A Framework to Support the Development of Manually Adjustable Light Shelves

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Abstract

This paper focuses on possibilites for simple, low-cost, manual adjustable lighshelves in comparison to static light shelves, which typically do not utilize their optimal potential of daylight harvesting due to lack of access to optmization procedures. A framework is presented on how to identify optima for seasonal manually adjustable light shelf configurations for a given context. After developing performance evaluation criteria for such light shelves, the study proceeds to identify a process to identify optimal parameters for selected cases, using a reduced set of light shelf variables, as a proof-of-concept. The optimization method is based on a seasonal assessment loop utilizing climate based daylight modeling, carried out in DIVA, controlled by Grasshopper with Daylight Autonomy (DA) as the performance metric. The study concludes with an outline of a framework for manually adjustable light shelf selection.

Introduction

The mere opening in a wall, or even the mouth of a cave for a cave dweller, can be considered a daylighting strategy. Since those historical beginnings, daylighting systems and components have come a long way to include sophisticated mechanisms that can ‘pipe’ daylight many stories underground or into the center of high-rise buildings with deep floor-plates. Such capabilities, however, have not come without a price. Active daylight harvesting strategies, currently available in the market, are often very costly to own and operate. They also tend to be complicated in their design and mechanism, making them difficult to fix, once they are broken. The high cost and imperfect performance of today’s active daylighting technologies have restricted their market acceptability (Leslie, Raghavan, Howlett, & Eaton, 2005). Passive daylighting systems such as light shelves are much more affordable as compared to any active system. Because of their inherent simplicity, passive systems tend to be less prone to failure over time. However, in harvesting daylight from a moving source, the sun, their static nature proves less efficient than active systems that often track the sun through computer controlled mechanisms – yielding higher output of daylight on a year-round basis.

Previous studies have identified promising potential of manually adjustable daylighting systems that capture the performance benefits of active systems while maintaining simplicity and affordability of manual systems (Javed & Reichard, 2014). The present research aims to assist in the development of a periodically manually adjustable light shelf system that is a hybrid of active and passive daylighting strategies. The assumption is that such a system will be able to capture some of the efficiency advantages of active systems without their higher initial cost or maintenance complexity during operation.

Motivation

Studies have shown many benefits of daylighting, including improved learning, increased productivity, and higher retail sales (HMG, 1999; Mullins, 1998). Despite this fact, one of the possible reasons why daylighting is not yet more widely incorporated into contemporary buildings is the lack of easily accessible design-tools that do not require significant computational resources. While highly automated and flexible light shelf systems can achieve great performance, they also create challenges in affordability and maintainability for many regions in the world. The authors see an opportunity in low cost manually adjustable light shelves that can increase daylight availability through seasonal changes as compared to simple static shelves as alternative.

To develop and utilize such systems, the authors propose a conceptualizing a framework to support tools for the development of manually adjustable light shelves. The goal of the proposed framework is to allow for a manufacturer to design applicable product solutions and once available for an architectural designer or building manager to identify optimal manually adjustable light shelf configurations from precalculated configurations for a given context.

A broadly conducted literature and market search has not found existance of any manually adjusted light shelves in the market at this time. It is hoped that this research can lead to their development in the future.

Background

Light shelf performance research can be tracked back to the seventies when, for example, Rosenfeld and Selkowitz published findings regarding the use of direct beam radiation from the sun for daylighting using reflective louvers (1977).

In the nineties we find experimental studies carried out at the Building Research Establishment (BRE) on daylighting systems such as prismatic glazing, prismatic film, mirrored louvers, and light shelves, which was summarized by Littlefair and others in a widely cited article (1994). The paper concluded that in the case of UK, the use of such devices lower daylighting levels at the back of a room when compared to unshaded windows. Thus, in such a context, these systems should primarily be used as shading devices, controlling glare and allowing more daylight than conventional blinds. In a later survey, Martin Kischkoweit-Lopin has classified daylighting systems into several broad categories (2002). The survey concludes that while the great number of daylighting systems allow for a wide range of application, they must be carefully matched to the building type and its lighting requirements. Otherwise, there could be unforeseen problems such as overheating and glare resulting in a failure of the system. Other experimental research on light shelves as daylighting delivery systems was conducted by Abdulmohsen to investigate their effectiveness in terms of redirecting direct and diffused solar radiation into the depth of interior spaces while reducing solar heat gain and glare (1995). Physical scale models were used within a daylighting laboratory to evaluate 15 options for shading and daylighting systems on the south façade of a model office space. In addition, a computer software model was developed to evaluate the energy performance of light shelves. Significant improvements in daylight penetration, glare reduction and energy savings were reported from this study with the use of appropriately designed light shelves.

Light shelf performance was also studied by Claros and Soler for Madrid using 1:10 scale models over a three year period using four types of materials and finishes for the light shelves and several color combinations for the interior surfaces (2002). Performance, defined as 'relative light shelf efficiency', was the 'ratio between illuminance inside the model equipped with the light shelf and a reference model without light shelf.' The mean hourly illuminance variation with the day of the year at a point 0.50m from a south facing side window was the data used for the study. Improved performance with certain light shelves and model combinations was found in the study. Even in cases where the illumination performance was not clearly superior the usefulness of a light shelf as a shading device was noted. The effect of solar elevation on the performance of light shelves was studied by Soler and Oteiza in the context of Madrid using 1:10 scale models (Soler & Oteiza, 1996). Claros and Soler used scale models again to compare the daylighting performance of light shelves and overhangs for a south facing opening in Madrid, Spain (2001). Results showed better performance of light shelves than overhangs for the same solar protection. The effect of external light shelves in the context of high-rise commercial developments in Hong Kong was studied by Close with the aim of transporting daylight deeper into the interiors (1996).

In one of the few publications on adjustable light shelves Raphael reported about research on active control of light shelves (2011). A methodology was presented, where the geometrical parameters of light shelves are modified in real time to minimize energy consumption in an office space. The control mechanism for this adaptable light shelf was treated as a global optimization problem with simulation results showing significant energy savings from active control.

In another more recent research, Rao reported on improved energy savings and occupant comfort from a building perimeter daylighting/shading system incorporating movable internal light shelves (2011). In his research an advanced façade system was investigated that had a fixed reflective overhang and a movable internal light shelf system in the upper window, while the view window was fitted with bottom-up roller shades. A classroom space in the Chicago, IL region was used as a test location for this simulation study. Significant improvement in daylight harvesting and lighting energy savings were reported from the use of the proposed setup.

No reference to 'manually adjustable' light shelf system was found in the literature, indicating an opportunity for research in this area – specifically in low income regions, which typically do not have access to high tech equipment and related maintenance needs.

Research Approach and Methodology

The purpose of this research is to formulate a proof-of-concept for the proposed framework to support the development of manually adjustable light shelves. Therefore, the study chose a limited set of light shelf variables to work with. The focus of this research is on manual adjustability of light shelves. This warrants a small set of defined positions in a pre-calibrated light shelf system that will be practical for a user or facility management personnel with simple tools to adjust. Considering the practicality of manual adjustability, this study chose a seasonal adjustment rate (four times a year) as the rate of change for the light shelves in this study.

Climate Based Daylight Modeling (CBDM) was used as the methodology of investigation for this study. The daylight simulation program 'DIVA-for-Rhino', together with the graphical programming software 'Grasshopper' was utilized to program preset scenarios to assess light shelf performance.

The hypothesis that daylighting performance in an open floor space setting can be enhanced through seasonally manually adjustable light shelves over static shelves was testes using simulation tools. Since no simple manually adjustable systems currently exist in the market that allow for different aspects of manipulation, an arbitrary set of parameters, specifically height, width, and tilt angle, were selected for this study as a proof of concept. Given the limitations of currently available tools some of the necessary individual simulation runs for this study took over a week to finish. Therefore, an algorithm and parameterization approach was utilized that allowed these tests to be run in series, without user intervention, over an extended period of time.

Daylight Autonomy (DA) was utilized as the overall performance metric. DA is defined as the 'percentage of the occupied hours of the year when a minimum illumination threshold is met by daylight alone' (Reinhart & Wienold, 2011). The authors divided the individual DA values generated from simulation tools into categories of 'well-lit', 'under-lit' and 'over-lit' to simplify the integrative process of comparative assessment of light shelf performance in a single metric.

Framework Outline

The proposed framework will be a selection tool to derive optimal light shelf configurations in a given context. A schematic diagram of the proposed framework is shown in Figure 1.

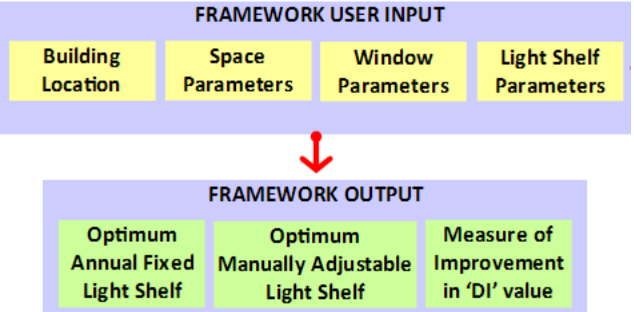

Figure 1: Diagram of framework for the development of manually adjustable light shelf system.

It consists of two major components: (1) user inputs and (2) the resulting output with various light shelf configuration and suggestions. Once the user has provided some basic information about the context of the light shelf the framework will come up with the optimal light shelf configuration using climate based daylighting simulation.

Simulation for Framework Development

For the convenience of this research a 30 x 30 ft. office space, with a ceiling height of 10.5 ft. was simulated for daylight performance. This space is considered to be at the ground floor level with no obstructions surrounding it. There is a large window band, with an integrated light shelf along one wall of this space. The window measures 30 ft. wide and 7 ft. high, with a sill height of 3 ft. The light shelf is adjusted through three parameters with four settings each resulting in 64 combinations (4x4x4=64):

- Rotation: 0, 15, 30 and 45-degree (exterior light shelf rotating upward from the horizontal)
- Depth: 2, 4, 6 and 8 ft. (equally divided between the interior and exterior side of the room)
- Height: 6, 7, 8 and 9 ft. from the finished floor

The room has a matrix of 121 (11x11) sensor nodes measuring illumination at the working height of 2.5 ft (Figure 2) above the finished floor..

Each simulation run, representing one set of light shelf parameters, therefore, generates a set of 121 DA values, one value at each node.

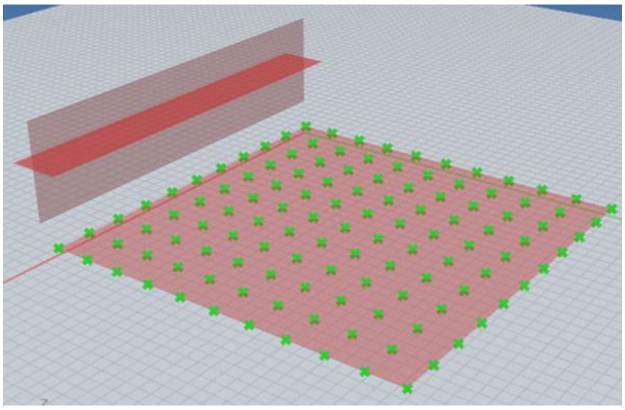

Figure 2: Matrix of sensor nodes shown without walls.

For the purpose of this research each of these 121 DA values were sorted into one of three categories:

- Under-lit: 0-49% DA
- Well-lit: 50-100% DA
- Over-lit: This is defined in DIVA as ten times (10x) the minimum threshold illumination (500 lux for this study) for 5% or more of the occupied hours and represented by negative numbers in the DIVA output (Figure 3). Nodes which are over-lit for less than 5% of the occupied hours are included in the well-lit category.

Under-lit Well-lit Over-lit

33	29	57	62	70	60	70	70	49	35	41
47	57	67	60	64	70	66	69	73	42	35
48	56	65	72	72	74	75	66	69	61	47
73	83	80	89	90	93	94	94	91	91	88
81	91	95	97	98	97	98	98	94	93	94
98	98	99	99	100	100	100	100	100	99	99
100	100	100	100	100	100	100	100	100	100	100
100	100	-6	-13	-18	-18	-17	-15	-9	-7	-5
-31	-48	-63	-72	-73	-74	-77	-74	-70	-56	-40
-42	-68	-78	-82	-83	-84	-83	-82	-84	-74	-54
-28	-42	-27	-27	-27	-27	-28	-28	-28	-38	-33

Figure 3: Matrix of DA numbers sorted into 3-groups

The categorization into these three groups allowed for a simple integration of DA performance across the 121 nodes by assessing the total number of acceptable versus unacceptable nodes, which in turn became the overall comparative single metric for the space.

For most interior spaces a higher number of well-lit and a correspondingly low number of under-lit and over-lit nodes is desirable. Thus, performance comparison of light shelves on the basis of well-lit areas of daylighting is considered a valid assumption for most cases.

For seasonally adjustable light shelves, the seasons were defined in such a way that the equinox and the solstices fall in the middle of these defined seasons, making the seasonal shift of the sun fall symmetrically around the middle of these seasonal definitions. The seasons as defined for this study are as follows:

- Winter: 06 November to 05 February (winter solstice, around 21st of Dec., falls in the middle),

- Spring: 06 February to 05 May (spring equinox, around 21st of March, falls in the middle),
- Summer: 06 May to 05 August (summer solstice, around 21st of June, falls in the middle), and
- Fall: 06 August to 05 November (fall equinox, around 21st of September, falls in the middle).

Calculation of Daylight Indices (DI)

Blacksburg, VA (37°N) was chosen as the first test location for the simulation runs associated with the framework development. Results from these simulations were exported to and analyzed in Excel, and are presented in Figure 4. Row1 lists the different light shelf configurations. In this study the naming of configurations follows a taxonomy defines as Rx-Hy-Dz, where x, y and z represents the values related to 'degree rotation', 'feet of hight' and 'feet of depth' of the light shelf. For example, the first light shelf, identified as R0-H6-D8 at the top of column-D represents a light shelf which is horizontal (rotation R = 0), at a hight of 6 ft. from the finished floor (hight H = 6) and has a depth of 8 ft (depth D = 8), divided equally between the interior and the exterior. The column under each light shelf represents their respective 121 raw daylight availability numbers in rows 2-122. Rows 124, 125 and 126 give the raw count of nodes in the under-lit, well-lit and over-lit categories respectively. While Rows 124-126 are number of nodes in the three categories out of a total of 121 nodes, Rows 132-134 are the same ratio of nodes in the three categories but converted to percentages of total nodes in the space (D132 = D124/121*100). This is done for standardization between DA matrix sizes should there be variation in matrix size within the same study. Next, Rows 132-134 were sorted left to right between columns D & BO (64 columns representing the 64 combinations of light shelf parameters) with the criteria of maximizing well-lit, minimizing over-lit and minimizing under-lit, in that order. The resulting 'well-lit' percentage was labeled as the daylight index (DI) of a space. This daylight index is not necessarily a new daylight performance metric but rather represents the single-value well-lit performance percentage of a space, which is more representative for comparision of configurations than the statistical average DA across all nodes. Nevertheless, Daylight Autonomy (DA) is the underlying performance matric used in this study to assess light shelves.

Performance Assessment of Light Shelves

The Daylight Index (DI), of row133 in Figure 4 shows the best theoretical light shelf combination of a fixed shelf to be R0-H6-D8 (row 1, column D), which is a horizontal light shelf with a height of six ft. and a depth of eight ft. A separate simulation was run for a 'no light shelf' scenario (R0-H6-D0) with results recorded in column BP. It can be observed that the optimum fixed light shelf, compared with the case of 'no light shelf' shows an improvement of 27 (66-39) DI points.

A similar procedure was adapted to investigate optimal, seasonally adjustable, light shelf configurations. For investigating the optimal seasonally adjustable light shelf, the performance of the previously found optimal fixed light shelf is utilized as the baseline. Static light shelves are fairly common and affordable in the market place and were thus used as a baseline. The premise of this research is to show that manual adjustability of light shelves to pre-determined set points by maintenance personnel or even occupants of buildings four times a year, can improve daylight availability. For this study, continuous and automatically controlled variability of light shelves was not considered as an alternative due to affordability and maintainabiliyt reasons in target regions and sectors of low-cost solutions.

Results from performance comparisons between an optimal fixed light shelf and a seasonally adjustable light

	A	B	C	D	E	F	G	H	I		BO	BP
1		R = Rotation	Light Shelf:	R0-H6-D8	R0-H7-D8	R15-H9-D8	R0-H8-D6	R0-H7-D6	R15-H9-D6	R1	R45-H6-D8	No LS_R0-H6-D0
2		H = Height	Node-1	70	67	40	17	68	39		18	43
3		D = Depth	Node-2	44	50	47	32	49	42		20	58
4			Node-3	56	50	53	36	48	66		32	62
121			Node-120	55	58	74	65	62	-5		-17	-27
122			Node-121	50	57	70	62	60	71		-14	-21
123												
124		Under-lit	Raw Number:	12	19	7	20	13	7		31	2
125		Well-lit	Raw Number:	80	72	68	64	62	61		21	47
126		Over-lit	Raw Number:	29	30	46	37	46	53		69	72
127			Total Nodes:	121	121	121	121	121	121		121	121
128												
129			Orig Seq:	49	53	62	41	37	46		52	
130			Annul Best:	1	2	3	4	5	6		64	
131			Light Shelf:	R0-H6-D8	R0-H7-D8	R15-H9-D8	R0-H8-D6	R0-H7-D6	R15-H9-D6		R45-H6-D8	No Light Shelf
132		Under-lit	Out of 100	10	16	6	17	11	6		26	2
133		Well-lit	Out of 100	66	60	56	53	51	50		17	39
134		Over-lit	Out of 100	24	25	38	31	38	44		57	60
135				100	100	100	100	100	100		100	100
136				Best	2nd	3rd	4th	5th	6th			

Fig 4: Performance comparison with Well-lit segment of the Daylight Autonomy (DA) numbers

shelf for Blacksburg, VA, for all four orientations are shown in Figure 5.

Table 1: Performance comparison between Optimal Fixed Light Shelf and Seasonally Adjustable Light Shelf for Blacksburg, VA.

Orient.	Seasons	Best Fixed (DI)	Best Adjust. (DI)	Change (DI)	Best Fixed Light Shelf	Best Adjustable Light Shelf
SOUTH	Winter	35	45	10	R0-H6-D8	R15-H9-D8
	Spring	75	75	0	R0-H6-D8	R0-H6-D8
	Summer	93	96	2	R0-H6-D8	R0-H6-D8
	Fall	76	76	0	R0-H6-D8	R0-H6-D8
EAST	Winter	20	36	17	R15-H9-D8	R15-H6-D8
	Spring	36	40	5	R15-H9-D8	R15-H8-D8
	Summer	51	51	0	R15-H9-D8	R15-H9-D8
	Fall	36	40	5	R15-H9-D8	R0-H7-D2
NORTH	Winter	51	57	6	R15-H7-D2	R30-H9-D2
	Spring	69	69	0	R15-H7-D2	R15-H7-D2
	Summer	79	83	5	R15-H7-D2	R15-H8-D2
	Fall	69	69	0	R15-H7-D2	R15-H7-D2
WEST	Winter	17	21	4	R0-H7-D2	R30-H7-D4
	Spring	17	23	6	R0-H7-D2	R30-H7-D8
	Summer	34	54	20	R0-H7-D2	R15-H9-D8
	Fall	22	31	9	R0-H7-D2	R15-H9-D6

Table-1 lists the specific light shelf configurations for the respective simulations. It becomes evident that seasonally adjustable light shelves will improve performance over optimally fixed ones, for most orientations and seasons (column with ‘change DI’). The spring and fall in the north and south orientations and summer in the east orientation are the (less significant) exceptions in this case.

Framework Development

The framework developed for this research is a proof-of-concept for an envisioned selection tool. The research has not progressed to the stage of development of such a tool but rather has set the foundation for its development. A schematic diagram of the front-end input masks of the proposed framework and respective user interface elements is shown in Figure 6.

A possible scenerio for the working of the proposed framework may go as follows: the framework allows users to input some basic values related to the context of their light shelf configuration and scenario. Based on these inputs it then calculates variations of configurations and suggests the possible optimum light shelf configurations for both an annually fixed and a seasonally adjustable version. For easier comparison of individual solutions it also provides a numeric indication of context specific light shelf performance in the form of Daylight Index (DI) values. Based on the selection of the building’s location the system accesses the Typical Meteorological Year (TMY) climate file for the location to conduct a climate based daylight performance evaluation of all relevant light shelf configurations. This Climate Based Daylight Modeling (CBDM) forms the back-end of the framework. It consists of a DIVA and Grasshopper based simulation loop (Figure 7) where output is subsequently post-processed in Excel to derive performance values for a given set of light shelf variables.

Because of the ‘manual adjustability’ focus of this study, the choice of variables that can be processed as input into the framework will consequently be limited. Users will have the option to input light shelf variables pertaining to a single light shelf or a limited range of variables

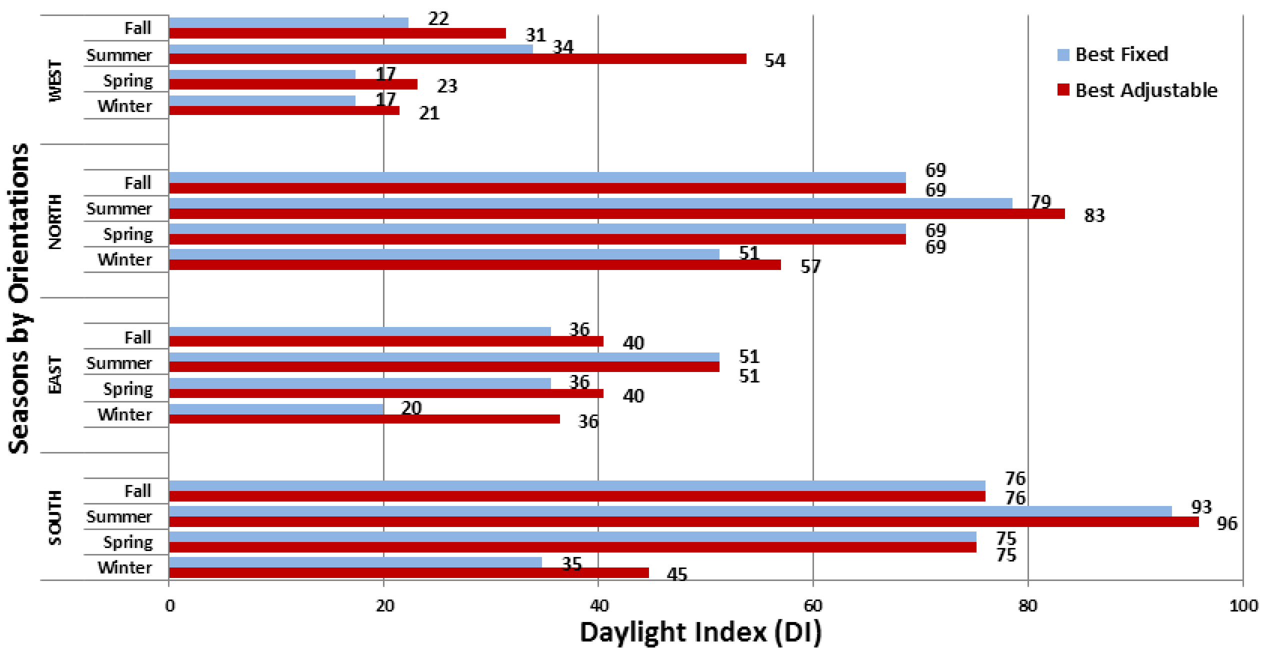

Figure 5: Performance comparison between fixed and seasonally adjustable light shelf

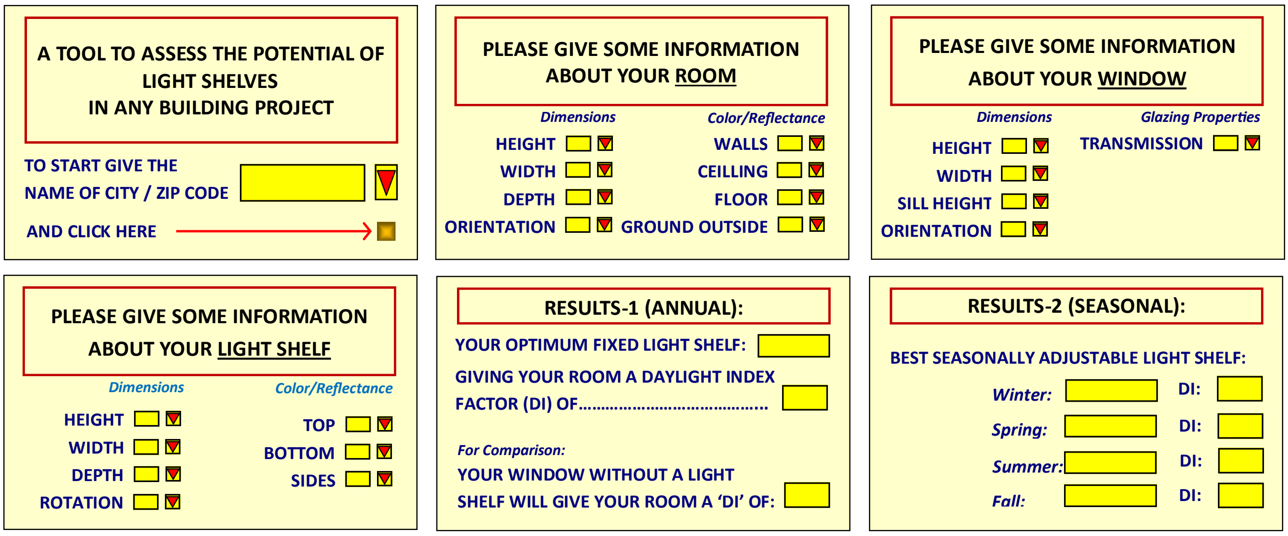

Figure 6: Conceptual layout of the front-end of the proposed framework for manually adjustable light shelves

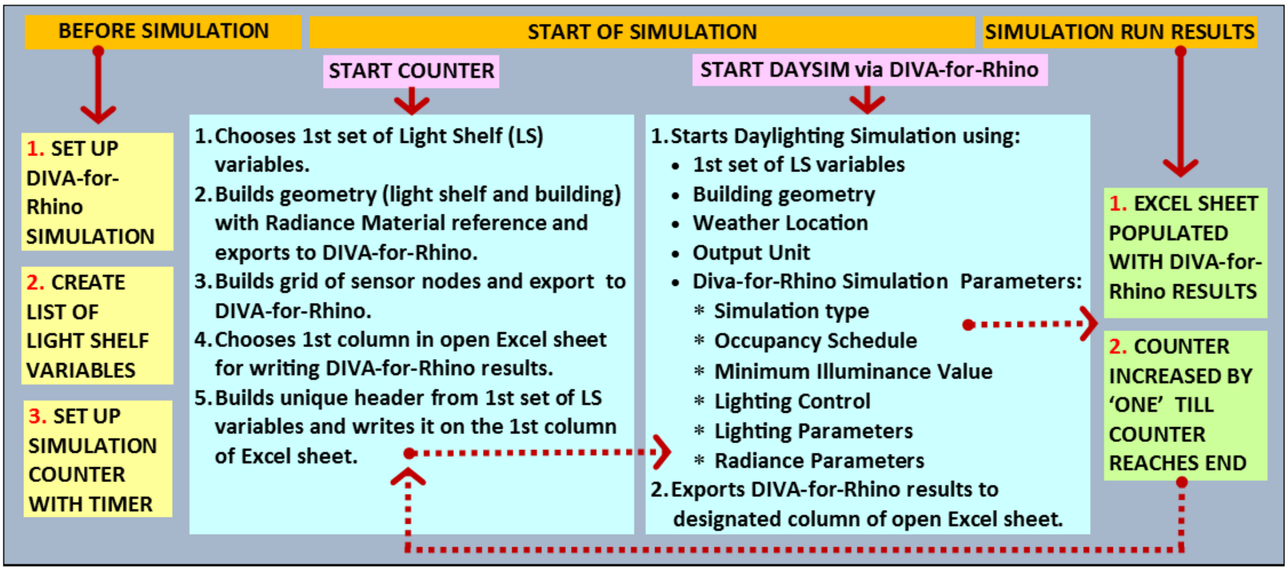

Figure 7: Diagram of the back-end of the framework for a manually adjustable light shelf system

pertaining to several light shelf options. In the first case the framework will report the performance of a single light shelf while in case of the second, results from a range of light shelf configurations will be presented, where the framework identifies the best solution in terms of DI values. This study restricts itself to only one light shelf per opening rather than an array of multiple light shelves stacked on top of each other in a single opening.

Limitations

In presenting a proof-of-concept the present study has looked at light shelf performance from the interior illumination point of view only. Other important issues that need to be addressed, before the viability of manually adjustable light shelf systems can be established include those relating to room geometry variation, heat gains/losses, user-interference, design and manufacturing constrains and shading values. The issue of glare and brightness contrast has not been dealt with either. These issues are left for future investigation.

Conclusion

This study has identified a promising potential for seasonal, manually adjustable light shelf systems that harvest some of the performance benefits of active daylighting systems and the simplicity and affordability of passive systems. This hybrid of the two systems, can provide higher levels of performance within an affordable solution (Javed & Reichard, 2014). This paper successfully demonstrates the viability for an optimization algorithm for daylight availability and proposed the outline for a framework that can make the selection of optimal light shelf configurations for a specific context easier for manufacturers (development of product lines) and users (development of user/settings manuals). The framework presented here used only a limited set of light shelf parameters as a proof-of-concept to illustrate the work-flow. The issues related to the computing-intensive nature of the present framework and the consideration of multiple user-preferences in determining ideal daylighting scenarios are important follow-up topics and are planned to be addressed in future development and research.

Acknowledgements

At this point we would like to point out the invaluable help received from many members of the different user-groups in the World Wide Web, specifically from people at ‘DIVA-for-Rhino’ (diva4rhino.com), ‘Performance and Form’ (http://performance-and-form.com) and last but not least ‘Designalyze’ (http://www.designalyze.com). An expanded explanation of the content of this paper can be found in the PhD dissertation “A Framework to Support the Development of Manually Adjustable Light Shelf Technologies” by Shamim Javed (2014) (http://hdl.handle.net/10919/49245) from which this paper has been derived.

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