AxF - Soft standardization of appearance in the supply chain

Gero Müller[1], Christopher Schwartz[1], Max Hermann[1] and Alexander Gress[1]

[1]X-Rite Inc., 4300 44th Street SE, Grand Rapids, MI 49512, USA

Abstract

Over the last ten years, X-Rite's Appearance Exchange Format (AxF) has been increasingly adopted across various industries for sharing digitized material appearances among departments, suppliers, and customers. Although not an official standard, AxF's neutrality (with regard to rendering applications) and the absence of a suitable industry standard have led many rendering applications to include support for the format. In particular, the AxF ecosystem supports the creation of truly trustworthy digital twins of real world materials by combining a well-defined and documented set of physically based material shading models with validation procedures to verify the shading models against calibrated measurement data. It also connects to existing and well-proven workflows based on established standards like color appearance models or gloss units.

Keywords

Appearance modeling, Digital twin, Standardization

1. Introduction

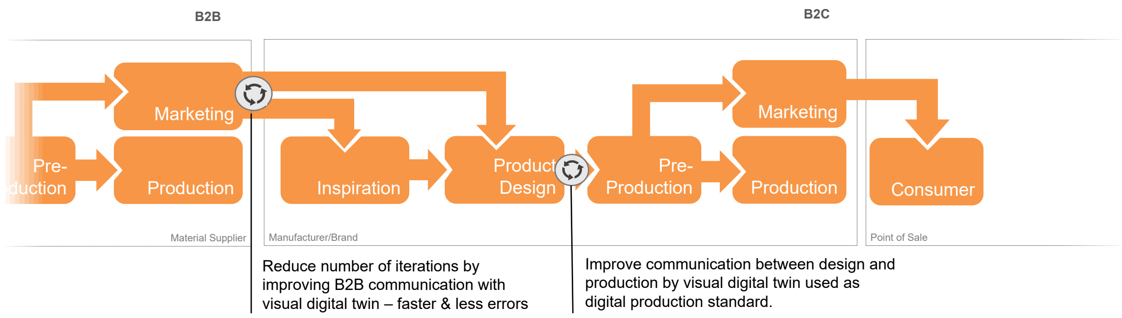

Figure 1: Examples for optimizing a global supply chain with regard to product color and appearance.

1.1. Supply Chain Optimization and Digital Twins

The pressures of a globalized economy are manifold: increased competition, shorter product life cycles, supply chain disruptions, and regulatory compliance requirements, to name a few. Equally numerous are the promises of digitalization: waste and cost reduction, increased efficiency, faster response times, quality improvements, etc. Consequently, more and more industries are introducing *digital twins* into their product development and production processes. The concept of the digital twin was first formally introduced by Michael Grieves (e.g., [1]), and has since become foundational alongside megatrends like digital manufacturing, Industry 4.0 and beyond. In this short paper, we focus on *visual* digital twins, which are digital representations of physical materials that can be used in design, simulation and quality control to benefit the entire supply chain by allowing efficient *supply chain optimization* (e.g., [2]) with regard to the communication of material appearance as illustrated in Figure 1.

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GMueller@xrite.com (G. Müller); ChristopherSchwartz@xrite.com (C. Schwartz); MaxHermann@xrite.com (M. Hermann); AGress@xrite.com (A. Gress)

1.2. Challenges in Digital Material Appearance Communication

The complexity and diversity of color and material appearances poses significant challenges in achieving a consistent and accurate digital representation of material appearance. This is especially true for industries such as automotive, consumer goods, fashion and architecture, where the visual quality and consistency of material appearance plays a crucial role in product design and customer satisfaction. Additionally, suppliers are located in different regions of the world, and the materials used often exhibit fundamentally different appearance characteristics.

Consequently, there currently exists a plethora of different approaches and tools tailored to the specific demands of each industry. We argue that many of these existing approaches fall short of facilitating the efficient communication of material appearance and can lead to misunderstandings and misinterpretations, which might result in costly mistakes and delays. Typical examples include the following:

- *Physical sample swatches* - are still the most common way to communicate material appearance, but they need to be produced, shipped and stored, which is time consuming and costly. Trying to imagine from a small swatch how the material will appear on the actual product is another challenge that can lead to unexpected outcomes. Furthermore, the samples are subject to aging and degradation, which can result in inconsistencies over time.
- *"Magic" numbers* - like SKUs, RGB values or gloss levels. This approach is widely used in industries where a huge number of material variations, like colorways for example, is offered and producing physical sample swatches for all variations is simply not feasible. However, single numbers are not sufficient to communicate the full appearance of a material. In practice, a lot of expertise is required to interpret the numbers correctly, and comparing "number systems" from different suppliers or manufacturers is often not possible.
- *Metaphorical language* - like "an earthy brown in the spirit of dried clay" is mainly used in design departments, but is highly subjective and can lead to misunderstandings and misinterpretations.
- *Uncalibrated images or videos* - can easily be misinterpreted and in general do not provide a true representation of the material's color and appearance.
- *Proprietary and artistic* PBR *material shaders* - most of the material models used in 3D rendering and visualization software packages are still crafted using uncalibrated methods like flatbed scanning and artistic ("by eye") tuning of appearance parameters like gloss, transparency or anisotropy. Despite recent initatives like OpenPBR [3] or glTF [4], these shaders cannot easily be shared and used in other applications because every 3D application still comes with its own proprietary PBR material shading model.

1.3. A Visual, Verifyable and Vendor-Neutral Digital Twin

We argue that many of the aforementioned problems can be mitigated by a *verifyable and vendor-neutral visual digital twin.* It needs to be *visual* to facilitate intuitive communication - number codes only understood by experts are not acceptable. *Verification* is necessary to build trust. Otherwise, decisions wouldn't be reliable and stakeholders would fallback to physical samples immediately. Last but not least, *vendor-neutrality* based on standardized data formats and protocols, is required to ensure interoperability and ease of use across different platforms and applications.

While to our knowledge there is no global standard for digital twins of material appearance, we would argue in the following that the Appearance Exchange Format (AxF) is a promising candidate, which fulfills many of the requirements for a visual digital twin. As a result, we see an increasing adoption of AxF in the industry, which could be understood as *soft standardization.*

One strength of AxF is that it builds on decades of experience gained in the management, measurement and communication of color, which is one of the most important visual properties of customer-facing materials.

Figure 2: Building on digital colors - using CxF as *visual* digital twin from design to production.

2. Digital Color Communication

In certain industries, the appearance of the final product is dominated and identified by *color*. An example is the printing industry, where the color of the printed material is usually its most important appearance aspect. Over the years, the industry developed a strong set of standards, devices, tools and protocols to facilitate the digital handling of colors and specify an almost complete visual digital twin of color:

- *Color naming systems* like RAL or Pantone provide a standardized way to identify and communicate colors and while originally based on physical samples, they are now also available digitally [5, 6].
- *Spectral color measurements* using spectrophotometers can be used to capture a highly accurate digital representation of colors, which can be stored in...
- ...*Standardized formats* like CxF [7] which allow for the exchange of color data between different applications.
- *Color appearance models* like CIELAB76 [8] and its successors provide a way to describe how color spectra are perceived by the human visual system under different viewing and lighting conditions. Maybe even more important, the Euclidean distance between two CIELAB76 colors (L_1^*, a_1^*, b_1^*) and (L_2^*, a_2^*, b_2^*) can be interpreted as perceptual difference between two colors:
$$\Delta E_{76} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \tag{1}$$
Perceptual color appearance metrics like ΔE_{76} (and its variants and successors) are essential for quality control and form the basis of...
- ...*Color management systems (CMS)* specify device profiles and color transformations between devices such that colors are reproduced correctly on different devices (like displays) and under different viewing conditions. A widely used standard are ICC profiles [9], which describe the color space of display devices and printers.

Based on these components, as illustrated in Figure 2, a comprehensive digital representation of color can be achieved, enabling seamless communication and collaboration across different stages of the product lifecycle.

3. Beyond Digital Colors

We sketched in the previous section that in some areas, like printing for example, a single dimension of appearance (like color) can be managed independently of others. *Gloss*, which can be measured by gloss meters and represented by perceptual gloss units, is another example where a set of standards and best practices does exist. However, only very few materials can faithfully be represented by a single appearance dimension like color or gloss.

In general, visual appearance emerges from the complex interaction between light and matter, and its different dimensions are highly interdependent. In fact, looking at gloss and color alone reveals that the perception of each dimension is highly dependent on the other (e.g. [10, 11]). Adding also spatial variation (texture) and transparency easily leads to the well known *curse of dimensionality* where capturing the variation along all dimensions quickly becomes impractical. Therefore, existing approaches developed for single appearance dimensions, such as color or gloss, are difficult to generalize and the development of a holistic yet practical representation of appearance remains a daunting challenge. As a result, there is a lack of practical solutions:

- *Lack of measurement devices* - while spectrophotometers or gloss meters are widely used for independent measurement of color and gloss, there exist only very few devices designed for measuring more than a single other aspect of material appearance.
- *Lack of standardization* - while there are some standards for color communication, like CxF, there are no widely accepted standards for most other aspects of material appearance. As a result, exchanging and comparing appearance data across different applications and devices is challenging.

While the lack of holistic and practical representations for appearance indicates that there is still a lot of fundamental research needed, the industry is pressured today and the need for the digitalization of the appearance supply chain is real. We therefore propose the Appearance Exchange Format (AxF) [12] which combines practical and proven experience in the communication of single appearance dimensions like color and gloss with the holistic appearance representations developed in the field of rendering and computer graphics.

4. Appearance Exchange Format (AxF)

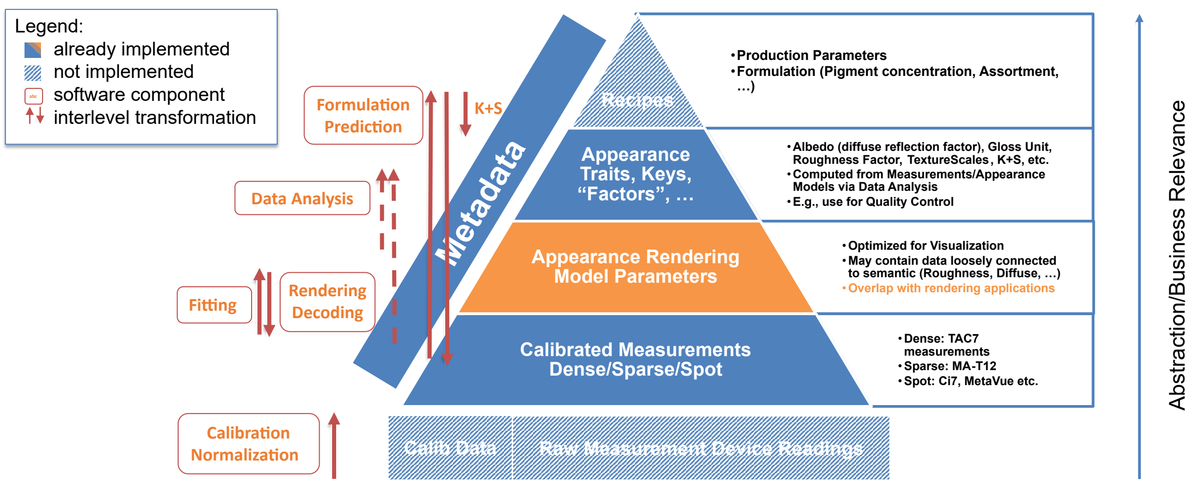

Figure 3: The AxF data pyramid. Representing different levels of abstraction of material appearance, from raw measurement data to high-level appearance traits.

In order to address the complexity of digital material appearance communication, the AxF formant has been designed to represent different aspects of material appearance at different levels of detail as illustrated in Figure 3.

4.1. Measurement Data

The foundation of the AxF data pyramid represents accurate appearance measurement data. Storing measurement data in AxF is essential to enable the verification of the visual digital twin for trust building.

Please note, that the lowest level is not yet implemented and used in practice. As of now, the calibration and normalization of raw sensor readings is usually done on the measurement device and only the resulting calibrated measurement data is stored in AxF. However, since data storage and transmission costs are continuously decreasing, it is expected that in the future raw measurement and calibration data will also be stored in AxF to allow full traceability.

In general the pyramid's foundation can be understood as an extended version of CxF, which cannot only represent colors and spectra but also images and other sensor readings like surface (height) profiles.

4.2. Appearance Representations and Shading Models

Figure 4: The main appearance rendering representations and their components as specified in AxF.

As mentioned in Section 3 the interaction of light and matter is a multi-dimensional process which can generally be modeled by a radiative transfer equation, with the classical rendering equation [13] as a special case:

$$L_o(\mathbf{x}, \omega_o) = L_e(\mathbf{x}, \omega_o) + \int_\Omega f_r(\mathbf{x}, \omega_i, \omega_o) L_i(\mathbf{x}, \omega_i)(\omega_i \cdot \mathbf{n})\, d\omega_i \tag{2}$$

where L_o is the outgoing radiance at point $\mathbf{x}$ in direction ω_o, L_e is the emitted radiance, L_i is the incoming radiance from direction ω_i, $\mathbf{n}$ is the surface normal, and f_r is the spatially varying bidirectional reflectance distribution function (SVBRDF) [14], which basically describes how the material reflects light.

Figure 4 summarizes the material appearance models specified in AxF. The majority are so-called (SV-)BRDF models like [15] and [16], which have been developed in the field of Computer Graphics to represent the appearance of spatially varying materials. These models can accurately represent dielectric and metallic materials with different types of gloss, transparency and also special appearance properties almost unique to fabrics, like the so-called Sheen effect resulting from the fabric's fibres [17]. Specific variants have been designed to represent metallic paints which exhibit effects like angular dependent color change or stochasticly glittering flakes (e.g., [18]).

Last but not least, AxF also provides models for homogenous volumetric materials like plastic that can be described by (spectral) scattering and absorption coefficients.

4.3. Appearance Traits and Abstractions

In order to facilitate the communication of material appearance on a higher level of abstraction, AxF also provides means to store *appearance traits* which are high-level abstractions of the material's appearance, such as a *dominant color*, gloss units, or profile roughness parameters. These traits allow to connect to workflows which still communicate based on single colors or gloss units. These traits can be derived from the appearance measurements and the shading model parameters using data analysis, but they can also be specified manually by a material expert or determined with devices like gloss meters or specialized laboratory equipment.

4.4. Recipes

The tip of the AxF pyramid is reserved for *recipes*, which are high-level descriptions of how to actually produce a material with a specific appearance. Recipes can include information about the material's composition, manufacturing process, and other relevant details. While not yet fully implemented, the connection with, e.g., paint formulation software is natural and enables the creation of a complete digital twin of the material, including its production process.

4.5. Metadata

Last but not least, AxF allows to store *customizable metadata* along all levels of detail.

5. AxF as Visual Digital Twin of Product Appearance

Deriving the parameters of the (SV-)BRDF models introduced in Section 4.2 from appearance measurements is a complex machine learning task, known as data *fitting*. The inverse process, which evaluates the model for a given set of parameters, is called *rendering* and allows to create a *visual* digital twin of the material's appearance. Given an accurate model of the original measurement device, this process can also be used for *verification*, i.e., to verify that the rendered appearance matches the original measurement data. The difference between the simulated and the measured appearance shall be quantified using perceptual appearance metrics that extend the well-known colour metrics introduced in Section 2. In many practical applications, though, this verification is still done by visual inspection, e.g., by comparing the rendered appearance with the original sample in a calibrated viewing booth as shown in Figure 5 (left).

Figure 5: AxF enabling visual digital twins of products' material appearance. Left: comparing digital twin and physical product in a calibrated viewing booth. Right: using digital material twins to achieve novel product visualizations (below).

5.1. Spectral Rendering

It is long known that tri-chromatic rendering is not sufficient to accurately simulate colors lit by spectrally different light sources (e.g. [19]). As illustrated in Figure 6, this is especially true for materials

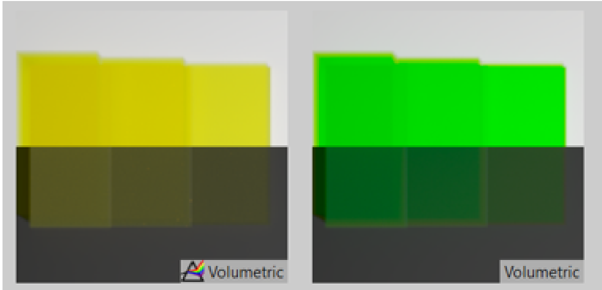

Figure 6: Left: spectral rendering of a yellow plastic as supported by AxF's spectral volumetric shading model, right: tri-chromatic rendering using RGB parameters derived from the same material.

with volumetric scattering, which exhibits a strongly non-linear behavior with respect to the incident light spectrum and the material's scattering properties. Nonetheless, spectral rendering is still not widely used in practice, but AxF provides a solid foundation for spectral rendering by allowing to specify colors spectrally. It can be expected that spectral rendering will become more common in the future, especially in industries where accurate color reproduction is critical.

6. Conclusion and Outlook

We have laid out that the Appearance Exchange Format (AxF) provides a solid foundation for the digital representation of material appearance, which can be used to create visual digital twins of materials. While AxF is not an official standard yet, its increasing adoption in diverse industries and at different parts of the supply chain (e.g., raw material suppliers, material suppliers, brands etc.) can be seen as a form of *soft standardization*. The adoption is mainly driven by the real need for the supply chain optimizations potential offered by visual digital twins. By combining accurate appearance measurements, physically based rendering models, and customizable metadata, AxF enables the creation of trustworthy digital twins that can be used across different applications and platforms.

From our experience one of the main missing ingredients required for the future progress of visual digital twins and their integration into the supply chain is a perceptual appearance metric which generalizes color metrics like ΔE_{76} (cf. Equation 1) to holistic appearance. Such a metric would allow to quantify the difference between an appearance standard and its rendered and physical versions for more efficient product development and manufacturing.

7. Declaration on Generative AI

During the preparation of this work, the author(s) used Github Copilot in order to: Drafting content and Grammar and spelling check. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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