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PROPERTIES AND PERFORMANCE INDICATORS OF VIRTUAL NATURAL LIGHTING SOLUTIONS

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ABSTRACT

Several studies have shown that in the built environment, natural light is highly preferred over electrical lighting for its positive effects on user satisfaction, health, and the potential on saving electrical energy. However, natural light is highly variable and limited by time and space. For example, significant fractions of working population in the world do their work during nighttime. Shift workers experience various discomfort issues, and increased long-term risk of some types of cancer due to a lack of synchronisation between the shift work schedule and the worker's light-dark cycle. Many buildings also have several inside spaces, while admission of natural light into work places is strongly suggested.

A possible way to overcome this problem is to develop and apply a Virtual Natural Lighting Solution (VNLS), which is a system that provides virtual natural light, with all of its qualities, which can be integrated inside new and/or existing buildings. One of the first challenges in developing such solutions is modelling their behaviour and predicting their impact on spatial use and performance of buildings. In order to model a VNLS, it is necessary to understand the relevant properties that the solution itself should have, as well as the relevant performance indicators which show how the solution affects performance of buildings where it is applied.

For the case of VNLS, the performance indicators of a building will be described in terms of visual comfort, space availability, thermal comfort, and energy consumption. A study is presented, based on literature reviews, in which the properties of currently known artificial windows and skylights are compared to that of real ones. The comparison shows that each existing solutions addresses a subset of all aspects required for a VNLS. The paper concludes by summarising the relevant properties and performance indicators with their expected range of values, which will be the input for developing a computational model of VNLS.

INTRODUCTION

Human beings have a strong preference for natural light. Several studies have shown that natural light is highly preferred over electrical lighting in the built environment for its positive effects on user satisfaction and health, (e.g., [1, 2]); as well as for the potential to save on electrical energy by reducing artificial lighting consumption by 50% to 80% (e.g., [3, 4]).

However, natural light is highly variable and limited in time and space. For example, significant fractions of the working population in the world do their work during nighttime [5, 6]. Night shift workers experience various discomfort issues and even increased long-term risk of some types of cancer due to a lack of synchronisation between the shift work schedule and the worker's light–dark cycle [7]. Furthermore, many office buildings have inside spaces which cannot be used as working space, because, for example according to Dutch regulations, admission of natural light into work places is strongly recommended.

A possible way to overcome those problems is to develop and apply a Virtual Natural Lighting Solution (VNLS), which is a system that ideally has the possibility to provide virtual natural lighting, with all of its qualities, including a realistic outside scene view, which can be applied and integrated inside new and/or existing buildings. One of the first challenges in developing such solutions is modelling their behaviour, and predicting their impact on building performance. Therefore, it is necessary to understand two main ideas: (1) describing the relevant properties that the solution itself should have and (2) describing the relevant performance indicators which show how the solution affects performance of buildings where the solution is applied. The objective of this paper is to classify the relevant properties and performance indicators and their expected range of values, in relation with VNLS. The properties are also used as mean for comparison, based on literature reviews, of the currently known artificial light windows and artificial view windows and skylights.

PROPERTIES REQUIREMENT OF VNLS

In the design stage of VNLS, it is important for product designers and developers to know what properties are required to present in the solution. The properties can be determined from that of the real natural light solution (i.e., window). Related to daylight and view, Boerstra [8] and Hellinga and Bruin-Hordijk [9] proposed quality levels for themes that influence visual comfort. Depth perception cues, i.e., movement parallax, occlusion, and blur, are also taken into account based on experimental research of IJsstelsteijn et al. [10]. Some of the quality levels are given in A, B, C, and D, which respectively represents the best, good, sufficient, and insufficient choice.

Table 1 summarises the requirement of VNLS properties as follows. The requirement can be taken as a general guideline, and continuous improvements are consequently needed.

Properties	Symbol	Unit	Possible range	Target range
Light quality				
Surface luminance	L_s	cd/m^2	0 ~ 8000	125 ~ 6000
Correlated colour temperature	CCT	K	2600 ~ 12000	2700 ~ 12000
Colour quality scale	CQS	-	0 ~ 100	82 ~ 98
Directionality	DIR	-	A, B, C, D	A or B
View quality				
Presence of green, sky, distant objects [9]	GSD	-	A, B, C, D	A or B
Information [8, 9]	INF	-	A, B, C, D	A or B
Complexity and coherence [8, 9]	ORG	-	A, B, C, D	A or B
Depth perception cues [10]	DPC	-	A, B, C, D	A or B

Table 1: Requirement of VNLS properties.

PERFORMANCE INDICATORS OF A BUILDING WITH VNLS

In order to model VNLS in a building, it is necessary to gain a complete understanding of all indicators which are relevant to describe the performance of the system. The term performance indicator (PI) will be used, which is a quantified expression of performance, having a range, definition, unit and a direction of increasing or decreasing value, in order to enable more structured negotiation between stakeholders, so that the design task can be expressed in the same set of criteria [11]. The indicators can be based on the principles of physics ("hard" indicators) or on environmental psychology ("soft" indicators) [12].

In the case of natural light, Dubois [13] suggested a number of simple PIs, i.e. workplane illuminance, illuminance uniformity, and luminance ratios. For design purposes, Reinhart et al. [14] suggested illuminance-based dynamic performance metrics such as daylight autonomy, continuous daylight autonomy, and useful daylight index. Pati et al. [12] suggested several PIs related to general work place lighting, which were classified in terms of energy efficacy, task lighting, view to outside, and visual comfort. Other aspects are also considered to describe indicators of the work environment, in terms of thermal comfort and energy.

For the case of a building with VNLS, the relevant PIs can be classified in the following terms.

1. Visual comfort: workplane or task illuminance, illuminance uniformity on the workplane, task-to-surround luminance ratios [14], task-to-wall luminance ratio, directional-to-diffuse luminance ratio [14], and unified glare rating [16].
2. Space availability: virtual criterion rating and space availability ratio (discussed below).
3. Thermal comfort: predicted mean vote, percentage people dissatisfied and summed weighted overheating hours [17].
4. Energy consumption: total annual electrical energy demand and total annual heating and cooling energy demands [8, 18].

PI	Symbol	Unit	Range	Target
Visual comfort				
Task illuminance	E_{task}	lx	0 ~ 25000	200 ~ 800
Illum. uniformity on workplane	U	-	0 ~ 1	≥ 0.6
Task-to-surround lum. ratio	$LR_{t\text{-}s}$	-	0 ~ ∞	1:20 ~ 20:1
Task-to-wall luminance ratio	$LR_{t\text{-}w}$	-	0 ~ ∞	10:1 ~ 40:1
Directional-to-diffuse lum. ratio	$LR_{d\text{-}d}$	-	0 ~ ∞	1.4:1 ~ 2.5:1
Unified glare rating	UGR	-	10 ~ 30	≤ 16
Space availability				
Virtual criterion rating	VCR	%	0 ~ 100	≥ 70
Space availability ratio	SAR	-	0 ~ ∞	*to be refined*
Thermal comfort				
Predicted mean vote	PMV	-	–3 ~ +3	–0.5 ~ +0.5
Predicted percentage of dissatisfied	PPD	%	0 ~ 100	5 ~ 10
Summed weighted overheating hours	WOH-∑	hrs	0 ~ 375	≤ 225
Energy consumption				
Total electrical energy demand	E_{ed}	kWh/m^2/yr	0 ~ 20	≤ 15
Total heating energy demand	E_{hd}	kWh/m^2/yr	50 ~ 500	≤ 325
Total cooling energy demand	E_{cd}	kWh/m^2/yr	50 ~ 250	≤ 60

Table 2: Performance indicators for a building with VNLS.

For visual comfort, an image-based lighting analysis procedure and tool called Virtual Lighting Laboratory (VLL) was introduced by Inanici and Navvab [15]. VLL is a computer environment where the user has been provided with matrices of per pixel data of luminance and illuminance values extracted from High Dynamic Range (HDR) images, processed through mathematical and statistical operations to perform more detail lighting analysis.

As suggested by Inanici [19], per pixel data analysis allows even more detailed study. For instance, it can be used to calculate a PI which quantifies the probability that a specific criterion (such as luminance, illuminance, and contrast) is met within a defined space or area [20]. The PI is called Virtual Criterion Rating (VCR), which is defined as:

$$\text{VCR} = \frac{\text{Number of pixels satisfying the criterion in a space / on a surface}}{\text{Total number of pixels}} \times 100\% \qquad (1)$$

As a guideline, it is suggested to study the task illuminance values to ensure that they are between 2/3 and 4/3 of the target values. It is suggested to aim for achieving the 2/3 to 4/3 range in 90 percent of the task locations [19].

Related to the VNLS application, the VCR can be applied to indicate how much additional space can be used for working (e.g. on paper or computer task), due to enhancement of the lighting and view quality, after installation of the VNLS in a given building space. The idea is to show the comparison between the VCR of the given space before and after the installation, in terms of task illuminance and surface luminance. Therefore, a new PI is proposed, namely Space Availability Ratio (SAR) in a given space at a given time, which is defined as:

$$\text{SAR} = \frac{\text{VCR in a space after the VNLS installation}}{\text{VCR in a space before the VNLS installation}} \tag{2}$$

PROPERTIES COMPARISON OF VNLS PRECURSORS

Several products have been developed to provide, or to mimic some aspects of real natural lighting solutions (e.g., windows and skylights). Based on their main function, the early attempts to approach VNLS (precursors) can be classified into two types: one that is dedicated mainly to provide "virtual" natural view (usually outdoor scenery); and one mainly to provide "virtual" natural light (for quality lighting or curing diseases).

Table 3 presents comparisons of some properties of some selected existing precursors of VNLS. The PIs presented in the Table 2 are not yet available to be compared for the precursors, since it requires a selected building case study followed by applications of modelling and simulation, which will be the next step to be taken.

Properties / **Features**	**Light quality**				**View quality**			
	L_s (cd/m^2)	**CCT (K)**	**CQS**	**DIR**	**GSD**	**INF**	**ORG**	**DPC**
Natural view								
Static, backlit transparent photos on lamp's surface	≤ 1200	2700 ~6500	64~80	C~D	A~C	B~D	A~C	B~C
Projection simulating sunlight and shadows	≤ 500	6500	64~80	A~C	B~C	D	C~D	C~D
Luminous / backlit translucent material	≤ 2500	2700 ~6500	82~92	A~D	C~D	D	D	C~D
Dynamic images on arrayed monitor	≤ 2500	2700 ~6500	82~92	D	A~B	B~D	A~C	B~C
Real-time dynamic images without parallax	≤ 1000	6500	82~92	D	A~B	A~B	A~B	B~C
Dynamic images with parallax	≤ 1000	6500	82~92	D	A~B	A~B	A~B	A~B
3D technique with parallax	≤ 1000	6500	82~92	D	A~B	A~B	A~B	A~B
Natural light								
No images, provide very bright light	≤ 8000	2700 ~6500	82~92	D	D	D	D	D
No images, provide enhanced blue light	≤ 250	6500	82~92	D	D	D	D	D

No images, provide gradual light levels	≤ 2500	2700 ~6500	82~92	D	D	D	D	D
LED light	≤ 50	2700	82~92	D	D	D	D	D
Fluorescent light	≤ 500	6500	64~80	C	D	D	D	D

Table 3: Comparison of properties of some VNLS precursors.

DISCUSSION

Based on the properties comparison in Table 3, it is clear that existing virtual natural view and light solutions have their own limitations. The virtual natural light solutions do not provide any viewed image, and therefore obtain the lowest score for the view quality properties. The virtual natural view solutions do provide viewed image with different levels of quality. The presence of green, sky, and distant object on the view can be provided either in static or dynamic solutions. For the information quality, the biggest challenge is to provide a constantly changing impression of the displayed information. The static solutions will mostly fail, since they only provide still image without any view variation. The dynamic solutions are also better in providing organisation (i.e., more detailed image) and depth perception cues.

The depth perception cues are determined by movement parallax, occlusion, and blur effects [10]. The movement parallax comes out as the hardest effect to imitate. The static solutions definitely cannot give any movement parallax; neither can the dynamic solutions which use normal large monitor display. The technique using head tracker for the viewer position and/or novel 3D television set should be applied to provide the effect, even though it seems to be still limited to one or two viewers.

For the lighting quality, it is very difficult to provide an artificial light source that can give 25000 lx of illuminance on workplane, without combining several sources. Most virtual windows or displays with light source can provide up to 5000 lx illuminance near the source, while most monitor display can provide up to 1000 lx. Virtual windows, which normally use lamps behind an image-covered translucent screen, generate light with CCT between 2700 and 6500 K. Typical monitor displays generate light with CCT of 6500 K.

Directionality of the incoming light (i.e., the balance between directional and diffuse component) is also an issue to be considered. Directionality can be evaluated by observing the light intensity polar diagram. Most virtual windows and large monitor displays will give almost only a diffuse light. Nevertheless, it is more meaningful to evaluate the effect on the luminous environment where the solution is placed, which will be discussed in later stages with the other performance indicators (PIs).

The PIs that belong to space availability, thermal comfort, and energy consumption are not yet available to be compared for the precursors, since they are very dependent on the building environment where the solutions are placed in. Therefore, to evaluate different PIs of the existing precursors and even non-existing solution, a building environment should be taken as case study. Again, comparisons are to be performed, with reference to the real windows. To this purpose, computational modeling and simulation will be used for steering the innovation process and early feasibility testing of the VNLS. Computational modeling is chosen since it comes with considerably lower required time and cost than real prototyping.

CONCLUSION

For the case of VNLS, the required properies can be given in terms of light and view quality. Performance indicators of a building with VNLS are currently classified in terms of: visual comfort (workplane or task illuminance, illuminance uniformity, task-to-surround luminance ratios, directional-to-diffuse luminance ratio, and unified glare rating); space availability (virtual criterion rating and space availability ratio); thermal comfort (predicted mean vote, percentage people dissatisfied, and summed weighted overheating hours); and energy consumption (total annual electrical energy demand and total annual heating and cooling energy demands). Comparisons of some properties of some selected existing precursors of VNLS are presented. The completeness of the PIs for VNLS cannot be fully tested yet, since a specific architectural conditions is required. For further research, a building environment will be defined as a case study, to completely evaluate PIs of the existing precursors, and compare to the real windows. Computational modeling and simulation will be used for this purpose.

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