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Effect of Window Glazing on Colour Quality of Transmitted Daylight

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Abstract

In this study, the colour quality of the daylight transmitted through different window glazing types is evaluated. The analysis considered four different types of window glazing: laminated, monolithic, coated and applied film glazing ranging in luminous transmittance from around 0.97 to <0.1. The spectral transmittance data of different window glazing types are taken from the International Glazing Data Base (IGDB), which is maintained by Lawrence Berkeley National Laboratories (LBNL). The study showed that the CIE CRI does not always seem to be the suitable method to predict the colour quality of daylight in building for particular situations. However, in the context of this study, the prediction of colour rendering properties of window glazing by other metrics such as Colour Quality Scale (version 9), Memory CRI, $R_{a,D65}$ (adjusted CRI metric with D65 as the reference illuminant) performed better. For most of the daylit situations inside the building, the chromaticity difference criterion was not met. Judging the colour quality of such situations requires different method.

1. Introduction

Window glazing technologies are developing and improving rapidly. This applies to coated, laminated, applied film and monolithic glazing systems. Advanced glazing systems have a great potential to save energy, costs from heating, air-conditioning and lighting, when correctly integrated in the building's façades to exploit the utilization of daylight. It plays a vital role in maintaining the visual and thermal comfort, view to outside, privacy and indoor air quality [1,2]. Window glazing enables the variation of the luminous transmittance, solar factor and spectrum of daylight within buildings. It has many benefits over conventional shading solutions such as less or unperceivable visual obstruction, lower maintenance requirements, the absence of movable parts and operation-related noises. Many studies have reported that window glazing types are capable of reducing energy consumption for cooling and lighting [3,6], increasing visual comfort [7,8] and glare protection [9,10]. However, the colour quality of daylight transmitted through smart glass is of serious concern.

For general lighting, the colour quality of a light source is a vital characteristic. To date, the colour quality of a light source does not have any rigorous definition. The word quality should be regarded as a general term. A dictionary defines the term quality as "the degree of excellence of something". In the case of the colour quality, it means the degree of colour excellence. Colour cannot be measured directly; it is always based on a comparison [11] which then allows the formulation of a colorimetric system such as the one consisting of the components hue, chroma and lightness. Similarly, it is not possible to measure the colour quality of light sources without a reference or comparison. However, various components/aspects of colour quality such as colour fidelity (colour rendering), colour discrimination, colour harmony, colour preference, visual clarity, colour acceptability, and brightness [12] can be determined. Even though there are different aspects of colour quality, currently, the light source is judged with the help of Commission International de l'Eclairage (CIE) Colour Rendering Index (CRI). CIE CRI is the only internationally recognized metric to measure and specify the colour rendering properties of a light source [13]. It is widely accepted and has been used for over 40 years. However, many deficiencies are associated with the CIE CRI [14–16], including the use of relatively low saturation test samples and the use of outdated colorimetric tools. The same CIE CRI has been used to judge the colour quality of the luminous environment resulting from different smart glazing systems in various studies [17–19].

Ghosh and Norton [17] examined the colour rendering properties of daylight transmitted through a suspended particle device smart glass. They found that the CIE CRI values and correlated colour temperature (CCT) of daylight transmitted

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through smart glass change with the change in smart glass transmittance. They also reported that suspended particle device glazing with transmittance above 14% is only able to produce CIE CRI value of above 80. Gunde et al. [18] compared the colour rendering properties of the daylight transmitted through gasochromic and electrochromic smart glazing types. They found that the appearances of coloured objects are highly distorted at higher coloration states of the glass windows. Lynn et al. [19] studied the colour rendering properties of transmitted light through the semi-transparent building-integrated photovoltaic (STPV) at the incident angles of 0.8° and 45°. They reported that the transmitted light renders the colours well in laboratory conditions if CIE CRI values of transmitted illuminant were above 90. All these studies use CIE CRI to compare the colour rendering properties of light transmitted through different smart glazing. However, none of these studies reported neither D_{uv} nor DC. D_{uv} is the Euclidean difference of chromaticity coordinate uv between the test light source to the closest point on the Planckian locus in the u', 2/3v' coordinate system, whereas DC is the Euclidean difference of chromaticity coordinate uv between the test light source and the reference illuminant. DC is calculated using equation Eq. (1). A D_{uv} value also provides direction of colour shift; a positive D_{uv} value indicates chromaticity coordinate of the light source is above the Planckian locus whereas a negative value indicates below the Planckian locus [20].

$$DC = \sqrt{(u_k - u_r)^2 + (v_k - v_r)^2} \tag{1}$$

where, u_k and v_k are the chromaticity coordinate of test source, and u_r and v_r are the chromaticity coordinate of reference illuminant.

According to CIE [13], the absolute value of DC shall be less than 0.0054 if possible "as a practical limit of difference". If the absolute DC value is greater than 0.0054, the resulting CIE CRI may not be accurate. For solid state lighting (SSL) products, the American National Standards Institute (ANSI) has defined the tolerances of D_{uv} to be from 0.000 ± 0.006 to 0.003 ± 0.006 for nominal CCT categories that lie between 2700 K to 6500 K (for details see [20]). However, there is no such tolerance limit defined for the daylight transmitted through different glazing types.

Moreover, the European standard EN 410:2011 [21] states that the colour rendering properties of glazing in transmission shall be expressed by the CIE CRI, however, the reference illuminant shall always be CIE standard illuminant D65. In other words, the light transmitted through the glazing needs to be compared to D65 rather than to the reference illuminant resulting from the CIE CRI method. In this study, the method with the fixed reference illuminance D65 is called $R_{a,D65}$.

In this research work, the colour quality of the daylight transmitted through different window glazing types are evaluated with respect to different colour quality criteria such as CIE CRI, $R_{a,D65}$, $R_{a,2012}$, D_{uv}, CCT, colour gamut area, and TM-30 [22].

2. Method

The spectral power distribution (SPD) of daylight transmitted through window glazing can be greatly affected by the spectral transmittance properties of the glazing. Next to the direct transmittance, there is a certain fraction of internal reflections occurring at the boundary layers between material and air as well as some absorbance and scattering. The internal reflections are typically in the order of 8% and may be reflected back out of the glazing system or undergo multiple internal reflections, as shown in Fig. 1.

When absorption and scattering is neglected, the resulting luminous transmittance for a surface luminous reflectance ρ is:

$$\tau = (1-\rho)^2 \cdot \sum_{n=0}^{\infty} \rho^{2n} = \frac{(1-\rho)^2}{1-\rho^2} \tag{2}$$

The naïve luminous transmittance only assumes the direct transmittance without inter reflections:

$$\tau_{naïve} = (1-\rho)^2 \tag{3}$$

The resulting error Err_τ is a function of ρ:

$$Err_\tau = \frac{\tau - \tau_{naïve}}{\tau} = \rho^2 \tag{4}$$

For an assumed surface reflection of $\rho = 0.08$, the error becomes 0.64%. Based on this, the resulting SPD of the transmitted daylight can calculated naïvely, i.e. by multiplying the SPD of daylight with the spectral transmittance of the glazing, without introducing a large error.

2.1. Window glazing transmittance

In this research, the four different types of window glazing are considered, namely; laminated, monolithic, coated and applied film glazing ranging in luminous transmittance from around 0.97 to < 0.1. These four types of window glazing cover a very wide range of glazing types. The spectral transmittance data of these window glazing are taken from international Glazing Data Base (IGDB) which is maintained by Lawrence Berkeley National Laboratories (LBNL). Each glazing type is identified by the NFRC_ID, the National Fenestration Rating Council Incorporated identification. It can be used to retrieve the product details from the Optics 6 [23] software by LBNL. The spectral transmittance curves of different window glazing types adopted in this study are shown in Fig. 2(a) (laminated), Fig. 2(b) (monolithic), Fig. 2(c)

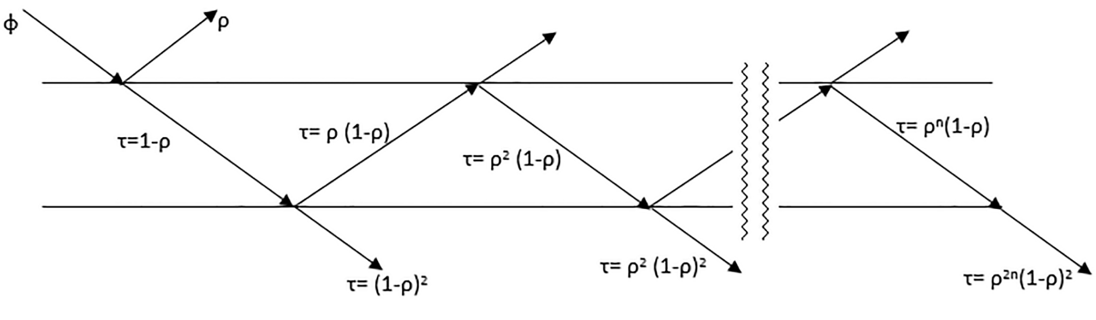
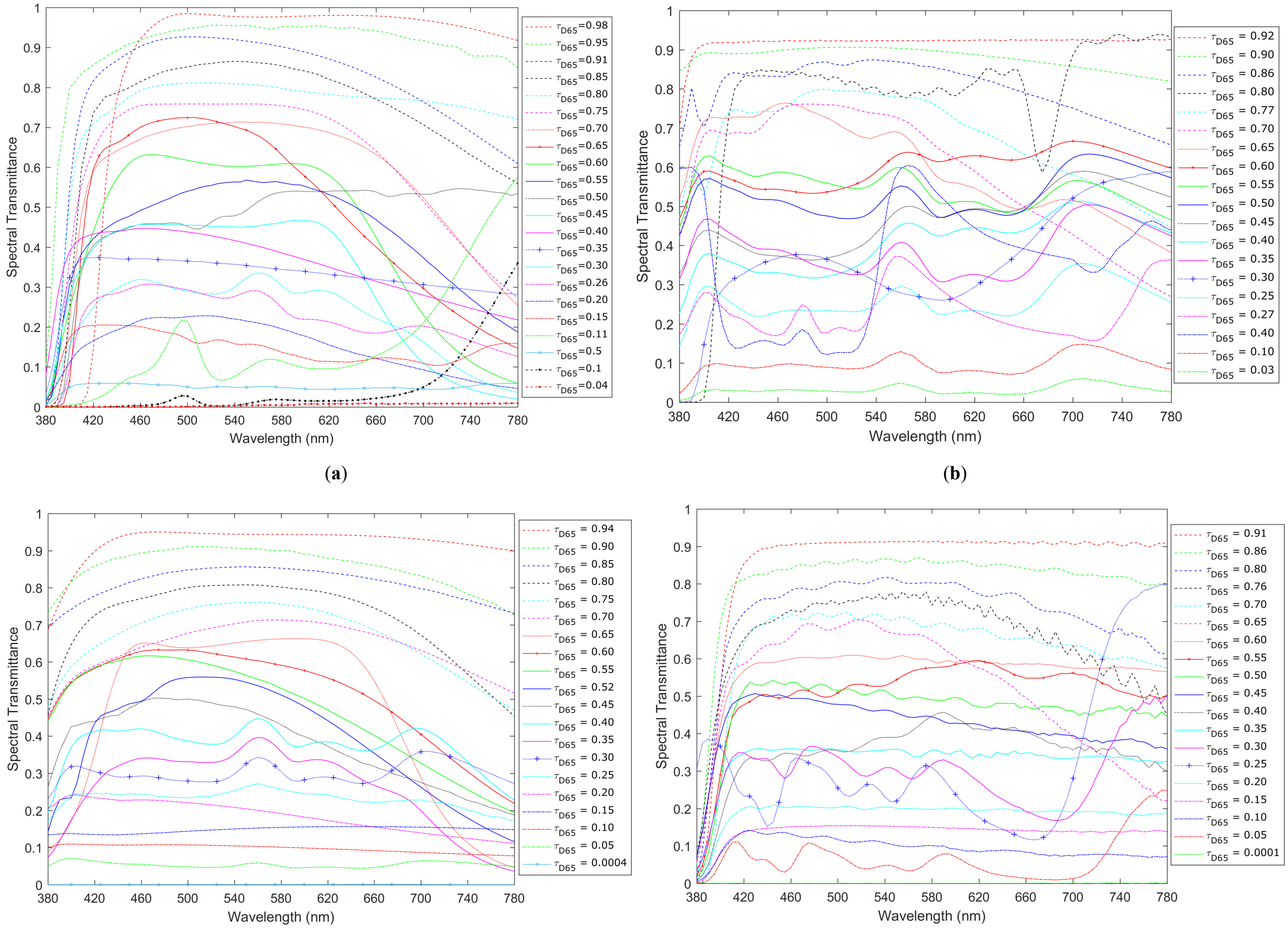


Fig. 1. The impact of internal reflections on the luminous transmittance.



(**a**) (**b**)

(**c**) (**d**)

Fig. 2. Spectral transmittance curves of (**a**) 22 different laminated, (**b**) 19 different monolithic, (**c**) 20 different coated, and (**d**) 19 different applied film glazing (adapted from [23]) in the visible range (380-780 nm) with different luminous transmittances shown in the legend.

(coated), and Fig. 2(d) (applied film). Laminated glazing consists of a layer of uncoated laminate glazing without structure reference and a layer of laminate glazing coated on backside with structure reference. Laminated glazing is made by permanently bonding two or more pieces of glass together with interlayers. Laminated glazing is considered as A grade safety glass. In IGDB, Monolithic glazing types are refer to float glass, arcylic glazing and suspended film without coating. The coated glazing is a glazing type with low e-coating with(out) substrate reference and the glass coated with suspended film without substrate reference. Coated glazing can be used to lower the solar heat gain by increasing the surface reflectivity of the coating. Generally, the used coatings are metallic or metal oxide layers. Applied films glazing is a glazing type with substrate reference. Applied film can reduce the heat loss if low e-coating is applied in innermost exposed layer of the film. It can block ultraviolet radiation (UV) very effectively, and it also reduce glare and eye strain.

The luminous transmittance of the glazing types for the standard illuminant D65 (τ_{D65}) is calculated using Eq. (5).

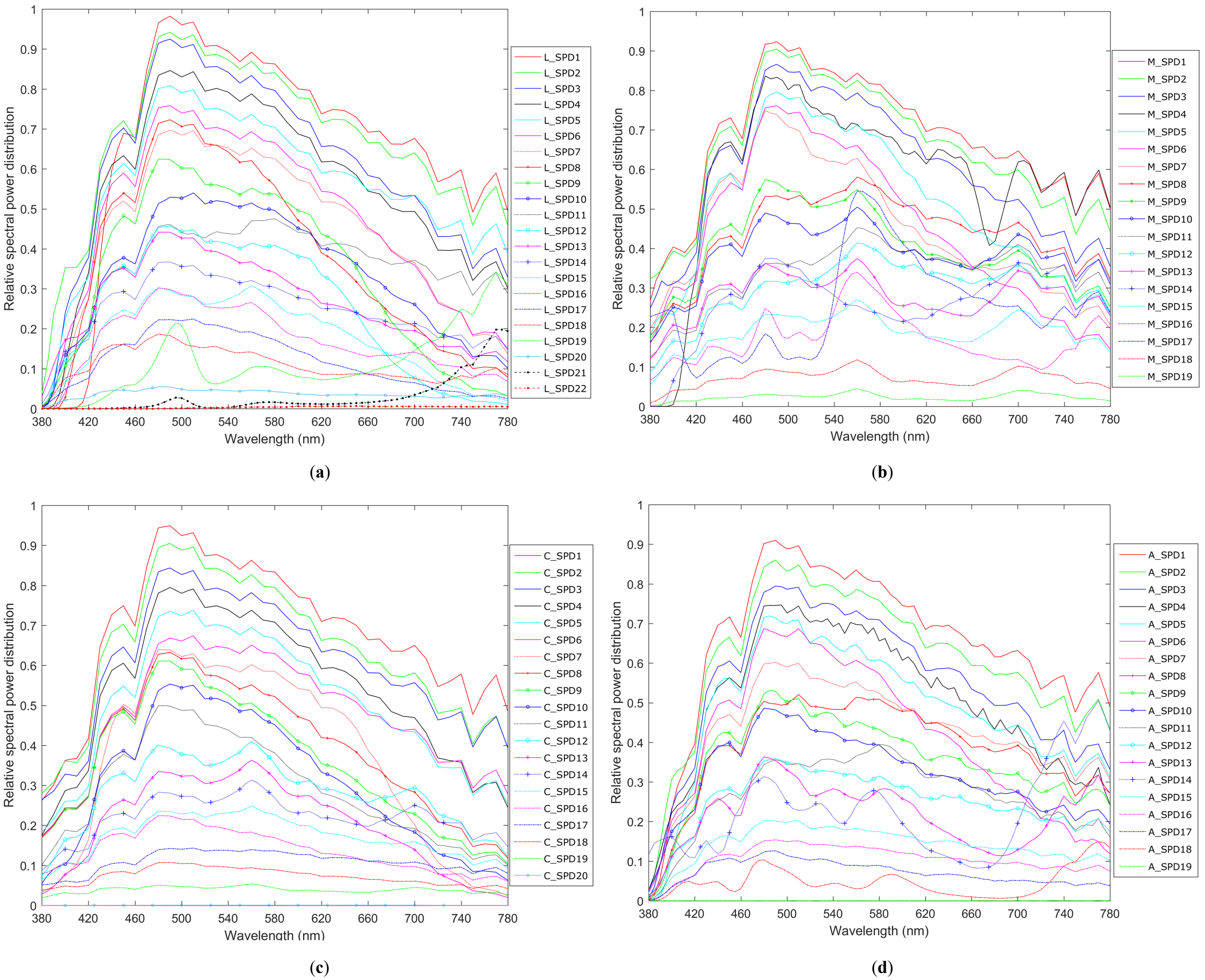
$$\tau_{D65} = \frac{\sum_{380}^{780} D_{65}(\lambda)V(\lambda)\tau(\lambda)\Delta(\lambda)}{\sum_{380}^{780} D_{65}(\lambda)V(\lambda)\Delta(\lambda)} \quad (5)$$

where, $D_{65}(\lambda)$ is the spectral power distribution of CIE standard illuminant D65, $V(\lambda)$ is the photopic spectral sensitivity function for human vision, $\tau(\lambda)$ is the spectral transmittance of the glazing.

2.2. Colour quality metrics

The colour quality of daylight transmitted through different window glazing types are evaluated with the help of eight different colour quality metrics. They are:

1. CIE colour rendering index (CRI) [13]
2. $R_{a,D65}$ (CRI taking constant reference illuminant i.e. CIE standard illuminant D65)
3. Colour quality Scale (CQS) [24]
4. Feeling of Contrast index (FCI) [25]
5. Memory colour rendering index (MCRI) [26–28]
6. Preference index of skin (PS) [29]
7. Illuminating Engineering society Method for evaluating light source colour rendition (IES TM-30-15) [22]
8. CRI2012 ($R_{a,2012}$)(Version n-CRI) [30]



(a) **(b)** **(c)** **(d)**

Fig. 3. Relative spectral power distribution of test illuminants (**a**) L_SPD1 to L_SPD22 (**b**) M_SPD1 to M_SPD19 (**c**) C_SPD1 to C_SPD20 (**d**) A_SPD1 to A_SPD19 determined using Eq. (5), the spectral transmittance of laminated glazing, monolithic glazing, coated glazing, and applied film glazing, respectively, and the standard illuminant D65.

2.2.1. CIE colour rendering index (CRI)

The CIE has defined colour rendering as "Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant" [13]. The CIE CRI is calculated using the CIE Test Sample method, in which the tristimulus values of 14 Munsell test colour samples are calculated using the SPD of the test light source and the reference light source. The reference illuminant needs to have the same CCT as the test light source: either a Planckian radiator (for CCT < 4999 K) or a daylight phase (for CCT ≥ 5000 K). The von Kries transformation is used to account for chromatic adaptation. The colour difference between the two light sources is calculated in the CIE 1964 U*V*W* colour space for each sample. Then, the special colour rendering index (R_i) is calculated for each sample using Eq. (6) by

$$R_i = 100 - 4.6 \cdot \Delta E_i \tag{6}$$

where, ΔE_i is the colour difference between the reference and test light source of ith colour sample.

The average of the first eight special colour rendering indices gives the general colour rendering index (R_a) or CIE CRI (for more detail see [13]).

2.2.2. $R_{a,D65}$

$R_{a,D65}$ is calculated in the same way as CIE CRI but keeping the reference illuminant constant to the CIE standard illuminant D65.

2.2.3. Colour quality scale

Colour quality scale (CQS) [24] is computed as CIE CRI with some modifications. Unlike in CIE CRI, it uses better chromatic adaptation model i.e., CMCCAT2000 and relatively uniform colour space i.e., CIELAB. In CQS version 9, 15 saturated test-colour samples were used. CQS has a range of 0-100. It uses the

Table 1. Luminous Transmittance (τ_{D65}), NFRC_ID and Colour characteristics of the daylight transmitted through laminated window glazing. (R9 is the CIE special colour rendering index of RED sample. CQS9 is Colour Quality Scale version 9. Rf and Rg respectively indicate IES TM-30 Fidelity Index and colour gamut.)

NFRC ID	τ_{D65}	Test illuminants	CCT	Duv	DC	CIE CRI	$R_{a,D65}$	R9	PS	CQS9	FCI	MCRI	Rf	Rg	$R_{a,2012}$
14773	.977	L_SPD1	5256	.0150	.0118	92	92	69	83	90	98	86	88	93	93
21458	.951	L_SPD2	5536	.0103	.0071	95	95	75	80	94	98	87	95	96	98
14746	.906	L_SPD3	5752	.0124	.0091	93	95	66	75	93	96	86	93	95	97
4416	.851	L_SPD4	5616	.0129	.0096	92	94	62	75	93	95	86	93	95	97
754	.801	L_SPD5	5650	.0116	.0083	94	95	72	78	94	97	87	94	96	98
18125	.750	L_SPD6	5745	.0122	.0090	92	95	60	74	93	95	86	93	95	97
20057	.704	L_SPD7	5567	.0128	.0095	92	94	61	76	93	96	86	93	95	97
2202	.654	L_SPD8	6627	.0221	.0189	85	84	18	54	86	83	79	87	90	91
18012	.600	L_SPD9	5820	.0132	.0099	91	93	47	71	91	92	85	90	93	94
25123	.552	L_SPD10	5433	.0150	.0118	90	93	49	73	91	94	85	92	93	96
3181	.503	L_SPD11	4966	.0060	.0060	94	90	75	85	94	101	89	94	96	97
25306	.450	L_SPD12	5793	.0123	.0090	90	93	38	68	90	91	85	91	94	94
18906	.400	L_SPD13	6544	.0148	.0116	91	91	55	66	92	90	84	92	94	96
16054	.351	L_SPD14	6046	.0109	.0077	94	96	72	74	94	95	87	95	96	98
18046	.300	L_SPD15	5837	.0121	.0088	89	92	46	69	90	92	85	91	94	95
6379	.263	L_SPD16	6868	.0194	.0162	86	84	36	57	88	85	81	89	92	94
8901	.203	L_SPD17	6625	.0247	.0215	83	82	10	51	84	82	77	85	89	90
16040	.149	L_SPD18	7964	.0154	.0123	90	84	56	57	92	86	83	92	94	96
16504	.106	L_SPD19	5455	.0212	.0179	80	80	82	87	71	86	75	71	83	77
16027	.049	L_SPD20	6490	.0083	.0051	95	95	79	73	95	95	88	96	97	99
16506	.012	L_SPD21	3341	.0071	.0071	72	57	80	100	60	82	67	56	69	61
21542	.004	L_SPD22	2339	.0137	.0137	80	11	55	86	16	108	8	38	38	39

$R_{a,D65}$, CQS9, MCRI, Rf, and $R_{a,2012}$ have an upper bound of 100 and a lower bound of 0, whereas PS, FCI, and Rg do not have an explicitly defined upper bound.

Table 2. Luminous Transmittance (τ_{D65}), NFRC_ID and Colour characteristics of the daylight transmitted through monolithic window glazing. (R9 is the CIE special colour rendering index of RED sample. CQS9 is Colour Quality Scale version 9. Rf and Rg respectively indicate IES TM-30 Fidelity Index and colour gamut.)

NFRC ID	τ_{D65}	Test illuminants	CCT	Duv	DC	CIE CRI	$R_{a,D65}$	R9	PS	CQS9	FCI	MCRI	Rf	Rg	$R_{a,2012}$
2600	.923	M_SPD1	5639	.009	.005	96	96	80	80	95	99	88	96	97	99
1609	.900	M_SPD2	5690	.010	.007	95	96	75	78	95	98	87	95	97	98
8202	.859	M_SPD3	5705	.012	.008	93	95	67	75	94	96	86	94	96	98
9025	.801	M_SPD4	5766	.008	.005	97	96	89	82	95	100	89	95	97	98
8223	.767	M_SPD5	5916	.015	.012	91	93	52	69	91	92	84	92	94	96
9875	.699	M_SPD6	6420	.019	.016	88	88	37	61	89	87	82	90	92	94
9862	.649	M_SPD7	6868	.016	.013	89	87	51	62	91	88	83	91	93	95
12294	.600	M_SPD8	5134	.007	.004	94	92	72	81	95	100	88	96	97	99
2921	.553	M_SPD9	6093	.012	.009	92	93	64	71	93	93	86	94	95	98
4126	.500	M_SPD10	5729	.008	.005	94	95	75	76	95	97	88	96	97	99
27033	.450	M_SPD11	4742	.005	.005	93	87	72	83	94	102	88	95	97	98
4113	.405	M_SPD12	4675	.006	.006	92	87	67	83	93	102	88	94	96	98
27024	.350	M_SPD13	6189	.009	.006	92	93	71	71	93	94	87	95	96	98
3505	.303	M_SPD14	6597	.010	.007	93	93	64	89	90	103	89	90	99	93
9891	.250	M_SPD15	5569	.014	.010	89	91	55	71	91	94	85	93	94	97
1228	.272	M_SPD16	4815	.015	.015	74	80	-18	55	76	83	76	80	86	86
1210	.397	M_SPD17	3258	.008	.008	65	64	-29	70	67	88	72	70	85	75
21041	.096	M_SPD18	5997	.018	.015	83	85	30	59	85	87	80	87	90	94
21042	.032	M_SPD19	6128	.023	.020	76	77	2	47	78	80	74	82	87	89

$R_{a,D65}$, CQS9, MCRI, Rf, and $R_{a,2012}$ have an upper bound of 100 and a lower bound of 0, whereas PS, FCI, and Rg do not have an explicitly defined upper bound.

root-mean-square to combine the colour difference. (for more detail see [24]).

2.2.4. Feeling of contrast index

Feeling of contrast index (FCI) [25] estimates the effect of visual clarity or feeling of contrast quantitatively for the test illuminant to the reference illuminant. It is computed as the ratio between the gamut area formed by a four-colour combination in CIELAB under the test light source at illuminance of 1000 lux and under a CIE standard illuminant D65 at illuminance of 1000 lux. The four colour combination consists of Red (5R4/12), Blue (4.5PB3.2/6), Yellow (5Y8.2/10) and Green (5.5G5/8). It is computed using the CIECAT02 chromatic adaptation and CIECAM02 colour appearance model. FCI does not have an explicitly defined scale.

Table 3. Luminous Transmittance (τ_{D65}), NFRC_ID and Colour characteristics of the daylight transmitted through coating window glazing. (R9 is the CIE special colour rendering index of RED sample. CQS9 is Colour Quality Scale version 9. Rf and Rg respectively indicate IES TM-30 Fidelity Index and colour gamut.)

NFRC ID	τ_{D65}	Test illuminants	CCT	Duv	DC	CIE CRI	$R_{a,D65}$	R9	PS	CQS9	FCI	MCRI	Rf	Rg	$R_{a,2012}$
14196	.944	C_SPD1	5647	.009	.006	96	96	79	80	95	98	88	95	97	98
21443	.900	C_SPD2	5691	.011	.007	94	96	72	77	94	97	87	95	96	98
17408	.850	C_SPD3	5578	.011	.007	94	95	72	78	94	97	87	95	96	98
6375	.800	C_SPD4	5607	.011	.008	94	95	68	77	94	97	87	94	96	98
11534	.750	C_SPD5	5532	.013	.009	93	94	62	76	93	96	86	94	95	97
1043	.701	C_SPD6	5353	.011	.008	93	94	66	78	94	98	87	94	95	98
14608	.651	C_SPD7	5456	.012	.009	92	94	58	78	92	96	86	91	94	95
16666	.600	C_SPD8	6067	.013	.010	92	94	59	71	92	93	85	93	95	96
12213	.549	C_SPD9	6635	.016	.013	90	89	47	63	91	89	83	91	93	95
8350	.521	C_SPD10	6107	.021	.018	86	88	27	60	87	87	80	88	91	93
21196	.450	C_SPD11	6606	.019	.016	88	87	37	60	89	87	81	89	92	94
1059	.400	C_SPD12	5849	.010	.007	92	94	66	73	93	95	87	94	96	98
26126	.350	C_SPD13	5617	.014	.011	88	91	40	69	89	91	84	90	93	95
16336	.300	C_SPD14	5604	.010	.007	91	93	62	73	93	95	86	94	95	98
21220	.250	C_SPD15	5598	.011	.008	91	94	56	72	93	95	86	94	95	97
17140	.199	C_SPD16	6725	.014	.011	91	90	56	65	92	90	84	92	95	96
4486	.151	C_SPD17	5246	.009	.006	95	93	75	81	95	100	88	95	96	99
14930	.102	C_SPD18	6033	.012	.008	94	95	69	73	94	95	86	94	96	98
27694	.050	C_SPD19	6097	.009	*.005*	92	93	68	71	93	94	87	94	96	98
4560	.0004	C_SPD20	4065	.018	.018	89	76	76	92	85	105	85	85	90	92

$R_{a,D65}$, CQS9, MCRI, Rf, and $R_{a,2012}$ have an upper bound of 100 and a lower bound of 0, whereas PS, FCI, and Rg do not have an explicitly defined upper bound.

Table 4. Luminous Transmittance (τ_{D65}), NFRC_ID and Colour characteristics of the daylight transmitted through applied film window glazing. (R9 is the CIE special colour rendering index of RED sample. CQS9 is Colour Quality Scale version 9. Rf and Rg respectively indicate IES TM-30 Fidelity Index and colour gamut.)

NFRC ID	τ_{D65}	Test illuminants	CCT	Duv	DC	CIE CRI	$R_{a,D65}$	R9	PS	CQS9	FCI	MCRI	Rf	Rg	$R_{a,2012}$
2783	.912	A_SPD1	5602	.009	.006	95	96	78	80	95	98	88	95	97	98
8611	.860	A_SPD2	5602	.010	.007	95	96	75	79	95	98	87	95	96	98
243	.801	A_SPD3	5622	.012	.008	94	95	68	77	94	97	87	94	96	98
6837	.756	A_SPD4	5602	.008	.009	92	94	62	75	93	95	86	93	95	97
2776	.699	A_SPD5	5816	.015	.008	94	96	71	76	94	96	87	94	96	97
19790	.654	A_SPD6	6126	.019	.014	89	90	44	65	90	90	83	90	93	95
8606	.600	A_SPD7	5691	.016	.007	95	96	76	78	95	98	87	95	96	98
19704	.552	A_SPD8	5126	.007	.004	95	92	73	83	95	100	88	95	97	98
4826	.500	A_SPD9	5994	.012	.007	95	96	76	76	95	96	87	95	97	98
4829	.451	A_SPD10	6259	.008	.007	95	95	74	73	94	95	87	95	96	98
19806	.401	A_SPD11	4888	.005	.008	92	91	58	80	92	99	87	93	95	96
8644	.351	A_SPD12	5767	.006	.006	95	96	78	78	95	98	88	95	97	98
19708	.300	A_SPD13	6248	.009	.008	90	91	37	65	89	88	84	90	93	94
2769	.251	A_SPD14	6316	.010	.016	78	79	-19	48	79	77	77	81	85	87
8643	.200	A_SPD15	5764	.014	.006	95	96	77	78	95	98	88	95	97	98
2728	.151	A_SPD16	5762	.015	.009	94	95	69	76	94	96	87	94	96	97
9606	.103	A_SPD17	7303	.008	.009	93	89	67	65	93	90	86	93	96	97
4844	.051	A_SPD18	7132	.018	.003	77	75	-14	56	75	72	79	75	87	79
274	.0001	A_SPD19	5242	.023	.049	71	72	23	52	60	80	52	71	77	79

$R_{a,D65}$, CQS9, MCRI, Rf, and $R_{a,2012}$ have an upper bound of 100 and a lower bound of 0, whereas PS, FCI, and Rg do not have an explicitly defined upper bound.

2.2.5. Memory colour rendering index

The memory colour rendering index (MCRI) is the index based on memory colours [26–28], which are associated with familiar objects in long term memory. MCI used ten familiar objects; a green apple, a banana, orange, dried lavender, a smurf figurine, strawberry yoghurt, a sliced cucumber, a cauliflower, Caucasian skin and grey sphere. Tristimulus values of these objects under D65 illumination are transformed using CIECAT02 and then transformed to the IPT colour space. It is a scale of 0-100. The geometric mean is used to obtain the general degree of memory colour similarity.

2.2.6. Preference index of skin

Preference index of skin (PS) [29] evaluates the colour-rendering properties of light sources based on preferred skin complexion. The tristimulus values of skin colour sample No. 15 defined by Japanese Industrial standard (JIS Z 8726) under test illuminant are transformed to corresponding colour under D65 illumination using CIE94 chromatic adaption and converted into CIE 1974 u’v’ chromaticity coordinates. Then, PS is computed by:

$$PS = 4 \times 5^{P} \tag{7}$$

where, $P = 446.846 + 202u' + 145u'^{2} + 8689u'^{3} - 4318v' - 8719u'v' - 1608u'^{2}v' + 12260v'^{2} + 18608u'v'^{2} - 12579v'^{3}$

2.2.7. Illuminating engineering society method for evaluating light source colour rendition (IES TM-30-15)

IES TM-30-15 is a two-measure system that evaluate the colour rendition properties of light sources. This method compares the test light source to a reference illuminant having same CCT as that of test light source with the help of colour fidelity (Rf) index and the colour gamut (Rg). The reference illuminant for light sources with CCT below 4500 K shall be a planckian radiator, from 4501 K to 5499 K a proportional blend of Planckian radiation and the CIE Daylight illuminant, and from 5500 K a phase of the CIE Daylight illuminant. The method also generates a colour vector graphic which helps to interpret the values of Rf and Rg. A colour vector graphic indicates average hue and chroma shift. The method utilizes 99 real and natural colour evaluation samples (CES) and CAM02-UCS uniform colour space. Both, Rf and Rg, use same set of colour samples and colour space. Rf is computed as the arithmetic mean of the colour difference of each CES under the test light source and reference. Rf is a scale of 0-100. Rg is a relative measure that compare the CES under the test and the reference illuminant. It is defined as the area enclosed by the polygon created by 16 hue angle bins. It computes an average gamut area for all CES. (for more detail see [22])

2.2.8. CRI2012 ($R_{a,2012}$)

The computational procedure of CRI2012 [30] is similar to CIE CRI with fundamental improvements. It uses the same criteria to select the reference illuminant as CIE CRI. It uses 17 mathematically derived colour samples and computations are performed using CIECAM02-UCS. The colour differences are combined and rescaled with a root mean square and a sigmoid function respectively. CRI2012 has a range of 0-100 (for more detail see [30]).

These eight colour quality metrics were calculated using the test illuminant – that is, the daylight that passes through the glazing. The test illuminant, $K_{TD}(\lambda)$ is determined by.

$$K_{TD}(\lambda) = \tau(\lambda) \cdot D_{65}(\lambda) \tag{8}$$

where, τ is the transmittance of glazing and D represents one of the spectral power distributions of CIE daylight illuminants. For this study, CIE standard illuminant D65 was considered.

3. Results

The calculated test illuminants using CIE standard illuminant D65 and the spectral transmittance functions of laminated glazing are shown in Figs. 2(a) and 3(a), respectively. The equivalent graphs for monolithic, coated and applied film window glazing types are respectively shown in Figs. 2(b) and 3(b), Figs. 2(c) and 2(c), and Figs. 2(d) and 3(d).

Table 1 shows that the CIE CRI values for the daylight transmitted through different window glazing types with different luminous transmittance values vary from 80 to 95, except for NFRC_ID 16506. The respective CCT values range from 2339 to 7964 K. If we only considered CIE CRI values, all the window glazing types would be characterized to have very good colour rendering properties. However, nearly all DC values are greater than 0.0054 (only exception: NFRC_ID 16027). The daylight transmitted through window glazing NFRC ID 21542 ($\tau_{D65} \approx 0.004$) has CIE CRI value of 80, whereas other metrics such as $R_{a,D65}$, CQS9 and MCRI values are much lower (< 17). It is worth to mention that the CQS9 and the MCRI both use 0 to 100 scale.

4. Discussion and conclusions

The results presented in Table 1 show that the D_{uv} values for daylight transmitted through different window glazing types have positive values, i.e. their chromaticity coordinates lie above the black body curve. Theoretically, this transmitted light will not be preferred by the user, as Dangol et al. [31] and Islam et al. [32] found that the observer preferred LED SPDs (spectral power distribution) with D_{uv} values of the light sources were either negative or close to the black body locus. D_{uv} values of light sources affect subjective preference. However, the influence of D_{uv} value on the colour rendering properties of light is not clear yet.

The DC values of daylight transmitted through laminated window glazing types are greater than 0.0054 (see Table 1). As mentioned above, the CIE CRI method may not work correctly any more for DC values greater than 0.0054. Therefore, by only looking at CIE CRI values, it is hard to judge the colour rendering properties of transmitted light through different glazing types. DC values of daylight transmitted through monolithic, coated and applied film window glazing are closer to the black body curve than the ones transmitted through laminated window glazing types. Ghosh and Norton [17] found that when the transmittance of the switchable window glazing increases, the CIE CRI also increases and the CCT decreases. However, this study does not support these

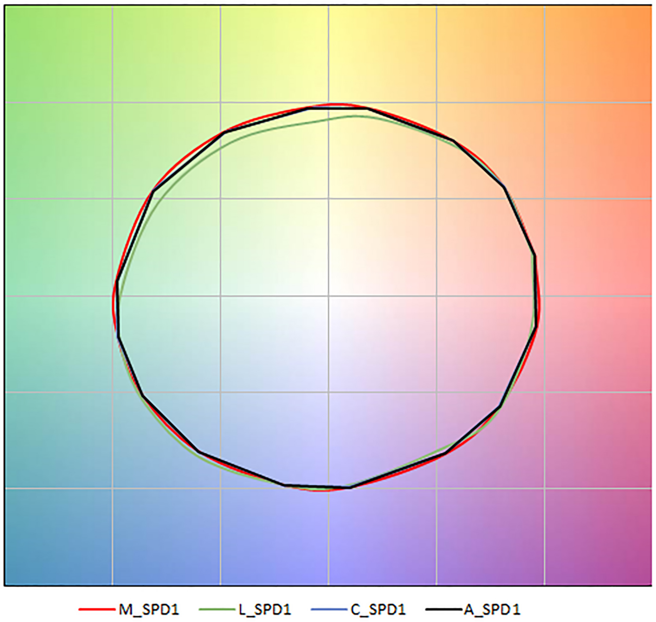


Fig. 4. Colour vector graphic of M_SPD1, L_SPD1, C_SPD1 and A_SPD1.

findings of Ghosh and Norton. Their conclusion may be based on observations collected from only one particular type of switchable window glazing. This study considered different types of window glazing and leads to different conclusions. The increment or decrement of CIE CRI and CCT values entirely depend upon the type of material used to manufacture the window glazing rather than the luminous transmittance value.

It is a well-known fact that the spectral transmittance of window glazing significantly affects the colour rendering properties of interior daylight. Almost all the window glazing types considered in this study fail to fulfil DC criterion to calculate CIE CRI. The daylight transmitted through laminated window glazing have higher D_{uv} or DC value than the daylight transmitted through others window glazing (considered in this study). Even the daylight transmitted through laminated window glazing with luminous transmittance of 97% i.e. L_SPD1 can not match DC criterion, whereas, the daylight transmitted through other window glazing with luminous transmittance greater than 90% have comparably better DC values. Also, the colour vector graphic (from TM-30-15 [22]) (Fig. 4) shows that the L_SPD1 cover relatively less gamut than other SPDs. It was also seen that laminated window glazing which has a luminous transmittance nearly equal to zero (L_SPD22, Table 1) has a CIE CRI value of 80. However, if we considered other metrics the values are much lower (see Table 1). This shows that the light transmitted through laminated window glazing has comparatively low colour quality. Therefore, special care should be taken while designing the laminated window glazing as light transmitted through it might not be preferred by the occupants. There is no doubt that the CIE CRI has many deficiencies and should not be considered as design aspect not even DC criterion is matched.

Moreover, from the studies [31–34], it was clear that R9 is not an indicator of subjective preference. However, the chroma and colourfulness values of object colours calculated using CAM02-UCS have a great influence on the subjective preferences, especially for the naturalness and colourfulness (subjective measure). The daylight transmitted through laminated glazing having luminous transmittance of 0.97 i.e. L_SPD1 have higher chroma and colourfulness values for Blue, Green and Yellow colour of Macbeth colour checker (MCC) than to L_SPD22. This a strong indication that even L_SPD22 have CIE CRI value of 80, it will not be preferred by the users. Under this test illuminant i.e.L_SPD22 (Table 1), the red objects will look very saturated and other colour objects such as blue, green or yellow will lose its actual colour property.

From Tables 1-4 and A5-A8, it is clear that when D_{uv} values of test illuminant are greater than +0.015, the chroma and colourfulness values of Red colour of MCC chart under that illuminant are lower, which means such illuminant can't preserve the colourfulness of red objects. Therefore, the higher value of CIE CRI or other metric does not by itself guarantee the good colour quality. If the D_{uv} or DC values of the illuminants are not within the limit, the prediction provided by the colour quality metric(s) may not be correct. CIE is currently working on developing new metrics within their Technical Committees TC1-91 and TC1-90. Such new metric(s) need to be applicable not only to the electric light sources but also to daylight in buildings with clear criterion than DC.

To gain a better understanding on the overall impact of glazing types on the quality of transmitted daylight, it is essential to perform user-acceptance studies using lighting booths or a real room installed with different window glazing systems. A good colour quality metric for daylight systems will provide a quantifiable measure to describe the added value of a daylight system with regards to excellent colour rendering. It would complete the list of characteristics addressing other aspects such as energy savings potential and limitation of glare. While measures for these characteristics need to be defined such that they are applicable to all systems, they also need to take the annual variation of daylight at a specific location into account. Climate-based daylight simulation would not only be applicable to determine the energy savings but also the overall colour quality aspect of a system. Such insights will avoid daylighting designs that do not perform well for a significant fraction of the year.

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Contributions

R. D., T. K. and A. R. conceived the study. R. D. and T. K. collected & analysed the data and interpreted the results. A. R. supervised computational analyses and advised on all aspects of the study. R. D. wrote the manuscript with contributions from all authors. All authors discussed the results and commented on the manuscript.

Appendix A

The values of chroma and colourfulness presented in Tables A5-A8 were calculated in CAM02UCS using the reflectance of four main colours (red, green, blue and yellow) of MCC chart and different test illuminants.

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Table A5. Values of chroma and colourfulness of Blue, Green, Red and Yellow colour of Macbeth colour checker (MCC) under different test illuminant (Fig. 2(a)) generated using different laminated window glazing types and CIE standard illuminant D65.

	Chroma				**Colourfulness**			
	Blue MCC	Green MCC	RED MCC	Yellow MCC	Blue MCC	Green MCC	RED MCC	Yellow MCC
L_SPD1	46.40	37.92	50.00	59.39	45.78	37.41	49.33	58.59
L_SPD2	46.69	39.84	49.78	61.05	46.06	39.31	49.11	60.23
L_SPD3	46.69	39.47	48.70	60.93	46.06	38.94	48.04	60.11
L_SPD4	46.65	39.37	48.61	60.84	46.03	38.84	47.96	60.02
L_SPD5	46.68	39.57	49.31	60.94	46.05	39.04	48.65	60.12
L_SPD6	46.75	39.38	48.22	61.01	46.12	38.85	47.57	60.19
L_SPD7	46.65	39.34	48.68	60.80	46.02	38.81	48.03	59.98
L_SPD8	46.56	38.12	43.63	60.45	45.93	37.61	43.04	59.64
L_SPD9	46.78	38.79	47.20	60.77	46.15	38.27	46.57	59.96
L_SPD10	46.50	39.03	48.00	60.49	45.87	38.50	47.35	59.68
L_SPD11	46.81	39.94	50.77	61.38	46.18	39.40	50.09	60.55
L_SPD12	46.83	39.19	46.56	61.13	46.20	38.67	45.94	60.30
L_SPD13	46.76	39.36	46.65	61.14	46.13	38.83	46.03	60.32
L_SPD14	46.81	39.92	48.60	61.37	46.18	39.39	47.95	60.54
L_SPD15	46.92	39.02	46.91	61.58	46.29	38.50	46.28	60.75
L_SPD16	46.70	38.33	44.68	60.96	46.08	37.82	44.08	60.14
L_SPD17	46.41	37.72	42.99	60.10	45.79	37.21	42.41	59.29
L_SPD18	46.98	39.48	44.99	61.77	46.35	38.95	44.38	60.94
L_SPD19	45.10	31.40	50.71	55.60	44.50	30.98	50.03	54.85
L_SPD20	47.07	40.12	48.24	62.13	46.43	39.58	47.60	61.29
L_SPD21	42.45	25.82	55.85	51.20	41.88	25.47	55.10	50.51
L_SPD22	21.27	32.16	56.87	20.57	20.99	31.73	56.11	20.30

Table A6. Values of chroma and colourfulness of Macbeth colour checker (Blue, Green, Red and Yellow) under different test illuminant (Fig. 2(b)) generated using different Monolithic window glazing types and CIE standard illuminant D65.

	Chroma				**Colourfulness**			
	Blue MCC	Green MCC	RED MCC	Yellow MCC	Blue MCC	Green MCC	RED MCC	Yellow MCC
M_SPD1	46.79	40.16	49.89	61.39	46.16	39.62	49.22	60.56
M_SPD2	46.76	40.00	49.45	61.30	46.13	39.46	48.78	60.47
M_SPD3	46.70	39.75	48.78	61.15	46.07	39.21	48.12	60.33
M_SPD4	46.89	40.02	50.53	61.20	46.26	39.48	49.85	60.37
M_SPD5	46.61	39.18	47.24	60.86	45.99	38.65	46.61	60.04
M_SPD6	46.57	38.65	45.40	60.71	45.95	38.13	44.78	59.89
M_SPD7	46.76	38.97	45.84	61.19	46.13	38.45	45.22	60.36
M_SPD8	46.81	40.37	50.22	61.79	46.18	39.83	49.54	60.96
M_SPD9	46.82	39.64	47.76	61.65	46.19	39.11	47.12	60.83
M_SPD10	46.93	40.23	49.14	62.15	46.30	39.69	48.48	61.31
M_SPD11	46.82	40.60	50.84	62.09	46.19	40.06	50.15	61.25
M_SPD12	46.82	40.50	50.61	62.13	46.19	39.96	49.93	61.30
M_SPD13	47.00	40.06	47.98	62.49	46.37	39.52	47.33	61.65
M_SPD14	46.70	39.95	53.04	60.54	46.08	39.41	52.33	59.73
M_SPD15	46.62	39.33	47.82	61.60	45.99	38.81	47.18	60.77
M_SPD16	46.59	37.64	43.10	62.31	45.97	37.13	42.52	61.48
M_SPD17	46.54	37.34	46.34	62.45	45.91	36.84	45.71	61.61
M_SPD18	46.66	38.33	45.00	61.85	46.03	37.81	44.40	61.02
M_SPD19	46.62	37.45	42.27	62.17	45.99	36.95	41.70	61.33

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Table A7. Values of chroma and colourfulness of Macbeth colour checker (Blue, Green, Red and Yellow) under different test illuminant (Fig. 2(c)) generated using different coated window glazing types and CIE standard illuminant D65.

	Chroma				**Colourfulness**			
	Blue MCC	Green MCC	RED MCC	Yellow MCC	Blue MCC	Green MCC	RED MCC	Yellow MCC
C_SPD1	46.78	40.01	49.82	61.29	46.15	39.47	49.15	60.46
C_SPD2	46.73	39.85	49.22	61.18	46.10	39.31	48.56	60.36
C_SPD3	46.69	39.79	49.43	61.09	46.06	39.25	48.77	60.27
C_SPD4	46.69	39.70	49.06	61.04	46.06	39.17	48.40	60.22
C_SPD5	46.61	39.45	48.78	60.85	45.99	38.92	48.12	60.03
C_SPD6	46.61	39.63	49.41	60.91	45.99	39.10	48.74	60.09
C_SPD7	46.74	38.87	48.74	60.59	46.11	38.34	48.09	59.78
C_SPD8	46.73	39.41	47.67	61.05	46.11	38.88	47.02	60.23
C_SPD9	46.74	39.14	45.92	61.06	46.11	38.62	45.30	60.24
C_SPD10	46.41	38.24	45.09	60.19	45.79	37.73	44.49	59.38
C_SPD11	46.59	38.60	45.18	60.66	45.96	38.08	44.57	59.85
C_SPD12	46.91	39.77	48.30	61.94	46.28	39.23	47.65	61.10
C_SPD13	46.76	38.83	46.83	61.28	46.13	38.31	46.20	60.46
C_SPD14	46.82	39.78	48.34	61.94	46.19	39.24	47.69	61.11
C_SPD15	46.83	39.87	47.98	61.76	46.20	39.33	47.34	60.93
C_SPD16	46.80	39.51	46.48	61.29	46.17	38.98	45.86	60.47
C_SPD17	46.66	40.05	50.31	61.14	46.04	39.51	49.63	60.32
C_SPD18	46.77	39.80	48.39	61.28	46.14	39.27	47.74	60.45
C_SPD19	47.03	40.33	47.94	62.66	46.40	39.79	47.29	61.81
C_SPD20	45.12	37.25	53.06	56.42	44.52	36.75	52.35	55.66

Table A8. Values of chroma and colourfulness of Macbeth colour checker (Blue, Green, Red and Yellow) under different test illuminant (Fig. 2(d)) generated using different applied film window glazing types and CIE standard illuminant D65.

	Chroma				**Colourfulness**			
	Blue MCC	Green MCC	RED MCC	Yellow MCC	Blue MCC	Green MCC	RED MCC	Yellow MCC
A_SPD1	46.78	39.97	49.84	61.24	46.15	39.44	49.17	60.42
A_SPD2	46.74	39.92	49.58	61.20	46.11	39.38	48.92	60.38
A_SPD3	46.70	39.68	49.00	61.05	46.07	39.14	48.34	60.23
A_SPD4	46.66	39.44	48.59	60.93	46.03	38.90	47.94	60.11
A_SPD5	46.76	39.67	48.93	61.10	46.13	39.14	48.27	60.28
A_SPD6	46.59	38.85	46.34	60.67	45.96	38.33	45.71	59.86
A_SPD7	46.75	39.89	49.53	61.18	46.12	39.36	48.86	60.36
A_SPD8	46.79	40.16	50.45	61.35	46.16	39.62	49.77	60.52
A_SPD9	46.86	39.97	49.01	61.39	46.23	39.43	48.35	60.57
A_SPD10	46.87	39.95	48.42	61.46	46.24	39.41	47.77	60.63
A_SPD11	46.73	39.76	49.52	61.28	46.10	39.22	48.85	60.45
A_SPD12	46.81	40.04	49.48	61.35	46.18	39.50	48.81	60.53
A_SPD13	46.77	38.59	45.61	61.02	46.14	38.07	45.00	60.20
A_SPD14	46.51	35.88	40.38	60.45	45.88	35.40	39.84	59.64
A_SPD15	46.82	40.02	49.48	61.36	46.19	39.48	48.82	60.53
A_SPD16	46.71	39.59	48.91	61.01	46.08	39.06	48.25	60.19
A_SPD17	47.00	39.82	46.59	61.64	46.37	39.28	45.96	60.81
A_SPD18	46.95	34.65	40.60	59.87	46.32	34.19	40.06	59.07
A_SPD19	40.71	34.38	45.01	50.78	40.16	33.92	44.41	50.09

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