2012

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A Research Monograph of the Printing Industry Center at RIT

No. PICRM-2012-03

R·I·T Printing Industry Center
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Rochester, NY
December 2011

PICRM-2012-03

The research agenda of the Printing Industry Center at RIT and the publication of research findings are supported by the following organizations:

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Abstract

Conformity assessment, a relatively new activity in the printing industry, is an attestation that specified requirements relating to a product or process have been fulfilled. Printing certification bodies assess printing conformity according to sampling, aim points, tolerances, and decision-making rules that are stipulated by printing standards. However, do we know if: sampling is too large or too small; normative requirements are too many or too few; tolerances are set too tightly or too loosely; and the pass/fail criterion is too stringent or too relaxed? Moreover, how do these factors impact the passing probability of a sample, a job, and the database as a whole?

To study inter-dependencies of these factors in production variation conformity, this research assumes that the number of jobs to be assessed for printing conformity is very large and that samples selected from a job are random. Statistical theory is used to study the relation between the passing probabilities of a printing job, a single sheet within each job, and each normative requirement. In our theoretical frame, given the tolerance levels of certain normative requirements, we can determine the passing probabilities of the criteria, the passing probability of a single sheet, and the overall passing probability of a printing job. Given the passing probability of a printing job, we can also determine the tolerance level of each normative requirement by reversing the procedure.

This research uses a real-life printing dataset and simulation techniques to determine the passing probabilities of a job as a function of sampling, tolerances, and the pass/fail criterion of a job.

This research offers two meaningful inferences: (1) the printing standards development community, i.e., ISO/TC 130, needs to be aware that sampling requirements, the number of normative requirements and their associated tolerances, and the pass/fail criteria impact the passing probability of a job; and (2) printers who are seeking printing certification need to know that, although sampling is random, the passing probability of a job ultimately depends on the process calibration and the effectiveness of local process control.

Acknowledgements

The authors wish to express their appreciation to the following individuals and organizations: the financial support of RIT Printing Industry Center to publish this research as a monograph; Mr. Jürgen Gemeinhardt of Fogra, for sharing the PSO dataset; and Dr. Patricia Sorce, for her encouragement and support of the project.

Introduction

With the development of process control and automation, printing has been transformed from a craft-based industry to a manufacturing-based industry. Printing standards and conformity assessment are strategic to printing companies who seek manufacturing efficiency and market differentiation.

Fundamental Changes in Printing Technology

Formerly, printing was largely a craft-based and skill-intensive industry. The quality of pictorial color image reproduction was in the hands of the journeymen. Print buyers were often required on-site to OK the color coming off of a print run. The OK sheet became the aim point for the remainder of print production.

The quality of pictorial color image reproduction has been largely influenced by hardware and software capabilities, as printing standardization provides aims and tolerances for given press-paper-ink combinations. Color measurement, coupled with process control, enables color repeatability. Digital color management further enables color predictability from design to prepress.

Printing Standards and Conformity Assessment

Variation exists in all phases of manufacturing. Understanding variation begins with sampling, measurement, and data collection. Conformity assessment is a demonstration that specified requirements relating to a product, process or system have been fulfilled (ISO/IEC 17000:2004). In 2010, ISO/TC 130 established a new working group—WG 13 Printing Certification Requirements—with a mandate to harmonize printing certification requirements and conformity assessment activities worldwide. Printing requirements—in terms of aims and tolerances—are specified by the working group ISO/TC 130/WG 3 Process Control. Printing conformity assessment helps build trust between printers and print buyers, because aim points specify the expected results and print tolerances separate consistent from inconsistent jobs.

An important question to ask is, “What contributes to nonconformity?” From a printer’s perspective, if the answer is, “We don’t know,” then there is fear that a print buyer can reject a job. But, if the answer is, “We know the causes of nonconformity and the remedies,” then there is an added confidence in place of this fear.

From the standards development and conformity assessment criteria point of view, there is a different kind of cause and consequence association. If conformity assessment becomes globalized, will ISO know:

1. What percentage of jobs pass conformity assessment?
2. How sampling rules, as specified in conformity assessment standards, impact nonconformance?

3. How normative requirements, as specified in product standards, impact nonconformance?

The paper is organized as follows: The *Research Objectives* section discusses the objectives of this research. The *Conformity Assessment Prediction Model* section describes a methodology that predicts the interdependency between the sampling rule and passing probabilities. The *Methodology for Predicting Probabilities and Tolerances* section introduces mathematical relations of these probabilities and shows how to determine the tolerance of each normative requirement. The *Numerical Results* section covers the numerical results of these probabilities. The *Discussion* section contains calculations of the tolerance of each requirement based on a printing dataset, and is followed by the final section, *Summaries of Major Findings*.

Research Objectives

There are two different causes of printing nonconformance, as introduced in the previous section. The first cause of printing nonconformance is printer-related, and the second is standards-related. The main objective of this research was to take an in-depth look at standards-related causes of nonconformance. By devising a conformity assessment prediction model based on reasoning and statistical theory, this research analyzed the factors that impact printing conformity. Since conformity assessment is a decision-making process based on random samples, the statistical theory developed in this research offers a solid foundation for predicting passing probabilities of a printing job.

Specifically, this research investigated the interdependency of normative requirements and the sampling rule on the passing probabilities of a single requirement, a sample, and a job. In addition, this research explored the use of a printing dataset and a simulation technique to study the effect of tolerances and sampling rules on the percentage of jobs passed.

Conformity Assessment Prediction Model

Each assessment procedure depends on a sampling rule. For example, in production variation conformity assessment a printing standard indicates that, for at least 68% of the prints, measured differences shall not exceed a certain tolerance (ISO 12647-2, 2004). A generalized definition of a sampling rule as used in this research follows.

M/K Sampling Rule

For each printing job, ***K*** samples are randomly selected from the job. Among these ***K*** samples, if at least ***M*** samples conform to requirements, then the printing job is said to pass the conformity assessment. In other words, we treat the number of samples required (***K***) and the number of passed samples (***M***) as variables.

In the sampling rule, we don't make any assumption on the distribution of measurement of each normative requirement in a job. The tolerance level of a normative requirement is estimated non-parametrically from the empirical quantile of the true data. In this paper we use the sampling rules "7/10" and "14/20" as examples to show how to determine the tolerance level. Here "7/10" is only a sampling rule. It does not mean that the passing probability of a single sheet is 70% or that the passing probability of a job is 70%. In other words, "7/10" has nothing to do with the probability that a normal random variable is within +/- one standard deviation (which is 68%). It only means that within 10 samples, if at least 7 samples—perhaps 7, 8, 9 or even 10 samples—conform to all normative requirements, then the job passes the conformity assessment. The true passing probability of the "7/10" sampling rule depends on the passing probability of each single sheet, and furthermore depends on the passing probabilities of all criteria.

When deciding on the sampling rule, the statistics, fit for use (or application requirements), and the costs must all be considered. Too few samples from a job may not offer enough information to make a sound decision. Too many samples may put a huge financial burden on the company. Too many passed samples, i.e., given ***K*** and when ***M*** is large, may challenge process capabilities. In this research, the '7/10' sampling rule and the '14/20' sampling rule will be compared.

After a sample is drawn from a printing job, the assessment body performs measurements on each sample to determine if the sample passes or fails. Usually, the measurements describe different normative requirements (e.g., ΔE of solid coloration, TVI of midtone tint, etc.). A passed sample must conform to all normative requirements.

Three Passing Probabilities

Although each assessed job either passes or fails the assessment, for the printing industry as a whole this event is totally random. Probability and statistical theory are needed to describe this randomness. In this instance, there are three related probabilities present in the assessment of a printing job:

1. The passing probability of a job. This probability is denoted by π. This is the probability that a randomly selected printing job passes the conformity assessment. It is the proportion of jobs that conform to requirements. From a macro perspective, if this probability (π) is too low, very few printing jobs conform to requirements. If π is too high, most jobs conform to requirements. Thus, the determination of this probability could be a degree of freedom whereby a reasonable value for π is chosen based on process capabilities and application needs.

2. The passing probability of each single sample in a job. We denote this probability by p. In each printing job assessed, each sample has only two fates: it either passes or fails the assessment. Due to the randomness of the sampling, the passing probability can be used to characterize the status of each sample. As shown below, there is a one-to-one correspondence between π and p, given the sampling rule. This means that given π, p is uniquely determined. The converse is also true. It must be emphasized that this relation depends on the sampling rule. Given the same π, different sampling rules will result in different p. The relationship between π and p is further explained in the next section.

3. The passing probability of each requirement. Suppose each sample needs to pass s normative requirements. The measurement of each requirement in a sample either passes or fails the assessment. Due to the randomness of the sampling, the passing probability can be used to characterize the status of each requirement in a sample. Let p_j, $j = 1, \ldots, s$, be the probability that a sample passes requirement j.

The final decision as to whether a sample conforms to requirements is based on the tolerance of each normative requirement. In this conformity assessment prediction model, the sampling rule and the passing probability π of all jobs assessed are first specified, and then the passing probability p of each sample in a job, the passing probability of requirements p_j, and finally the tolerance c_j of each requirement are determined. The next section discusses the relationships between these three probabilities and shows how to determine the tolerance of each normative requirement.

Methodology for Predicting Probabilities and Tolerances

This section discusses the mathematical relationships between the three probabilities introduced in the previous section, and shows how to determine the tolerance of each requirement based on its cumulative distribution function.

Passing Probability of a Job

Suppose the passing probability of each sample is p. In the M/K sampling rule, let X $(0 \leq X \leq K)$ be the number of samples that confirm to the requirements in a printing job. Therefore, X is a random variable and has binomial distribution. Let $\Pr\{X = j\}$ be the probability that exactly j samples confirm to the requirements within K samples. Then,

$$\Pr\{X = j\} = \binom{K}{j} p^j (1-p)^{K-j}, \; j = 0, \ldots, K,$$

where $\binom{K}{j}$ are binomial coefficients, i.e.

$$\binom{K}{j} = \frac{K!}{j!(K-j)!}$$

From the M/K sampling rule, the passing probability π of a job is:

$$\pi = \Pr\{X \geq M\} = \sum_{j=M}^{K} \Pr\{X = j\} = \sum_{j=M}^{K} \binom{K}{j} p^j (1-p)^{K-j}. \qquad (1)$$

Passing Probability of a Sample within a Job

Once the sampling rule and the passing probability π of a job are given, the passing probability p of each sample can be determined. To this end, Equation (1) should be solved for p given π.

The right-hand side of Equation (1) is a polynomial of p, and it is difficult to solve such an equation analytically. However, from the connections between binomial sums, and the incomplete beta function and related cumulative distribution function of beta and F distribution (Agresti, 2001, p. 18), it is possible to obtain an easy way to calculate p, which is

$$p = \left[1 + \frac{K - M + 1}{M \cdot F_{2M,2(K-M+1)}(\pi)}\right]^{-1} = \frac{M \cdot F_{2M,2(K-M+1)}(\pi)}{M \cdot F_{2M,2(K-M+1)}(\pi) + (K - M + 1)}, \qquad (2)$$

where $F_{a,b}(c)$ is the c^{th} quantile of the F distribution with degrees of freedom a and b.

The quantile function of the F distribution can be easily obtained from statistical tables, such as Pearson and Hartley (1966) or many statistical software packages, such as R (R Development Core Team, 2007).

Passing Probability of Each Normative Requirement

Suppose that each sample has s normative requirements used to determine whether the sample conforms to requirement. The sample is said to confirm to requirements if and only if the sample passes all those s requirements. Suppose the probability that the sample passes the requirements j ($j = 1,\ldots, s$) is p_j. Then the probability that the sample confirms to requirement is:

$$p = \prod_{j=1}^{s} p_j = p_1 \cdot p_2 \cdots p_s \tag{3}$$

Note that Equation (3) shows that given p, there are infinite possible combinations of p_j satisfying the equation. This means that it is impossible to determine the passing probability of each requirement uniquely. However, suppose it is assumed that each requirement has the same probability to conform to requirement, i.e. $p_1 = p_2 = \ldots = p_s = p_0$, then the result would be:

$$p_0 = p^{1/s}. \tag{4}$$

From Equation (4) it may be seen that, as the number of normative requirements increases, the passing probability of each requirement must increase in order to maintain the same job passing probability.

Predicting Tolerance for Each Normative Requirement

For each sample in a job, let $X = (X_1,\ldots, X_s)$ be the measurement from s requirements. Assume that smaller X_j means that the sample is closer to the aim. For requirement j, the function

$$F_j(x) = \Pr\{X_j \le x\} \tag{5}$$

is the cumulative probability distribution function of X_j. Let

$$F_j(c_j) = p_0 = p^{1/s}. \tag{6}$$

The tolerance c_j of requirement j is the solution to Equation (6).

The sample fails in the j^{th} requirements if $X_j > c_j$. The sample fails the assessment if it fails at least one requirement.

Numerical Results

The interdependency of sampling rules and the three probabilities may be illustrated with numbers. The following sections describe two ways to illustrate the conformity assessment prediction. The first is to hold the passing probability of a job as a constant. The second is to hold the passing probability of a normative requirement as a constant.

Holding the Passing Probability of a Job as a Constant

Table 1 describes the numerical results for three types of probabilities, π, p and p_0, for two different sampling rules. The passing probability, π, is first chosen, and it is then possible to calculate the passing probability p_0 of each single sample using Equation (2). The passing probability of each requirement is then calculated using Equation (4).

Table 1. Sampling rules and three probabilities

π	7/10 sampling rule			14/20 sampling rule		
	p	p_0		p	p_0	
		$s = 4$	$s = 9$		$s = 4$	$s = 9$
0.20	0.5163	0.8477	0.9292	0.5816	0.8733	0.9416
0.25	0.5423	0.8581	0.9343	0.6000	0.8801	0.9448
0.30	0.5655	0.8672	0.9386	0.6164	0.8860	0.9476
0.35	0.5869	0.8753	0.9425	0.6314	0.8914	0.9502
0.40	0.6070	0.8827	0.9460	0.6455	0.8963	0.9525
0.45	0.6262	0.8896	0.9493	0.6589	0.9010	0.9547
0.50	0.6449	0.8961	0.9524	0.6720	0.9054	0.9568
0.55	0.6633	0.9025	0.9554	0.6850	0.9097	0.9588
0.60	0.6816	0.9086	0.9583	0.6979	0.9140	0.9608
0.65	0.7001	0.9147	0.9612	0.7111	0.9183	0.9628
0.68	0.7115	0.9184	0.9629	0.7192	0.9209	0.9640
0.70	0.7192	0.9209	0.9640	0.7247	0.9226	0.9648
0.75	0.7391	0.9272	0.9670	0.7390	0.9272	0.9670
0.80	0.7606	0.9339	0.9700	0.7546	0.9320	0.9692
0.85	0.7844	0.9411	0.9734	0.7722	0.9374	0.9717
0.90	0.8124	0.9494	0.9772	0.7933	0.9438	0.9746
0.95	0.8500	0.9602	0.9821	0.8227	0.9524	0.9785

If it is desirable to have 70% of jobs conform to requirements, then the result in the row with $\pi = 0.70$ in Table 1 will show the results for each probability. In the 7/10 sampling rule, the required passing probability of each sample is 0.7192. If there are 4 ($s = 4$) normative requirements for each sample to pass, the required passing probability of each requirement is 0.9209. Now if the number of requirements is raised to 9 ($s = 9$), the required passing probability of each requirement is 0.9640 in order to hold the passing probability π as a constant. Similar interpretation for these probabilities can be found in the 14/20 sampling rule.

In summary, Table 1 shows the interdependency of the passing probability of a job, the passing probability of a sample, and the sampling rules. From a macro perspective, if the passing probability of a job is treated as a constant, then the passing probability of a sample and its associated sampling rule are fixed. This, in turn, suggests that tolerances for each of the normative requirements must fulfill these conditions. However, printing standards and conformity assessment activities do not behave in this way, because the tolerances and the sampling rules are specified and the passing probabilities are unknown.

Holding the Passing Probability of a Normative Requirement as a Constant

Table 2 presents the numeric results in another way. The passing probability p_0 of each normative requirement is then chosen. In this case, it is assumed that each requirement has the same probability to conform to requirement, and that the 7/10 sampling rule is used in the assessment. The passing probability of each sample is therefore $p = p_0^s$. The passing probability of a job is calculated from Equation (1).

Table 2. Passing probabilities of a single sample and a job for 7/10 sampling rule given p_0

p_0	p		π	
	s = 4	s = 8	s = 4	s = 8
0.80	0.4096	0.1678	0.0622	0.0003
0.81	0.4305	0.1853	0.0810	0.0005
0.82	0.4521	0.2044	0.1045	0.0010
0.83	0.4746	0.2252	0.1333	0.0018
0.84	0.4979	0.2479	0.1684	0.0033
0.85	0.5220	0.2725	0.2104	0.0059
0.86	0.5470	0.2992	0.2597	0.0104
0.87	0.5729	0.3282	0.3168	0.0180
0.88	0.5997	0.3596	0.3815	0.0304
0.89	0.6274	0.3937	0.4532	0.0502
0.90	0.6561	0.4305	0.5304	0.0810
0.91	0.6857	0.4703	0.6113	0.1274
0.92	0.7164	0.5132	0.6928	0.1944
0.93	0.7481	0.5596	0.7713	0.2867
0.94	0.7807	0.6096	0.8428	0.4066
0.95	0.8145	0.6634	0.9033	0.5504

Two cases are considered in terms of the number of normative requirements in Table 2: s = 4 and s = 8 (twice the number of normative requirements of s = 4). For example, suppose the passing probability of each requirement is set at p_0 = 90%. If 4 requirements are used, and each sample needs to pass all 4 requirements to conform to requirements, the passing probability p of the sample is 65.61%, and the passing probability of a job is π = 53.04%. However, if the number of requirements is raised to 8, then the passing probability p of a sample is only 43.05%, and the passing probability π of a job is only 8.10%.

In Table 2, it is easily seen that the passing probabilities of a single sample and a job when $s = 8$ are dramatically smaller than their counterparts when $s = 4$. From a standard development point of view, it is important to keep the number of normative requirements to a vital few. If not, this will result in low passing probabilities and do a disservice to the industry.

Discussion

In this research, the interdependency between printing standards and conformity assessment was reviewed, along with the knowledge gap in understanding the factors that impact the passing probabilities of a job, sampling rules, and tolerances.

A conformity assessment prediction model was developed based on statistics and probability theory. Through this pursuit, the dynamics between the passing probability of a job and a sampling rule is better understood. The conformity assessment prediction model can also predict the tolerances of each normative requirement based on the passing probabilities of each sheet.

Determining the Tolerance of Each Normative Requirement

The PSO (Process Standards Offset) dataset, courtesy of Fogra, contains 185 printing jobs that pass its conformity requirements according to ISO 12647-2. Assuming 20% of the jobs submitted did not pass the conformity assessment, and were thus removed from the dataset, it is necessary that we modify the dataset by adding simulated data into the dataset to achieve a failure rate of 20%. This will allow the PSO dataset to be used to generate passing probabilities based on all jobs submitted. Appendix A is a detailed derivation of the dataset containing 370 jobs with a 20% failure rate.

In this dataset, there are four normative requirements in terms of ΔE^*_{ab} of C, M, Y, K solids. The tolerance of each normative requirement is 5 ΔE^*_{ab}. The right-continuous generalized inverse of the empirical distribution (Feng, Wang, & Tu, 2011) was used to find the tolerance from the empirical distribution. The result is shown in Table 3.

Table 3. Tolerance of ΔE^*_{ab} for each requirement in the PSO dataset

π	7/10 sampling rule				14/20 sampling rule			
	C	M	Y	K	C	M	Y	K
0.20	4.8814	3.8350	4.1804	4.1794	5.0961	4.0028	4.4656	4.3866
0.25	4.9729	3.9055	4.2885	4.2605	5.1382	4.0666	4.5418	4.4415
0.30	5.0430	3.9669	4.4095	4.3450	5.1812	4.1127	4.6124	4.5061
0.35	5.1145	4.0162	4.4895	4.4080	5.2209	4.1420	4.6732	4.5612
0.40	5.1614	4.0798	4.5713	4.4586	5.2534	4.1792	4.7347	4.6265
0.45	5.2069	4.1323	4.6598	4.5492	5.2968	4.2177	4.7818	4.6660
0.50	5.2508	4.1792	4.7347	4.6255	5.3398	4.2352	4.8430	4.7119
0.55	5.3162	4.2241	4.8053	4.6948	5.3924	4.2685	4.8858	4.7673
0.60	5.3749	4.2605	4.8748	4.7599	5.4335	4.3151	4.9177	4.7998
0.65	5.4452	4.3238	4.9269	4.8060	5.4828	4.3494	4.9826	4.8481
0.68	5.4864	4.3534	4.9867	4.8499	5.5286	4.4111	5.0363	4.8844
0.70	5.5286	4.4111	5.0363	4.8844	5.5382	4.4270	5.0537	4.9023
0.75	5.5981	4.4866	5.1213	4.9650	5.5981	4.4866	5.1213	4.9650
0.80	5.6852	4.5669	5.2148	5.0582	5.6768	4.5507	5.1942	5.0208
0.85	5.8023	4.6479	5.3145	5.1432	5.7487	4.6080	5.2572	5.1114
0.90	5.9432	4.7673	5.4868	5.3071	5.8343	4.6819	5.3937	5.2090
0.95	6.1041	4.9407	5.6567	5.5450	5.9715	4.8346	5.5278	5.3612

For each normative requirement, it is possible to estimate the empirical distribution. In Table 1, it can be seen that for a given passing probability of a job (for example π = 0.90), the passing probability of a single sample should be $\boldsymbol{p}$ = 0.8124 and the passing probability of each requirement is $\boldsymbol{p_0}$ = 0.9494. From the empirical distribution of each requirement, it can be seen that (1) the corresponding tolerance for C (cyan solid) requirement is 5.9432 ΔE^*_{ab}, and (2) the corresponding tolerance for M (magenta solid) requirement is 4.7673 ΔE^*_{ab}, etc. An interesting interpretation of such a finding is that (1) the cyan solid has a lower passing probability in the dataset studied, and (2) the cyan solid requires a larger tolerance (5.9432 ΔE^*_{ab}) than the magenta solid (4.7673 ΔE^*_{ab}) to achieve the same passing probability.

Summaries of Key Findings

This research emphasizes the importance of statistics and probability theory in standards development and conformity assessment. Due to the randomness of sampling, this research illustrated the impact of normative requirements, tolerances, and sampling rules on the passing probabilities of a sample and of a job.

Based on statistical reasoning, this research proposed a conformity assessment prediction model that illustrates the passing probabilities of all jobs as a function of sampling rules and the passing probabilities of a sample. The model can also predict the passing probabilities of a job as a function of the number of normative requirements. When applying real data to the model, it will calculate tolerances required for each normative requirement in order to yield a specified passing probability of a job.

This research is meaningful to the standards development community. When standards are being developed, it is important to keep in mind that (1) variation conformity assessment requires sampling (which is random in nature), and (2) the number of normative requirements, tolerances, and sampling rules can impact the passing probabilities of a job.

This research is equally meaningful to printers who are seeking printing certification. Although sampling is random, the passing probability of a job ultimately depends on the process calibration and the effectiveness of local process control.

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Appendix A: Dataset Description

The PSO (Process Standards Offset) dataset is a "filtered" dataset, i.e., it contains 185 printing jobs that pass its conformity requirements according to ISO 12647-2. The objective is to add simulated data into PSO dataset to achieve an "unfiltered" dataset with a failure rate of 20%. Below are the procedures used:

Step 1. Duplicate the dataset, so the new dataset has 370 jobs (original 185 plus the duplicated 185).

Step 2. Multiply the (ΔL, Δa, Δb) of the duplicated 185 jobs with a small constant value (gain), such as 1.1, to increase their ΔE^*_{ab} values. Then, calculate the total failure rate of all 370 jobs.

Step 3. Repeat Step 2 with a higher constant value until the total fail rate of all 370 jobs close to 20% (failure rate is 20.3% when gain = 1.16).

Step 4. Calculate the corresponding CIELAB values:

New_CIELAB = SCCA + Gain*(ΔL, Δa, Δb)

Note: SCCA (substrate-corrected colorimetric aim) is calculated per ISO 13655 as shown below:

$$X_2 = X_1(1 + C) - X_{min}C$$

$$C = \frac{X_{w2} - X_{w1}}{X_{w1} - X_{min}}$$

X_1 is one of the tristimulus values of Substrate_1 or target aim.
X_2 is one of the substrate-corrected tristimulus values based on Substrate_2.
C is a constant.
X_{w1} is one of the measured tristimulus values of Substrate_1.
X_{w2} is one of the measured tristimulus values of Substrate_2.
X_{min} is one of the minimum tristimulus values of TAC_{Max} printed on Substrate_1.

Step a) Obtain the CIELAB values of the paper white.

Step b) Calculate the SCCA for the CMYK solids from ISO aims:

Step c) Calculate the ΔE^*_{ab} values between the measurements and the SCCAs, and round the ΔE^*_{ab} values to the nearest integer.

Step d) When any of the solids in a sheet fail the tolerance (5 ΔE^*_{ab}), that sheet is marked as NG. For each job, if there are more than three sheets marked as NG, the conformance assessment result of that job is failure (using the 7/10 rule.) There are a total of 23 jobs in the PSO dataset that fail the conformance assessment, resulting in a fail rate of about 12% (23/185). Tables A1 and A2 show the "pass" and "fail" examples, respectively.

Table A1. Example of a passing job[1]

Job_ID	Sample_ID	Description	L	A	B	Aim_L	Aim_A	Aim_B	ΔE*ab	<=5ΔE
55	2	C100 solid	55.6	-38.4	-49.0	53.7	-35.9	-51.5	4	OK
55	2	M100 solid	46.1	74.3	-4.0	46.9	72.6	-4.5	2	OK
55	2	Y100 solid	86.8	-4.5	95.7	87.0	-4.4	89.8	6	NG
55	2	K100 solid	22.0	0.3	1.8	16.0	0.0	0.0	6	NG
55	3	C100 solid	56.0	-38.5	-48.7	53.7	-35.9	-51.5	4	OK
55	3	M100 solid	46.3	74.5	-4.0	46.9	72.6	-4.5	2	OK
55	3	Y100 solid	87.1	-4.5	95.5	87.0	-4.4	89.8	6	NG
55	3	K100 solid	16.7	0.3	1.8	16.0	0.0	0.0	2	OK
55	4	C100 solid	55.3	-38.4	-49.0	53.7	-35.9	-51.5	4	OK
55	4	M100 solid	46.1	74.2	-4.0	46.9	72.6	-4.5	2	OK
55	4	Y100 solid	86.4	-4.5	95.0	87.0	-4.4	89.8	5	OK
55	4	K100 solid	16.6	0.3	1.9	16.0	0.0	0.0	2	OK
55	5	C100 solid	55.3	-38.2	-48.9	53.7	-35.9	-51.5	4	OK
55	5	M100 solid	45.8	74.1	-4.0	46.9	72.6	-4.5	2	OK
55	5	Y100 solid	86.3	-4.5	95.3	87.0	-4.4	89.8	5	OK
55	5	K100 solid	16.6	0.3	1.8	16.0	0.0	0.0	2	OK
55	6	C100 solid	55.5	-38.4	-48.8	53.7	-35.9	-51.5	4	OK
55	6	M100 solid	45.5	74.8	-2.5	46.9	72.6	-4.5	3	OK
55	6	Y100 solid	86.7	-4.5	95.3	87.0	-4.4	89.8	5	OK
55	6	K100 solid	16.6	0.3	1.9	16.0	0.0	0.0	2	OK
55	7	C100 solid	55.3	-38.4	-48.9	53.7	-35.9	-51.5	4	OK
55	7	M100 solid	45.4	74.7	-2.6	46.9	72.6	-4.5	3	OK
55	7	Y100 solid	86.2	-4.5	94.9	87.0	-4.4	89.8	5	OK
55	7	K100 solid	16.3	0.3	2.0	16.0	0.0	0.0	2	OK
55	8	C100 solid	55.2	-38.3	-48.9	53.7	-35.9	-51.5	4	OK
55	8	M100 solid	45.4	74.5	-2.7	46.9	72.6	-4.5	3	OK
55	8	Y100 solid	86.2	-4.5	94.9	87.0	-4.4	89.8	5	OK
55	8	K100 solid	15.8	0.3	1.7	16.0	0.0	0.0	2	OK
55	9	C100 solid	55.5	-38.4	-48.9	53.7	-35.9	-51.5	4	OK
55	9	M100 solid	45.9	74.4	-3.6	46.9	72.6	-4.5	2	OK
55	9	Y100 solid	88.8	-4.5	95.7	87.0	-4.4	89.8	6	NG
55	9	K100 solid	16.6	0.3	1.6	16.0	0.0	0.0	2	OK
55	10	C100 solid	55.3	-38.3	-49.1	53.7	-35.9	-51.5	4	OK
55	10	M100 solid	45.8	74.4	-3.5	46.9	72.6	-4.5	2	OK
55	10	Y100 solid	86.5	-4.6	94.9	87.0	-4.4	89.8	5	OK
55	10	K100 solid	15.9	0.3	1.7	16.0	0.0	0.0	2	OK
55	11	C100 solid	55.5	-38.3	-48.8	53.7	-35.9	-51.5	4	OK
55	11	M100 solid	45.8	74.3	-3.7	46.9	72.6	-4.5	2	OK
55	11	Y100 solid	86.4	-4.7	94.7	87.0	-4.4	89.8	5	OK
55	11	K100 solid	15.9	0.3	1.8	16.0	0.0	0.0	2	OK

1 - In this case, there are three sheets, marked as Sample_ID 2, 3, and 9, fail the criteria. This job passes according to the 7/10 rule. (Note: Although there are a total of four NGs in the table, two NGs belong to the same sheet, Sample_ID 2.)

Table A2. Example of a failing job[2]

Job_ID	Sample_ID	Description	L	A	B	Aim_L	Aim_A	Aim_B	ΔE*ab	<=5ΔE
25	2	C100 solid	56.1	-34.1	-47.4	54.7	-36.4	-52.2	5	OK
25	2	M100 solid	47.4	71.6	-5.4	47.7	74.1	-4.5	3	OK
25	2	Y100 solid	87.7	-3.4	94.8	88.5	-4.2	91.4	4	OK
25	2	K100 solid	20.8	-0.7	0.6	16.0	0.0	0.0	5	OK
25	3	C100 solid	56.3	-34.4	-47.7	54.7	-36.4	-52.2	5	OK
25	3	M100 solid	47.5	72.0	-5.5	47.7	74.1	-4.5	2	OK
25	3	Y100 solid	87.8	-3.6	94.8	88.5	-4.2	91.4	3	OK
25	3	K100 solid	21.2	-0.7	0.6	16.0	0.0	0.0	5	OK
25	4	C100 solid	56.6	-34.7	-47.6	54.7	-36.4	-52.2	5	OK
25	4	M100 solid	46.9	72.6	-5.9	47.7	74.1	-4.5	2	OK
25	4	Y100 solid	87.2	-3.6	95.1	88.5	-4.2	91.4	4	OK
25	4	K100 solid	20.6	-0.8	0.7	16.0	0.0	0.0	5	OK
25	5	C100 solid	56.2	-34.3	-48.2	54.7	-36.4	-52.2	5	OK
25	5	M100 solid	47.7	72.0	-5.4	47.7	74.1	-4.5	2	OK
25	5	Y100 solid	88.2	-3.6	95.6	88.5	-4.2	91.4	4	OK
25	5	K100 solid	21.6	-0.7	0.6	16.0	0.0	0.0	6	NG
25	6	C100 solid	56.1	-34.3	-47.8	54.7	-36.4	-52.2	5	OK
25	6	M100 solid	46.9	72.7	-4.6	47.7	74.1	-4.5	2	OK
25	6	Y100 solid	88.0	-3.4	95.6	88.5	-4.2	91.4	4	OK
25	6	K100 solid	20.8	-0.7	0.5	16.0	0.0	0.0	5	OK
25	7	C100 solid	55.9	-34.4	-48.0	54.7	-36.4	-52.2	5	OK
25	7	M100 solid	47.4	72.0	-5.3	47.7	74.1	-4.5	2	OK
25	7	Y100 solid	87.9	-3.6	94.9	88.5	-4.2	91.4	4	OK
25	7	K100 solid	20.6	-0.7	0.5	16.0	0.0	0.0	5	OK
25	8	C100 solid	56.0	-34.2	-47.8	54.7	-36.4	-52.2	5	OK
25	8	M100 solid	47.2	72.4	-5.3	47.7	74.1	-4.5	2	OK
25	8	Y100 solid	87.8	-3.6	94.8	88.5	-4.2	91.4	4	OK
25	8	K100 solid	21.2	-0.7	0.6	16.0	0.0	0.0	5	OK
25	9	C100 solid	56.2	-34.3	-47.6	54.7	-36.4	-52.2	5	OK
25	9	M100 solid	47.5	71.6	-5.6	47.7	74.1	-4.5	3	OK
25	9	Y100 solid	87.7	-3.6	94.6	88.5	-4.2	91.4	3	OK
25	9	K100 solid	21.7	-0.6	0.6	16.0	0.0	0.0	6	NG
25	10	C100 solid	56.2	-34.4	-47.8	54.7	-36.4	-52.2	5	OK
25	10	M100 solid	47.3	72.2	-5.4	47.7	74.1	-4.5	2	OK
25	10	Y100 solid	87.9	-3.5	95.4	88.5	-4.2	91.4	4	OK
25	10	K100 solid	21.6	-0.7	0.7	16.0	0.0	0.0	6	NG
25	11	C100 solid	56.4	-34.4	-47.1	54.7	-36.4	-52.2	6	NG
25	11	M100 solid	47.3	71.5	-6.2	47.7	74.1	-4.5	3	OK
25	11	Y100 solid	87.3	-3.8	94.2	88.5	-4.2	91.4	3	OK
25	11	K100 solid	20.9	-0.7	0.8	16.0	0.0	0.0	5	OK

2 - In this case, there are four sheets, marked as Sample_ID 5, 9, 10, and 11, that fail the criteria. This job fails because more than three sheets failed the criteria.

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