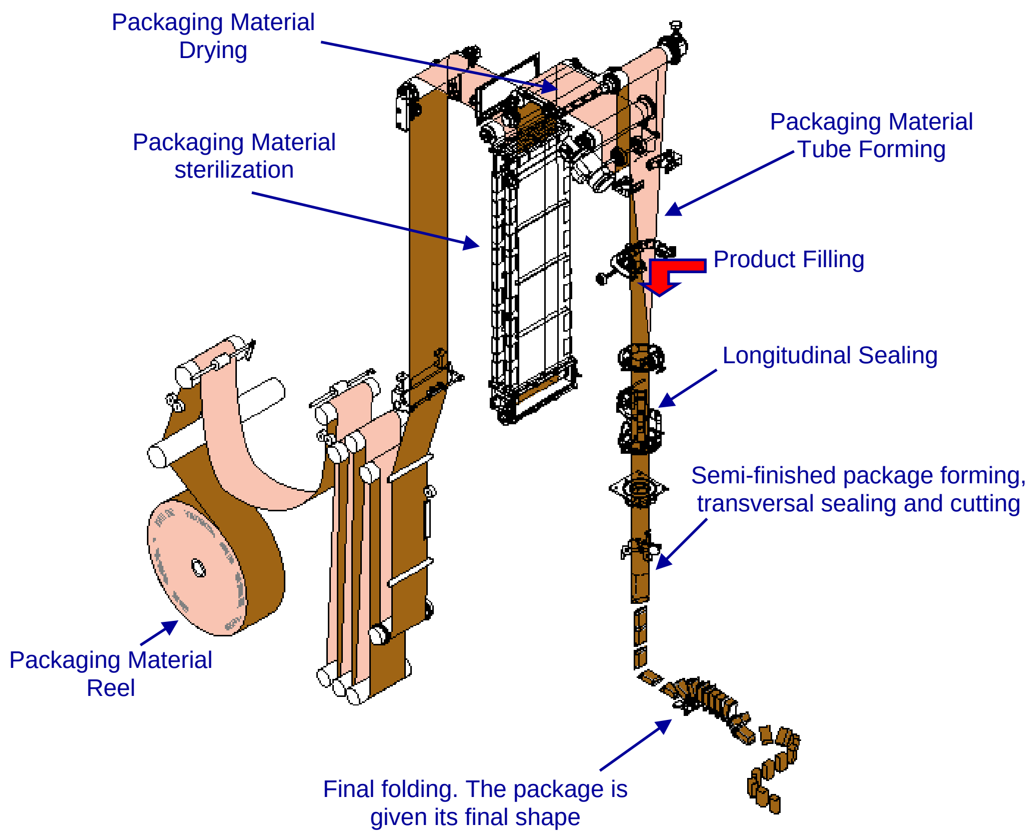

Figure 2. Filling machine schematic.

The present paper describes how simulation and optimization are successfully used as part of our design process.

2. Preliminary Forming Study

Before working on the development of the forming section for a filling machine we start with the simulation of the forming process as a sequence of basic operations. With this type of analysis we are able to understand the feasibility of a design by computing the levels of stresses and strains introduced by the process. The analysis starts from a flat portion of packaging material that already includes the crease lines. A bunch of rigid planes whose motion is controlled by the use of connector elements is used to form our origami. The analysis is performed using an explicit approach.

2.1 Crease lines modeled with shell elements

If shell elements are used to model both the crease lines and the panels we need to define a material for the crease lines that is weaker than the one defined for the rest of the packaging material. The panels are modeled as multilayer composites where the most important structural properties are given by the board which is modeled as an elastic-plastic material with orthotropic elasticity and a Hill anisotropic yield criterion. The material used for the shell elements modeling the crease lines is similar to the one used to model the panels but with weaker elastic properties.

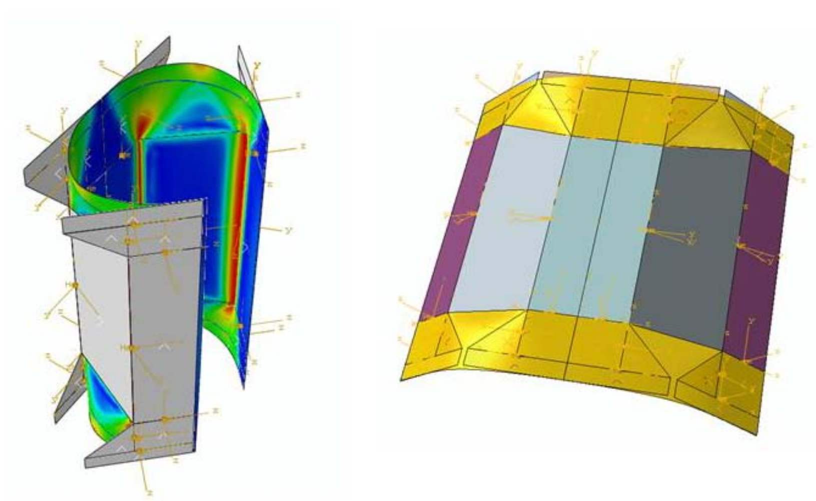

Figure 3a. Preliminary forming study.

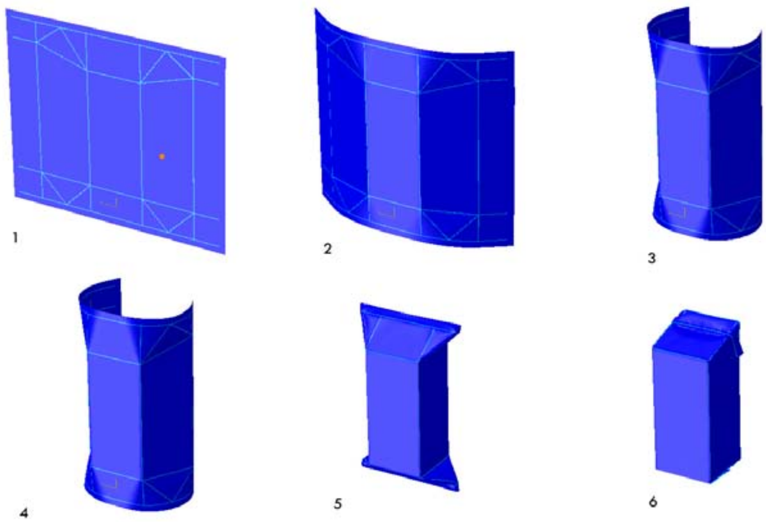

Figure 3b. Forming sequence.

2.2 Crease lines modeled with on purpose developed interface elements

An interface element able to model the main macroscopic effects of the crease lines has been developed by Andrea Giampieri as part of a PhD thesis at the ‘Politecnico di Milano’. The interface element has been implemented at the moment in a special purpose finite element code and tested against available data, giving very positive results. We are now implementing the element in Abaqus.

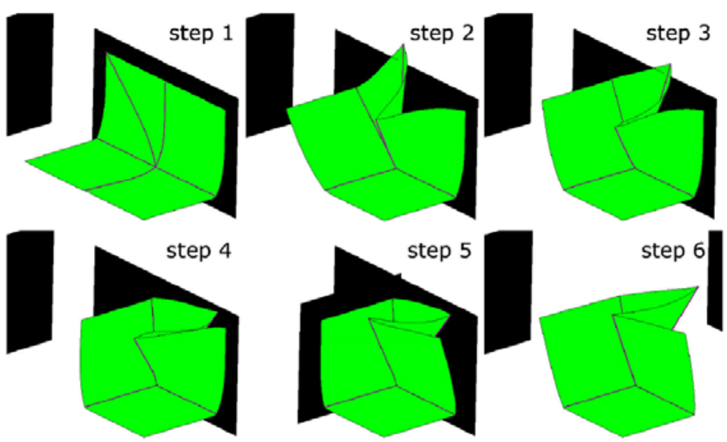

Figure 4. Folding with interface elements.

3. Tube Forming

The forming process inside the filling machine starts by shaping the web in the form of a cylinder. This is accomplished by the tube forming section of the machine: a number of forming rings each of which is constituted by a sequence of tangent rollers (Figure 5).

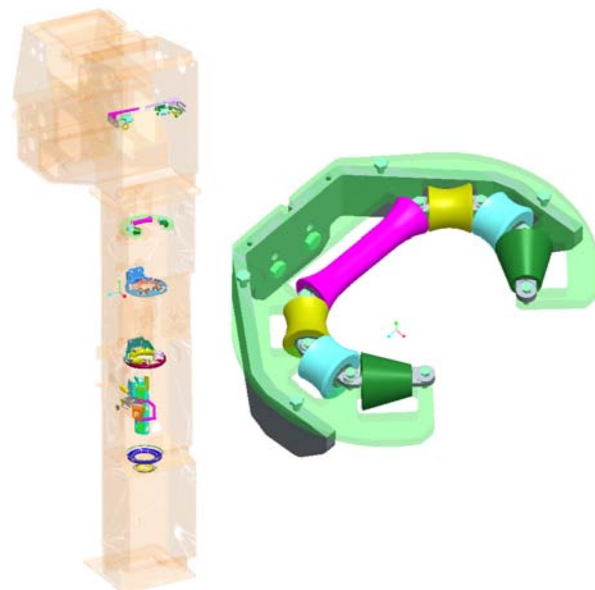

Figure 5. The tube forming section.

The design of this section of the machine is crucial for the entire forming process, for this reason a design procedure involving simulation and optimization techniques has been adopted. A customization of Abaqus/CAE has been developed in order to completely automate the simulation of the tube forming process using Abaqus/Explicit. To understand the effect of the most important design parameters of the forming section on certain responses like particular measures of stresses and strains along the tube, a Design of Experiment that works on the simulation through the mentioned customization is performed using Isight. The designer, based on his experience and on the DoE results, creates a first guess of the tube forming section then using the customization computes the resulting shape of the tube as well as stresses, strains and curvatures. If this first design is judged satisfactory a multi-objective optimization process using Isight is launched. The optimization loop uses again the simulation through the developed customization. The obtained design needs to be tested on the machine; for this task a “universal forming section kit” has been developed. The kit is capable of physically represent any possible shape designed and it can be plugged into an existing filling machine. Once the design is tested with positive results, the real shape of the formed tube is captured using a laser scanner, imported in our CAD system and used to design the inductor for the longitudinal sealing.

3.1 The Customization

The developed customization collects the tube forming design parameters through a GUI (Figure 6) and creates launches and post process an Abaqus/Explicit analysis simulating the tube forming process.

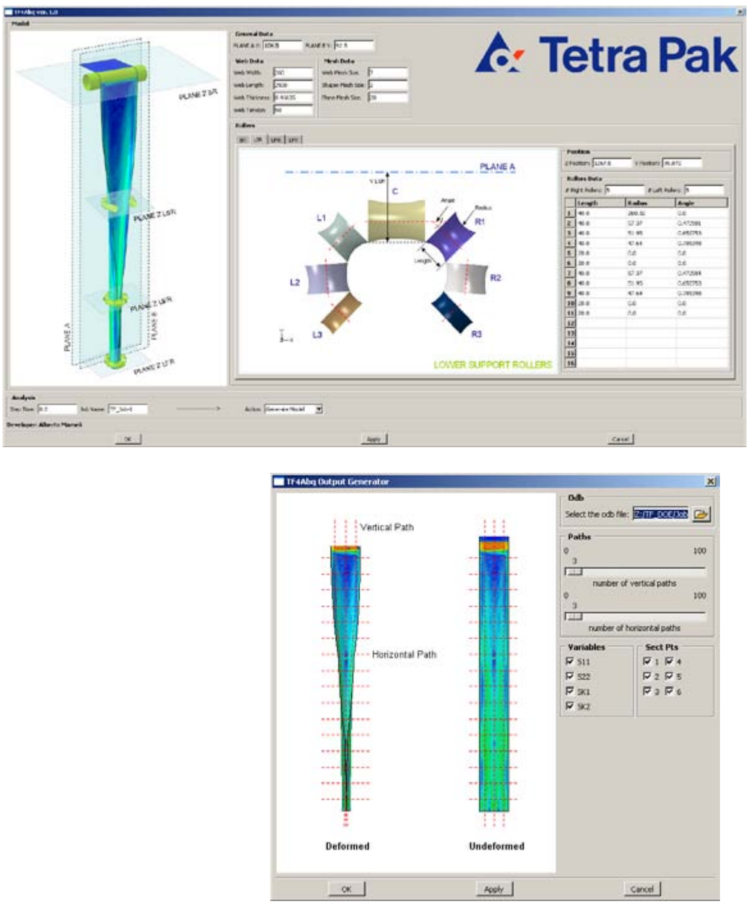

Figure 6. GUI of the customization.

The analysis is made up of three steps, in the first a flat web of packaging material is bent around a rigid cylinder and it is inclined toward different series of aligned rollers, in the second step the different rollers are driven in order to wrap the web and to form a tube, in the third step the bottom of the tube is pulled down simulating the flow of the packaging material. The packaging material is modeled using shell composite elements as described in the paragraph 2.1 and it can include the crease lines pattern. The rest of the components are modeled as rigid bodies. Connector elements are used to drive the relative motion of the rollers.

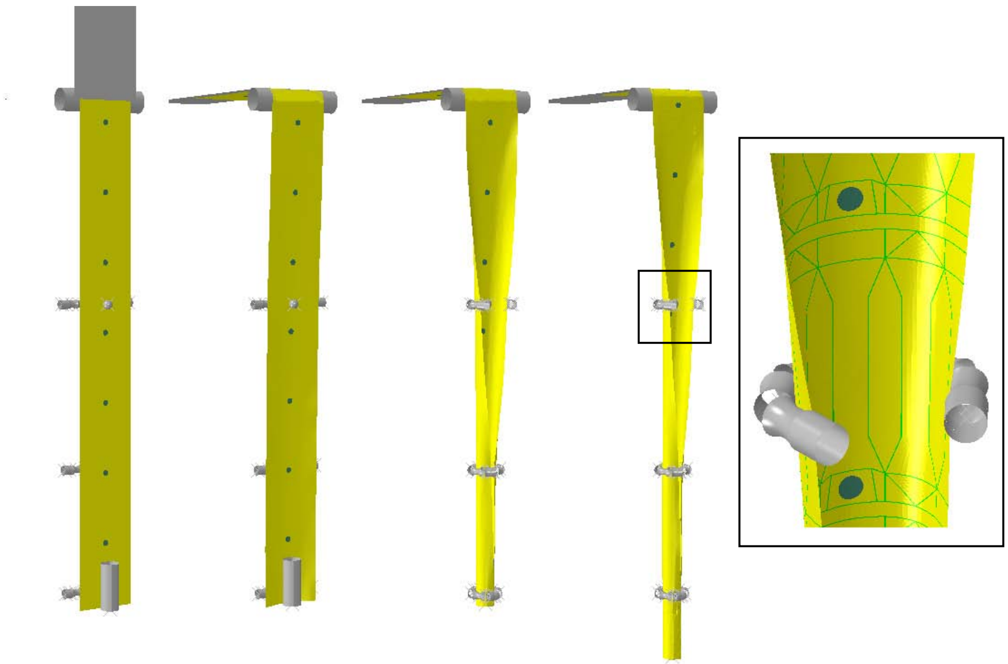

Figure 7. Tube Forming Simulation.

The automated post-processing generates path plots of stresses strains and curvatures. The paths are obtained slicing the tube longitudinally and transversally. Figure 8 shows a typical output of a measure of stress along the tube. These kinds of results are used as responses for the DoE and as part of the objective function for the optimization.

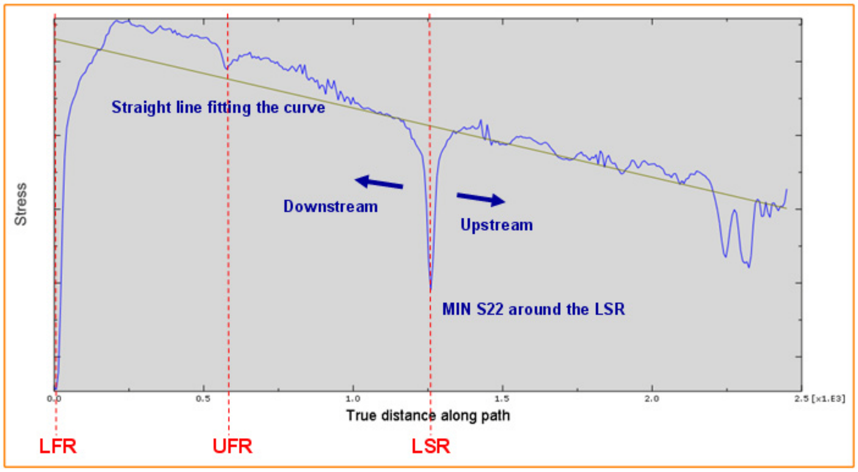

Figure 8. Stress along a longitudinal path.

3.2 The Design of Experiment

The implemented Design of Experiment wants to evaluate the effects of certain machine parameters related to the tube forming section on the state of stress and strain generated along the tube. The DoE has been performed using Isight and Abaqus/Explicit. The design variables are the positions and the shapes of the forming rings. The DoE workflow is shown in Figure 10.
The design matrix is generated in the range of variation of each parameter according to the "Optimal Latin Hypercube" algorithm available with Isight-DoE; due to the high computation time of the simulation, a relatively low number of experiments (120) with respect to the design variable number can been used with the DoE approach: for this reason the Optimal Latin Hypercube method has been chosen. The Optimal Latin Hypercube try to uniformly cover the hyper-space design (see Figure 9).

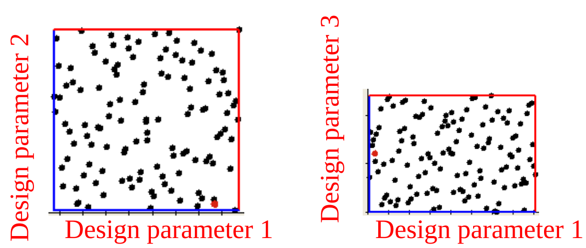

Figure 9. Two scatter plot example of the 120 DoE-Optimal Latin Hypercube experiment.

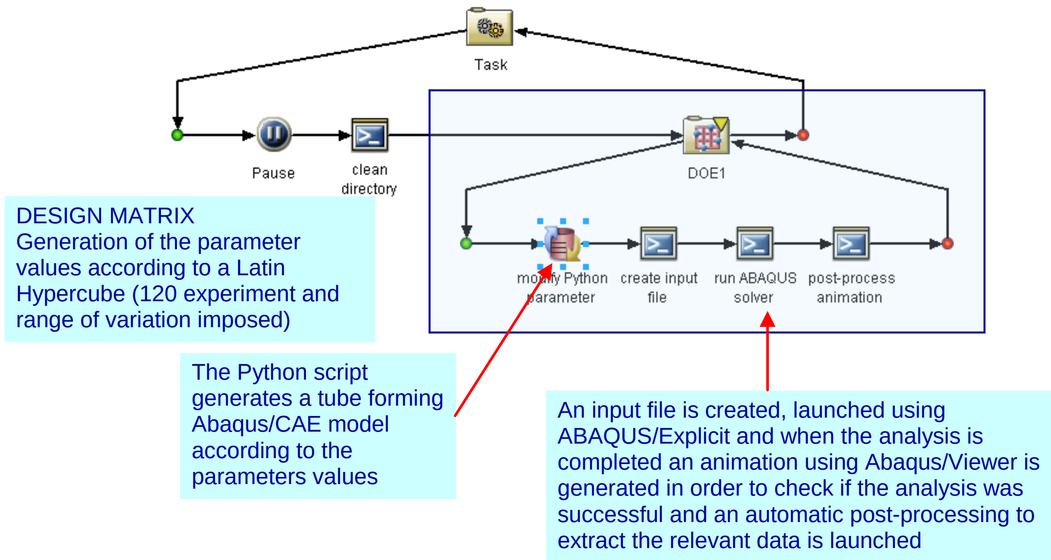

Figure 10. DoE WorkFlow.

The Optimal Latin Hypercube DoE tests uniformly all the design parameters 120 times in their allowed range, this characteristic of the Latin Hypercube Montecarlo let unveil un-linear behavior of some design variable on the output respect to other classic DoE method (like CCM, orthogonal Array, etc). The parameters mutual-interaction analysis is instead a function of the number of Latin Hypercube samples, the number of variable and the “complexity” of the problem. There isn’t any universal rule available to define a minimum number of Optimal Latin Hypercube DoE samples to get all the information on the problem, but a *try&test* approach is advised with a new problem approach.

The results of the DoE expressed through Pareto and Scatter plots are extremely useful for the designer. In the example of the Figure 11 the scatter plot allows to identify a behavior of the paper compression stress related to a geometric position of a roller: the designer can identify some ranges of the design parameter that minimize the compression stress: the scatter plot allows to spot the range of the output too. The influence of a variable on the output robustness can be captured from the scatter looking for the region of less variation: the designer must take into account that all the variables are changed simultaneously during the Latin Hypercube, so the region with less output variation means an intrinsic robustness of the system on that design configuration.

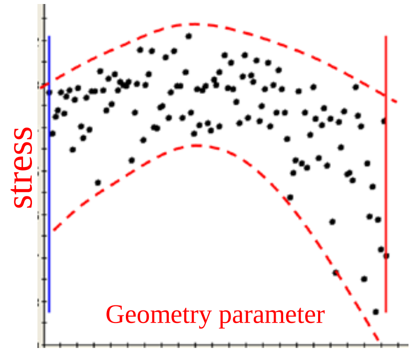

Figure 11. Scatter plot about a paper compression stress related to a design parameter.

3.2.1 Mathematical Approximation Model

The 120 samples table has been used to teach a radial base function (RBF) approximation model in order to get a fast mathematical model of the numerical simulation. The scope is to substitute the high time consuming Abaqus/Explicit simulation within a fast surrogate model: a surface approximation response. The final scope is to implement an optimization technique.
The RBF method has been preferred to the polynomial method because of the unknown behaviour of the responses.

Therefore, the RBF approximation model obtained from the 120 samples has been validated through the automatic cross-correlation available on the Isight approximation module. An example of the cross-correlation diagram is show on the Figure 12. The average error of the interpolation point is about 10%, which is too high to be used for an optimization.

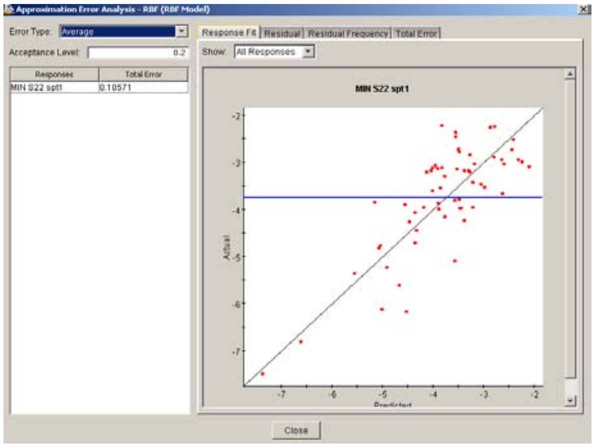

Figure 12. Cross Correlation Diagram of the RBF response.

3.3 Optimization

Once a good starting design is achieved we use it as a starting point for a multi-objective optimization. The Optimization has been set up based on the previous DoE loop.
The Optimization is performed using Isight and Abaqus/Explicit. Figure 13 describes the workflow.
In order to obtain a feasible geometry configuration of the "Universal forming section kit" the variables are defined with restricted and discrete allowed values to respect the kit allowed configurations and the forming machine cluttered space. The ASA (*simulation annealing*) algorithm has been chosen for the optimization problem: it is an explorative algorithm and it supports discrete variables formulation. A maximum of 120 Abaqus runs were allowed to the ASA algorithm, but nor special algorithm setting neither optimization strategy has been required for this problem.

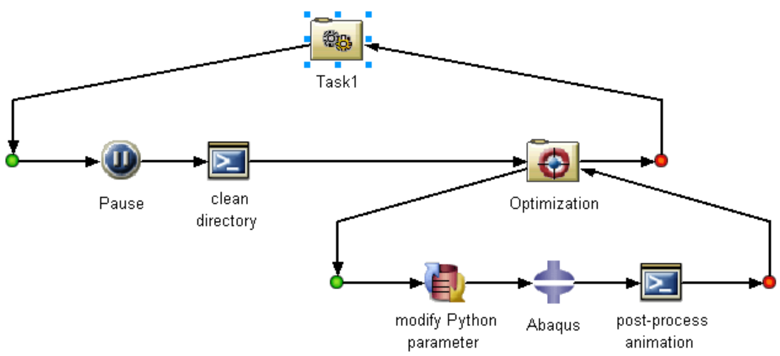

Figure 13. The Optimization WorkFlow.

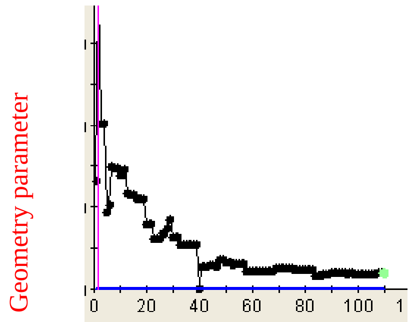

Figure 14. A design geometry history during the optimization.

3.4 The “Universal forming section kit”

The design obtained as a result of the optimization needs to be tested on the field before being industrialized. To do so we have developed a “universal forming section kit” that is a forming section characterized by a variable geometry that can replicate any design and can be plugged in an existing filling machine.

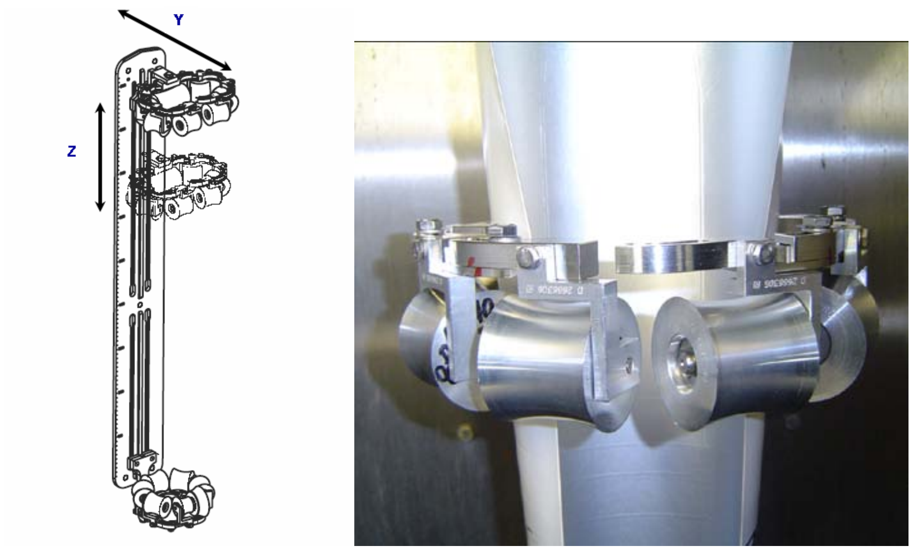

Figure 15. The universal forming section.

Using this kit we physically replicate the design obtained with the virtual tools and we can validate it running some tests on existing filling machines.

3.5 Reverse engineering for the inductor

If the tests mentioned before validate the design, we use a reverse engineering technique to design the inductor heating system used to seal the tube vertically. The inductor heating system has a surface that needs to be at a constant distance from the surface of the tube in the sealing region. To design it we acquire the formed tube geometry using a 3D laser scanner in the form of a cloud of points. The acquired cloud is imported in our CAD system where the surface is reconstructed and used to design the inductor.

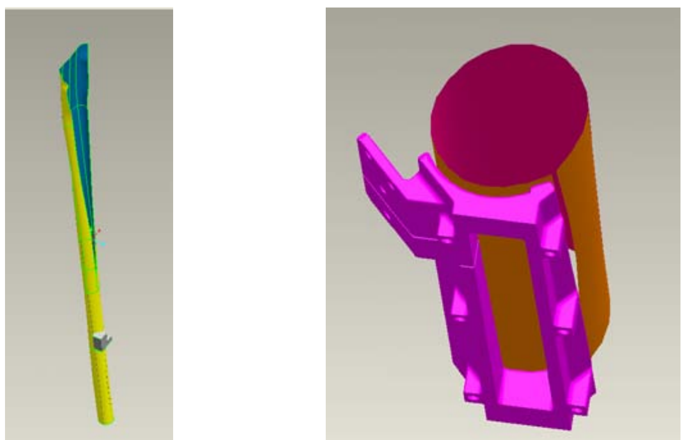

Figure 16. Reverse engineering.

4. Package Forming

The packaging material formed in the shape of a cylindrical tube and filled with the desired liquid enters in the section of the filling machine where it is formed in the shape of a package, transversally sealed and cut into single packages. We have developed two types of systems, one for the normal machines and one for the high speed machines. The first is a two jaws system moving in an alternate fashion, the second is a chain system carrying ten jaws moving in a continuous way. In both the systems the base jaw is made up of a volume box that acts as a mould, two folding flaps, a transversal sealing system and a cutter. The design of this section is very complex because the profiles of motion of the components define the interaction between the machine and the packaging material as well as the interaction between the packaging material and the fluid. The design of the profiles of motion is an iterative process that makes use of multibody dynamics codes. Once the profiles of motion are defined, we perform a virtual forming test using Abaqus/Explicit. The machine is modeled using rigid bodies and connector elements, the designed profiles of motion are imported and implemented as boundary conditions and connector motions.

The packaging material has already the shape of a tube and contains the crease lines pattern; it is modeled as described earlier on this paper. The fluid is modeled imposing an equivalent internal pressure on the tube or using the CEL technique. The output of this analysis gives us a lot of useful information; we can spot macroscopic defects on the formed packages and discover when and how they first appear. We can as well identify critical areas and potential microscopic defects through the analysis of the state of stress and strain.

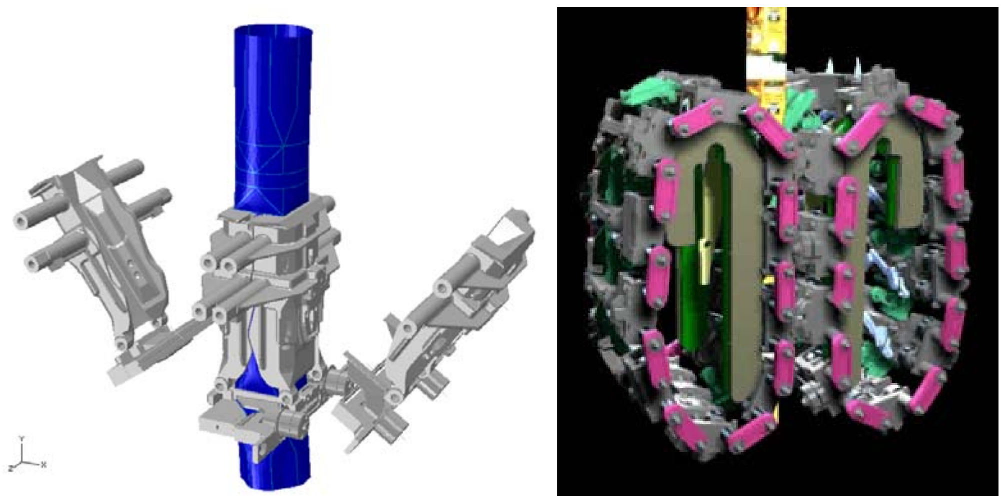

Figure 17. Forming Systems.

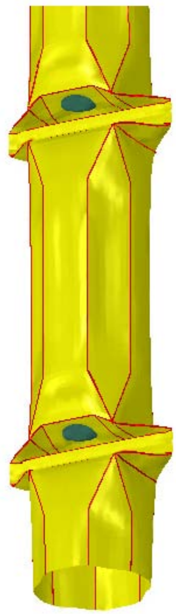

Figure 18. Formed Package.

5. Conclusions

The present paper described how we successfully use advanced simulations, customizations and optimizations techniques as integral part of the design process of the forming units for our filling machines. The use of these techniques allows us to optimize the forming process, to reduce the design time, to have more control on the entire process improving the quality of the final products.

6. References

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