

Using JMP® for Design of Experiments and Variability Analysis for Semiconductors

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Abstract: JMP® is an interactive statistical analysis program that promotes the visualization and discovery of important patterns and outliers in your data. It accomplishes this through unique graphics and the dynamic linking of points. This paper will address two aspects of a quality certification process namely an initial variability analysis of the measurement tool and a final response surface analysis for simultaneous optimization of multiple responses.

Introduction: Eleven years ago, a unique experiment was initiated between fourteen companies in the U.S. semiconductor industry and the U. S. government. The experiment called SEMATECH, joined together more than 80% of the US semiconductor industry to bring the U.S. semiconductor industry back to world leadership in semiconductor manufacturing technology. One outcome of the consortium was the evolution of the SEMATECH Qualification Plan (Qual Plan), a flexible guideline for effective process characterization and improvement relying heavily on statistical and graphical techniques. The guideline uses statistical methods to achieve engineering goals including gage studies, data collection, design of experiments, statistical process control and reliability (Czitrom & Spagon (1997)). In our first example we will show how JMP can be used to evaluate the capability of a measurement tool (gage), the first step in the qualification process, and the second example will illustrate simultaneous optimization of a designed experiment, one of the last steps of a semiconductor design process.

Example 1: It varies (Variability plots, Gage R & R reports)

Many manufacturers need to make their products and make measurements with gages (i.e., digital calipers, voltmeters, etc.) The trouble is that these gage measurements are made across production lines, operators, parts (i.e., wafers or steppers if you are a chip manufacturer), day of the week, and other factors, and each of these entities within the process introduces a possible source of variation measured by the gage.

As an example suppose semiconductor manufacturer wants to characterize a new type of furnace used for the deposition of thin films on silicon wafers. The process uses chemical vapor deposition (CVD) techniques to deposit approximately 1100 Angstroms of silicon nitride on batches of 150mm wafers (this example motivated by a paper by Reece and Shenasa chapter 30 in Czitrom & Spagon). The gage analysis estimates of the short-term measurement error (repeatability error) and the longer term error (reproducibility) involving different wafer sites and different wafers. To concentrate on repeatability, the engineers measure the same site 10 times in each of 5 sites in three wafers chosen to span the range of expected wafer thickness (900 to 1200 Å). There is no effort to isolate the reproducibility error since only 3 wafers were used (Figure 1).

Obviously the repeatability error is relatively small and independent of nominal film thickness over this range. The P/T ratio for repeatability is just:

$$P/T = (5.15 * \sigma_{\text{repeatability}}) / (USL - LSL).$$

Now if the target is 1100 Å or $\pm 10\%$ then the denominator is 220 Å and $P/T = 1.819\%$ (from Figure 2). Since a P/T of less

than 5% is highly desirable in a measurement tool then we conclude that this measurement tool does an excellent job since it represents less than 2% of our tolerance.

Example 2: Just DOE it! (Prediction Profiler, Plots of Interactions, Contour Profiler)

A unique mix of prediction profiles, effect and interaction plots and overlay contours makes JMP very useful to a company wanting to do both the generation and the analysis of designed experiments. In this example a chip manufacturer takes multiple chip measurements across several wafers in an attempt to find out what settings should be made for Thickness (thickness of photoresist), PEB (post-exposed bake time), PUDDLE (developer puddle time on the wafer), Time (exposed time), and Focus (lens setting) to meet a tolerance setting for the chips in both the wx (horizontal) and yz (vertical) directions and yet simultaneously minimize the standard deviation in chip size in both directions. The desirability profiler in JMP will give good, robust values that are reasonably optimal. The engineer can then overlay contours to see the "sweet spot" regions of acceptable designs. In this example we set our desirabilities for the means to 1.38 with a tolerance of $\pm .02$ and simultaneously want "smaller is better" for the standard deviations. With a full response surface model we get preferred settings for each of the independent variables (Fig 3a). The profiler, together with the interaction plot for SD ckt yz, and a contour plot showing the "sweet spot" region for Thickness vs. Time are shown in Figures 3a, 3b, and 3c.

So far the problem of multi-response optimization in JMP has been handled with the exact same model form for each response. In many real-world applications the analyst wants a separate model for each response using only the significant factors for each response. Even here JMP can still be used to optimize all the responses (Obermiller 1997). The steps are as follows:

- a> Create a model for the first response using the Standard least squares report and Save the Prediction Formula.
- b> Repeat a> for each response
- c> Fit an overall model such that each individual response model is a subset of this overall model in the Screening personality specifying the predicted values as the responses.
- d> Ignore model fitting results but use the contour profiler and/or the desirability functions.

In this example Mn ckt wx uses Thickness, time and PEB; Mn ckt yz uses time; SD ckt wx uses time*Thickness and SD ckt yz uses focus*PEB. So we refit a screening model with predicted values as the responses and with Thickness, PEB, time, focus, time*Thickness, and focus*PEB as factors. This frees us to design for robust optimization using any value of PUDDLE (Figure 3d).

References:

Czitrom, V. and Spagon P., (1997) *Statistical Case Studies for Industrial Process Improvement*, Philadelphia: ASA SIAM.

Obermiller, D. "Multiple Response Optimization Using JMP", Proceedings of the 22nd SAS Users Group International Conference

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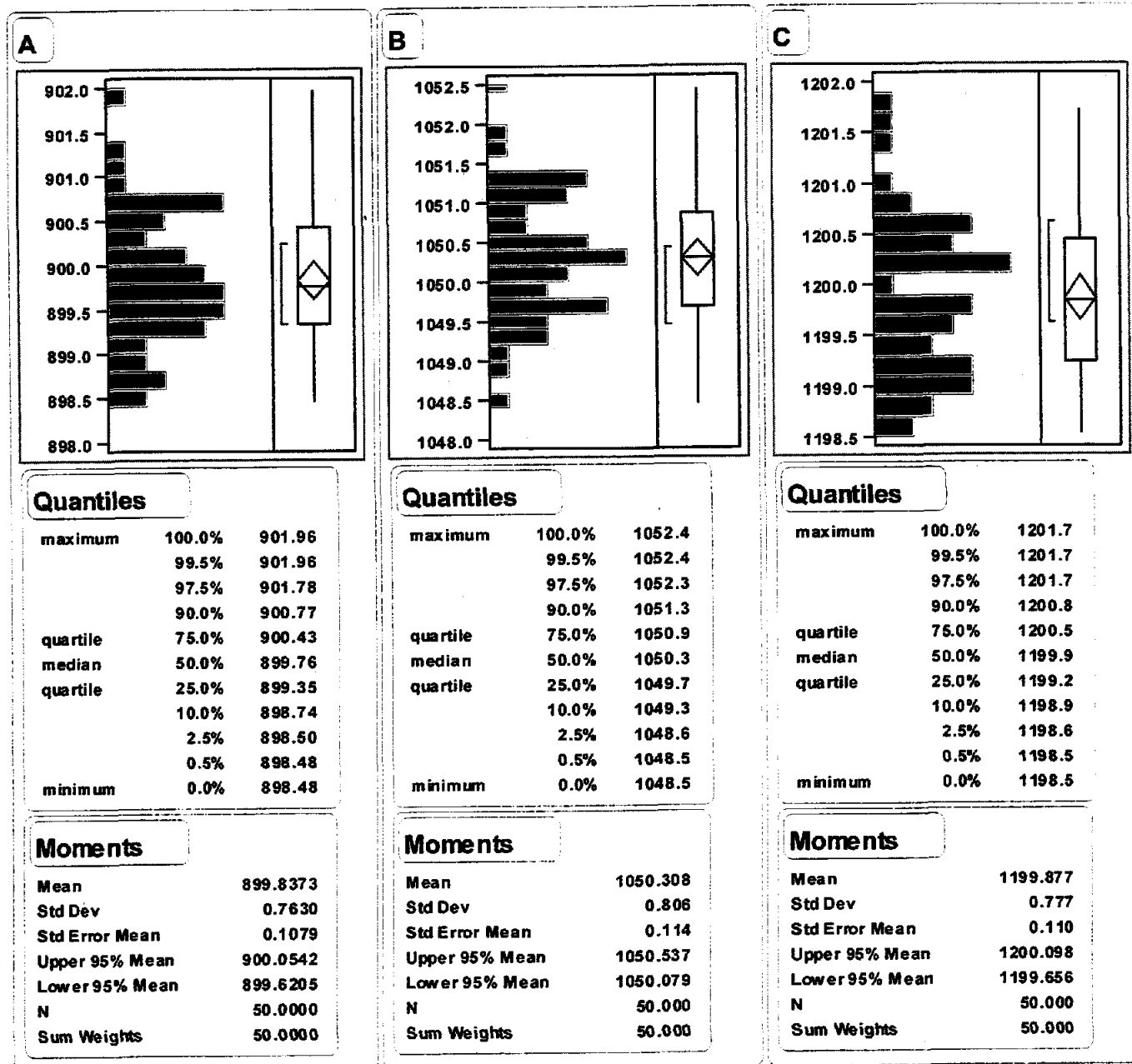


Figure 1. Measurement repeatability error for each wafer. Notice, all three wafers have similar interquartile distances of 1.1, 1.2, and 1.3.

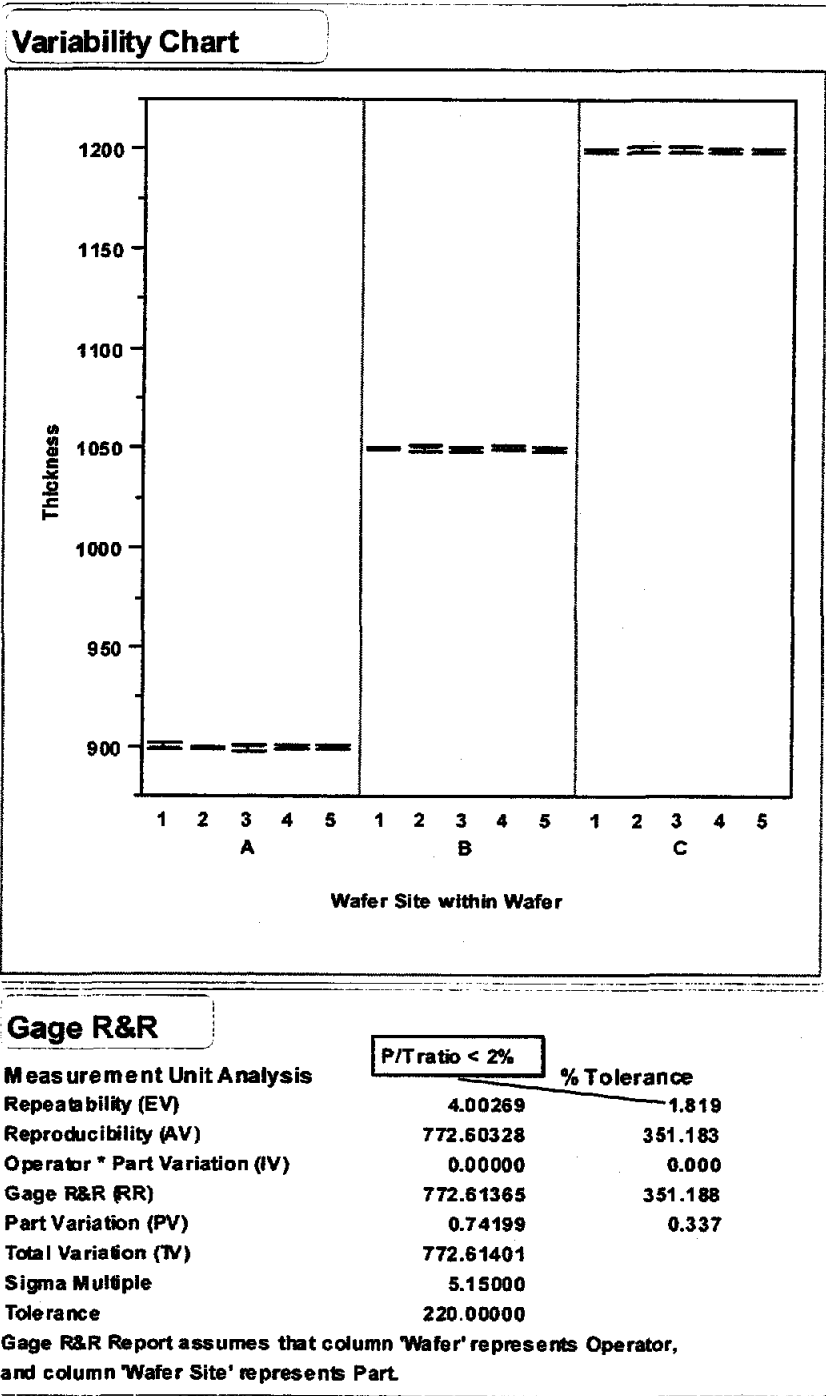


Figure 2. Very small variation in the measurement tool, P/Trept=1.819%

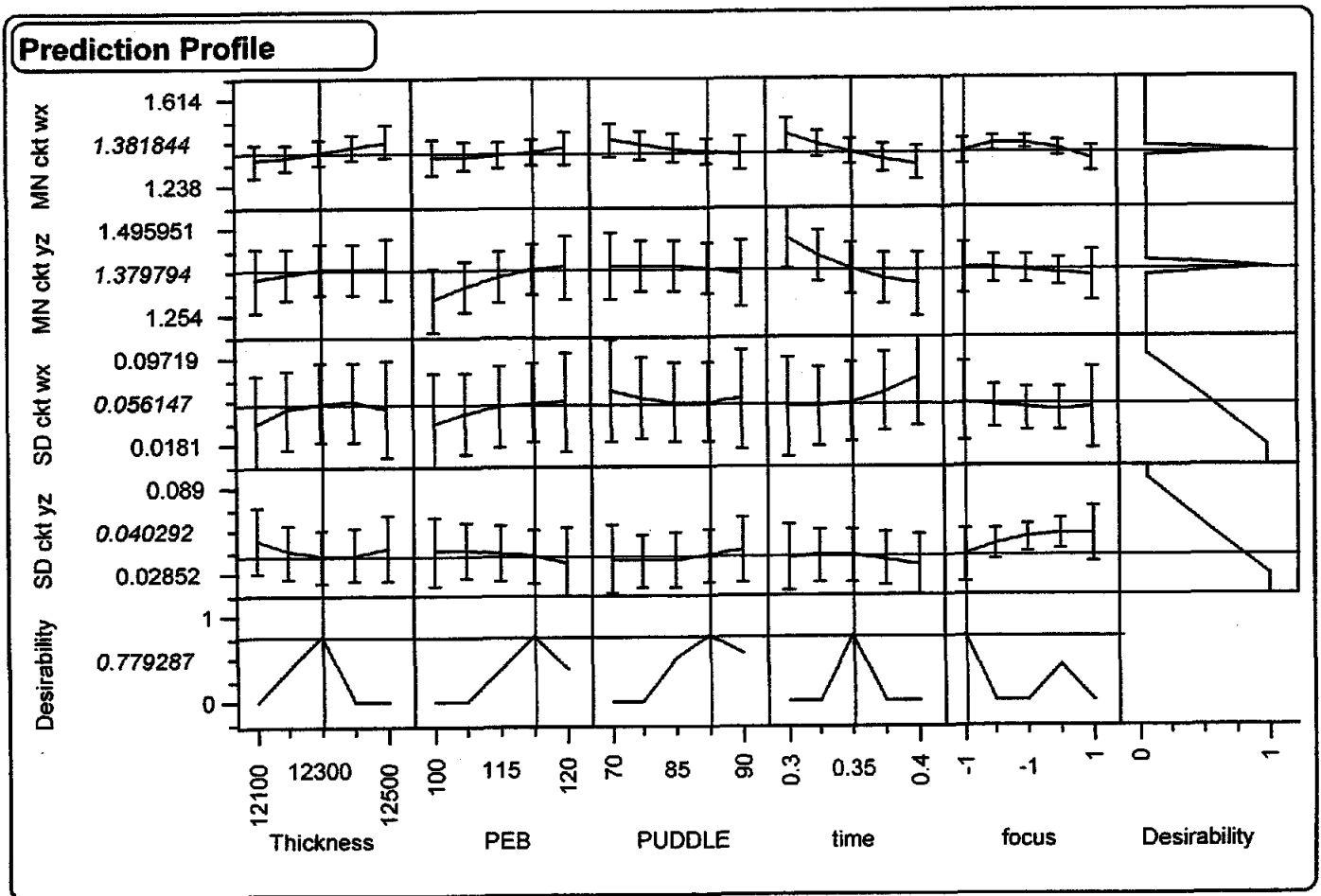


Figure 3a. JMP's Prediction Profiler with desirability settings. Here we see that by setting a tight "most desirable" setting at 1.38 for the means, and a "smaller is better" setting for the standard deviations, the last row in the profiler displays the best combination of factor settings to best accommodate these desirability constraints.

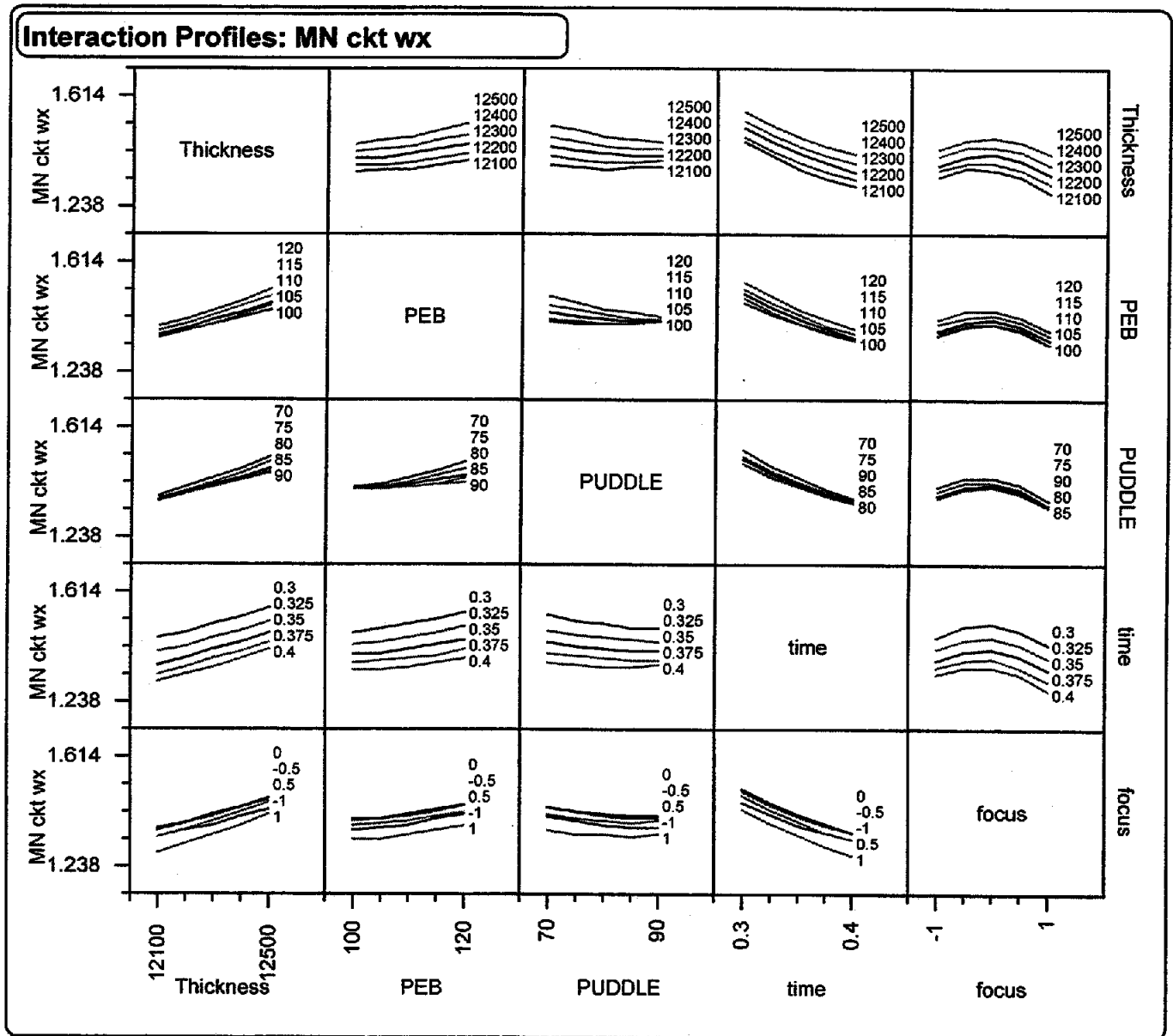


Figure 3b. JMP's two-way interaction profiler. For good, robust designs we want to "design on flats" when at all possible. This will make a factor relatively insensitive to other factor settings and thus minimize variability. In this plot we see that a factor setting of PUDDLE=70 would lead to excess variability with a small change in setting of Thickness, PEB, or time but that PUDDLE=85 (our design value) designs more on flats and is therefore is preferable as a setting for robust engineering design.

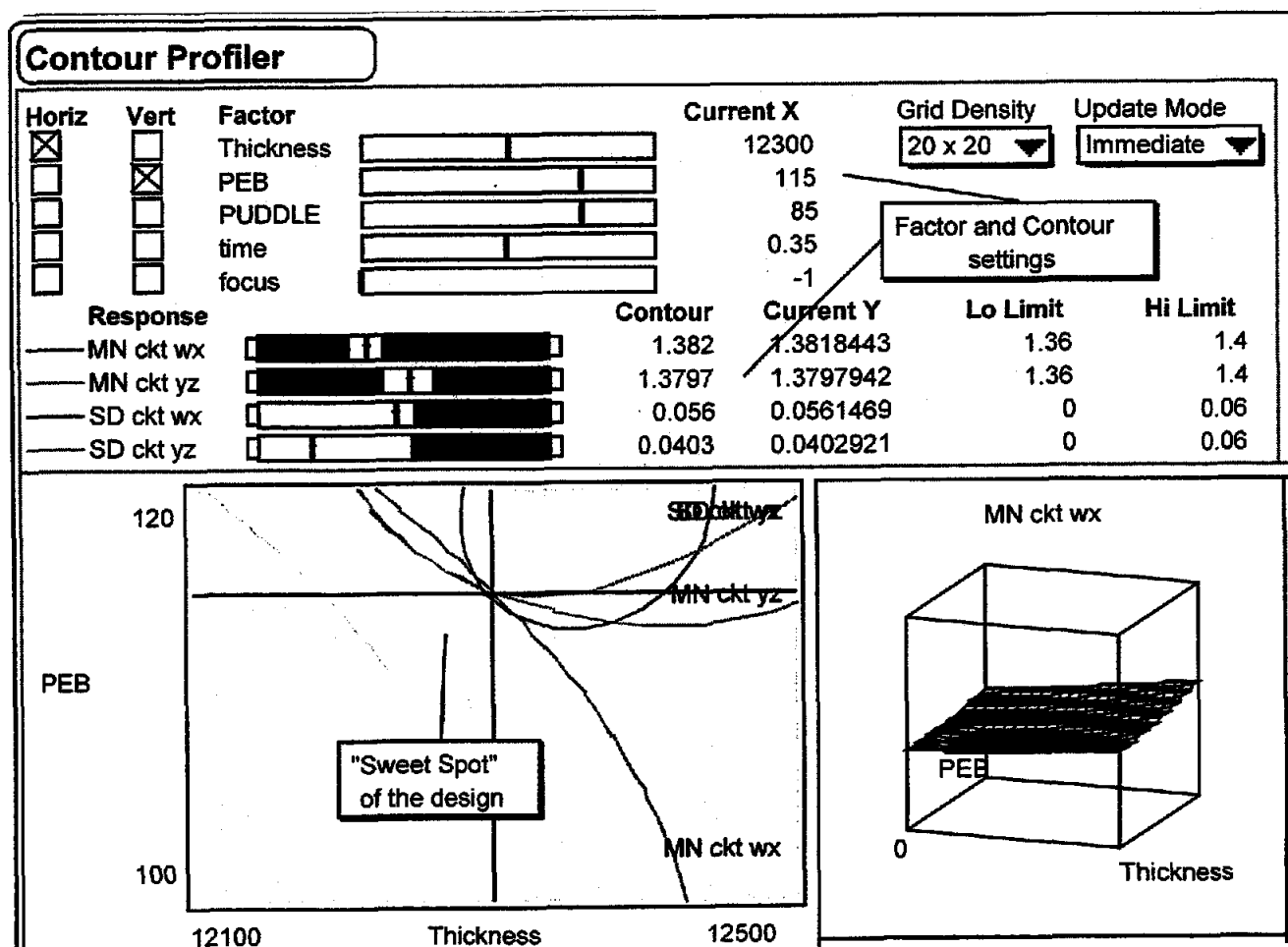


Figure3c. JMP's overlay contour profiler shows overlaid contours for each response variable for any set of independent variables taken two at a time. The white space ("sweet spot") is the region of robust designs that satisfy the constraints. If minimizing cost is a consideration moving the crosshair tool to one of the corners of the sweet spot and designing at that corner may be appropriate.

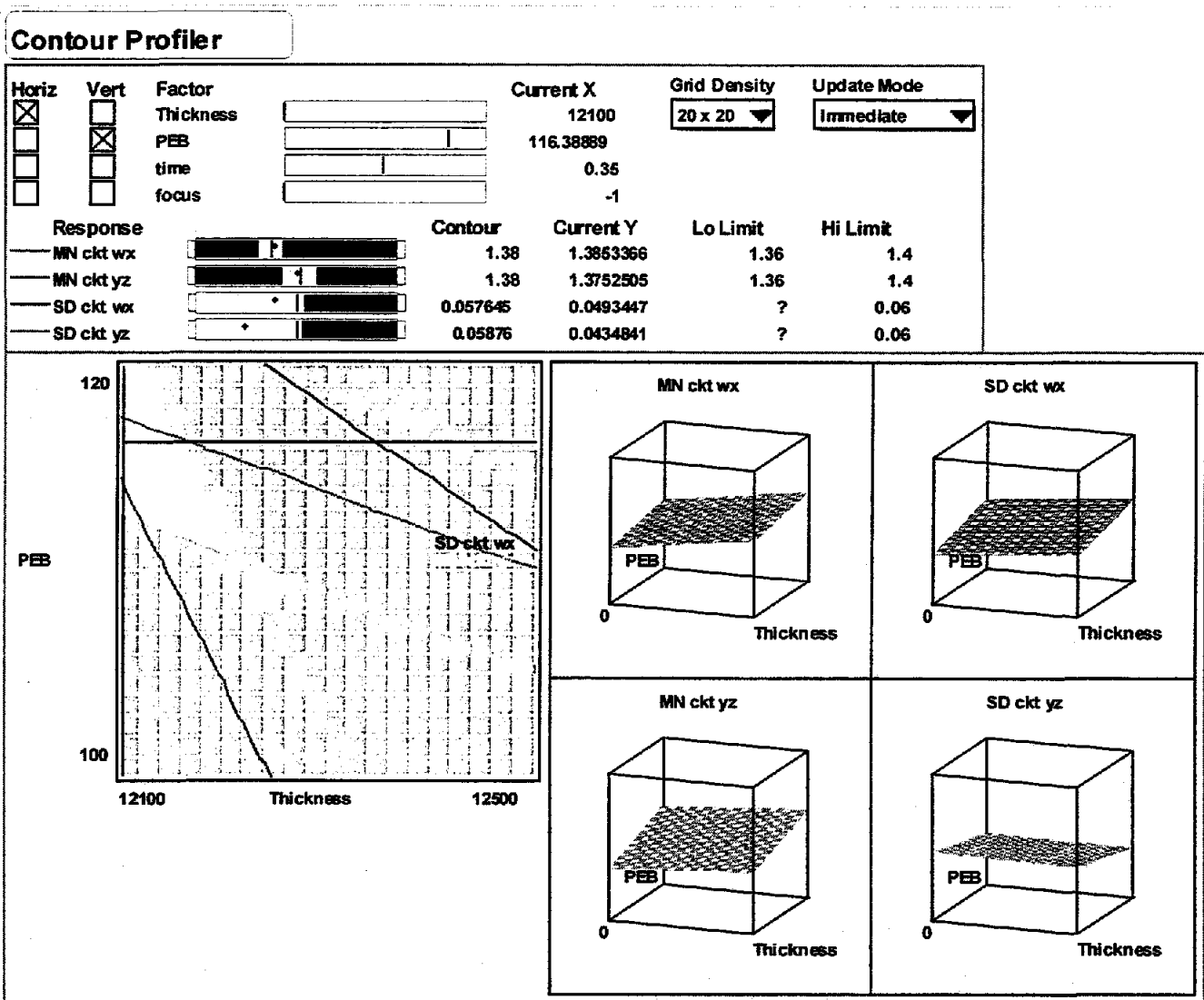


Figure 3d. Separate Models: In this example Mn ckt wx uses Thickness, time and PEB; Mn ckt yz uses time; SD ckt wx uses time*Thickness and SD ckt yz uses focus*PEB. So we refit a screening model with predicted values as the responses and with Thickness, PEB, time, focus, time*Thickness, and focus*PEB as factors. This frees us to design for robust optimization using any value of PUDDLE.