

Robustness and Cost-of-Conformance Analysis during Scale-Up of Textile Spin-Finish Formulations

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Abstract

Scale-up of a textile spin finish is successful only when laboratory performance is reproduced across raw-material batches and operating conditions while the final textile remains conforming. A hierarchical acceptance framework is proposed that separates raw-material batch, independent formulation preparation, finish add-on, and relative-humidity effects. The first contribution is a robustness criterion based on independent preparations and measurement uncertainty rather than on the number of yarn segments. The second contribution is a cost-of-conformance boundary that combines actual finish consumption with non-finish operating costs and is applied only after the required quality limits are met. This changes the economic comparison from nominal formulation price to the cost of producing one tonne of conforming textile.

Keywords

textile spin finish; pilot scale; robustness; batch effect; finish consumption; cost of conformance; acceptance window

Introduction. A laboratory-selected textile spin finish may fail during pilot translation even when its nominal composition is unchanged. New base-oil lots can alter polarity and impurity content, ambient humidity can modify electrical response, and the application system can change actual finish consumption. Therefore, scale-up requires an acceptance window rather than a single mean laboratory value.

Economic comparison must also be conditioned on conformity. A cheaper finish is not economically superior if it increases washing demand, reprocessing, downtime, or off-specification production. The objective is to link formulation robustness and practical cost within one decision sequence.

Materials and Methods

The verification design treats base-oil batch b , formulation f , finish add-on q , and relative humidity h as distinct factors. Three base-oil batches and three formulations are combined, with three independent formulation preparations per cell. Each preparation is applied at predefined q levels, and yarn segments are treated as technical observations nested within the corresponding application run. Relative-humidity conditions are imposed through independently stabilized chamber cycles rather than by treating individual yarn pieces as independent RH replicates.

Acceptance limits for friction, electrical resistance, viscosity, and other required responses are defined before inspection of results. For a measured value v with expanded measurement uncertainty U , compliance with an upper specification limit L requires $v + U \leq L$; for a lower specification limit it requires $v - U \geq L$. Pilot translation begins only after laboratory robustness is demonstrated.

Results: Robustness and Cost-of-Conformance Boundary

The framework first establishes an acceptance hierarchy in which the independent experimental unit is explicitly defined. Between-preparation variability, base-batch variability, application-run variability, and chamber-cycle variability are not replaced by repeated measurements on the same yarn lot. A formulation advances when its conformity margin remains positive across independent preparations and tested raw-material batches.

It then introduces a cost-of-conformance equation. Let d be actual finish consumption in kg per tonne of conforming dry textile, p the finish price per kg, and C_b the mutually

non-overlapping non-finish costs per tonne, excluding finish purchase. Then $C_t = d \cdot p + C_b$. With $x = d_{\text{new}}/d_{\text{ref}}$, $y = p_{\text{new}}/p_{\text{ref}}$, and $z = (C_{b,\text{new}} - C_{b,\text{ref}})/(d_{\text{ref}} \cdot p_{\text{ref}})$, the equal-cost boundary is $x \cdot y + z = 1$. The condition $x \cdot y + z < 1$ identifies lower total cost only for alternatives that have already met the same functional acceptance requirements.

Verification level	Independent unit / control	Decision use
Base batch $\times$ formulation	Independent preparations in each cell	Tests raw-material robustness
Application	Separately adjusted q runs	Tests process sensitivity
Environment	Independent RH chamber cycles	Tests humidity robustness
Pilot preparation	Independent 5-10 L batches	Confirms scale-up reproducibility

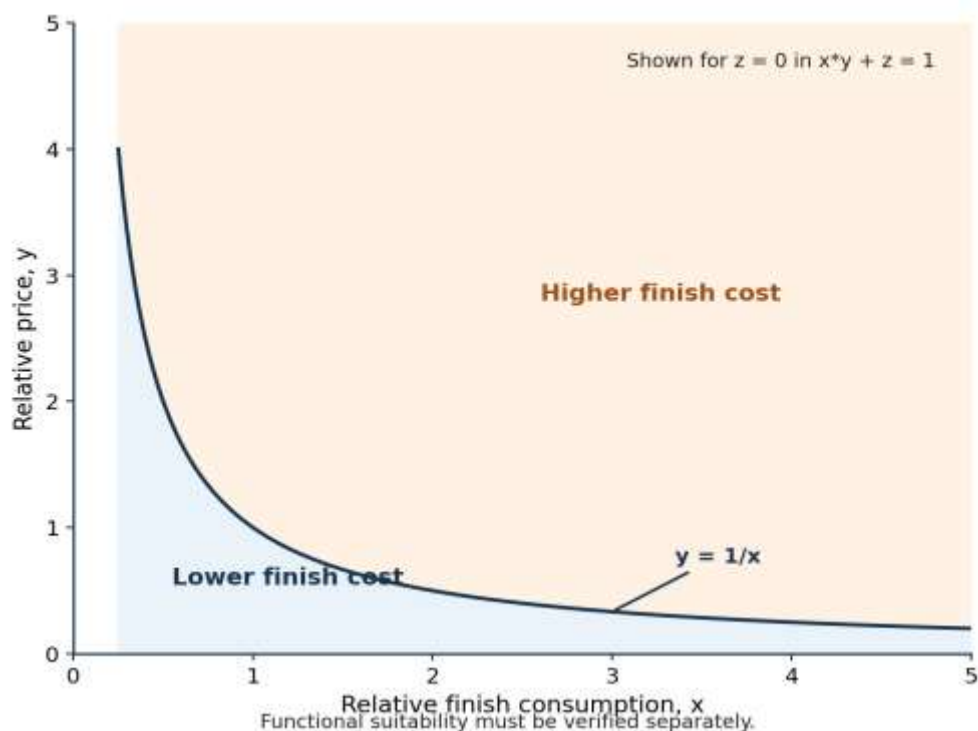


Figure 1. Cost-of-conformance boundary for equal non-finish costs ($z = 0$): $y = 1/x$ after functional acceptance has been demonstrated.

Discussion

This sequence prevents two common errors. First, it prevents technical repeats from inflating the apparent number of independent observations. Second, it prevents a lower nominal price from being presented as a saving before actual consumption and downstream operating costs are considered.

At $x = 0.80$ and $z = 0$, a relative price $y = 1.25$ lies on the equal-cost boundary: a 20% reduction in actual consumption offsets a 25% increase in unit price. Such calculations are not experimental findings; they are consequences of the accounting equation and become meaningful only when conformity is preserved.

Conclusion

Scale-up decisions should be based on robustness and cost of conformity rather than on one laboratory batch and nominal finish price. The proposed hierarchy connects raw-material batch effects, independent preparation variability, application conditions, and measurement uncertainty with an economic boundary expressed per tonne of conforming textile. This provides a defensible basis for selecting a formulation for pilot production.

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