On the Art of Daylighting Calculations:
LUMcalcul as a prediction tool in the early design stage

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ABSTRACT: LUMcalcul is a daylighting calculation tool used early in the design process to discuss preliminary architectural strategies for a new horticultural pavilion. A clear advantage of LUMcalcul is that it includes a more intuitive relationship with design sketches and representation tools such as architectural sections. It has proven particularly efficient in introducing daylighting strategies in the Integrated Design Process. The paper illustrates the design process that ultimately led to physical modelling in an artificial sky and the use of high dynamic range (HDR) image brightness analysis of the selected spatial typologies. LUMcalcul, although schematic to represent the distribution of lighting levels, remained relevant in the initial design stages to accelerate to decision process and provide a discussion on the variables that affect daylighting.
Keywords: daylighting, light, calculation, artificial sky, physical modelling, early design

INTRODUCTION

The integration of plants in an educational building dedicated to horticultural sciences has lead to a reflection on the integration of daylighting prediction tools within the design process. Interestingly, the fact that plants have particular lighting needs, sometimes higher than those required for human indoor activities, led the integrated design team to favour daylighting strategies early in the design process to ensure viability of the architectural concept. Recognized rules of thumb were part of the initial design charrettes for discussing daylighting challenges. Relevant rules of thumb provide a good insight to dimension apertures in relation to spaces, but with several limitations, in particular as the design evolves beyond basic spatial typologies [1, 7]. These were soon complemented with LUMcalcul, a daylighting calculation tool that uses a comprehensive spreadsheet in relation to architectural sketches and drawings [2]. Several softwares simulate daylighting, providing generally good prediction models. These tools are however often associated with later design stages as they may require a certain expertise, and sometimes associate with substantial acquisition costs, which also limit their use. LUMcalcul consists of a connection between sophisticated computer modelling and daylighting rules of the thumb, providing a recognized premise to assist architects from basic design questions (Fig. 1) to more developed schemes. A clear advantage of the tool is that it includes a more intuitive relationship with design sketches and representation tools such as architectural sections. LUMcalcul requires the use of a simple spreadsheet, supported by most graphical tablet that can process them. It therefore corresponds to the immediate needs of discussing lighting concepts within the design process without the necessity to process complex spatial data. Moreover, it affords a more direct interaction between input data and results than simulation tools.

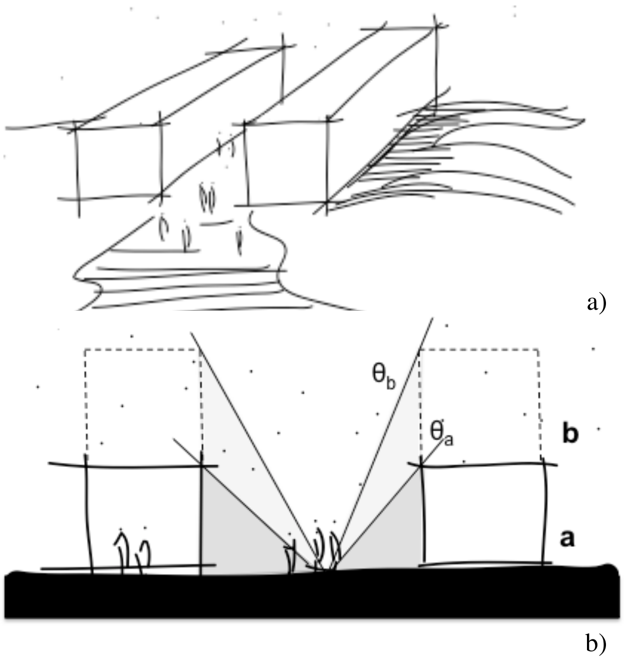


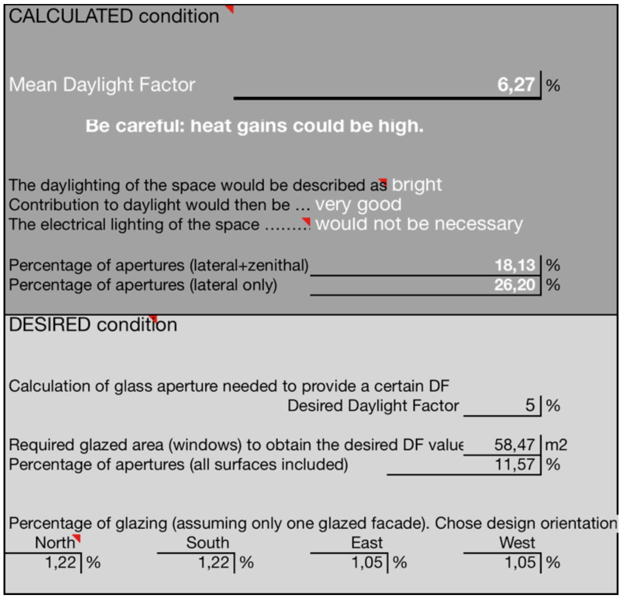
Figure 1: Evaluating daylighting at street level: a) design proposal; b) skyview angles of two design solutions.

METHODOLOGY

The spreadsheet informs designers of the relative impact of data entered within the average daylight factor equation [8]:

$$\overline{D} = \frac{A_g \, \theta \, \tau}{A\,(1 - \rho_2)}$$

where A_g represents the total area of glass, A is for the total area of internal surfaces, θ for the skyview angle, τ for the transmittance of glass and ρ for the average reflectance of surfaces [8]. The area of glass is associated with a coefficient relative to the importance of frames and members in the window system [4]. A maintenance factor, representing the coefficient of dirt, can also be added in relation to the location of the project [1, 8]. The average daylight factor is thus provided (Fig. 2), as well as an interpretation of the results in terms of potential risks of heat gains, brightness impression of the space, contribution to daylight and electrical contribution [1, 8]. At the scale of a site, the importance of daylighting access at street level can be experimented with LUMcalcul, emphasising the importance of the proportion between the width of space versus the height of its surrounding buildings [5]. This concept can be explored with LUMcalcul, using the skyview angle to calculate the predicted mean daylight factor (Fig. 1).



CALCULATED condition

Mean Daylight Factor 6,27 %

Be careful: heat gains could be high.

The daylighting of the space would be described as bright
Contribution to daylight would then be ... very good
The electrical lighting of the space .... would not be necessary

Percentage of apertures (lateral+zenithal) 18,13 %
Percentage of apertures (lateral only) 26,20 %

DESIRED condition

Calculation of glass aperture needed to provide a certain DF
Desired Daylight Factor 5 %

Required glazed area (windows) to obtain the desired DF value 58,47 m2
Percentage of apertures (all surfaces included) 11,57 %

Percentage of glazing (assuming only one glazed facade). Chose design orientation

North	South	East	West
1,22 %	1,22 %	1,05 %	1,05 %

Figure 2: Sample results using LUMcalcul.

There are inherent limitations related to the equation as it only describes the mean daylight factor on a horizontal plane, which does not consider its distribution. It is also assumed that the reflective potential of a surface is reduced to its reflectance, a variable that does not take into consideration the particular configuration of the space. However, this research shows that later design developments of the project using physical modelling and high dynamic range (HDR) image brightness analysis were of course more precise, but the daylight factor predictions offer an acceptable error margin for early design.

The advantages of the daylighting equation encompass the main variables that connect two important variables to the qualification of an architectural space, namely transparency (windows, skylights, glass openings) and opacity (walls, ceilings). Opacity and transparency, two concepts that belong to the architectural language, are clearly identified within LUMcalcul to generate an exploration of daylighting opportunities. It also produces several graphs related to key parameters of architectural design. Figure 3 shows the graph that relates the effect of average surface reflectance and mean daylight factor to discuss the materials specified in the project.

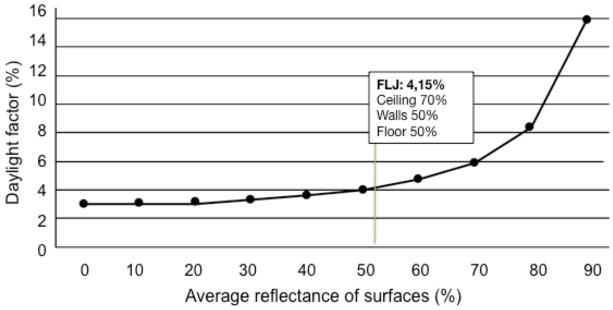


Figure 3: Daylight factor variation in relation to reflectance of surfaces.

LUMcalcul expands the discussion of window transmittance, suggesting that not only glass could be considered in a design. Indeed, figure 4 includes data that show a theoretical transmittance of 0%, which corresponds to an opaque surface such as a panel. A 100% transmittance suggests the absence of glass, therefore referring to a simple aperture that connects the space with the exterior such as a veranda. Other low transmittance data could refer to the use of materials such as translucent insulation. These theoretical conditions are particularly important at the early design stages. LUMcalcul also enables the comparison of lateral and zenithal daylight strategies of a design proposal. The combination of apertures, illustrated in figure 5, shows that lateral lighting strategies affect the daylight factor more importantly than the modelled skylight that generates zenithal light. Early in the design process, LUMcalcul may serve as an interactive tool to discuss the notion of transparency and opacity. The act of entering the data into the spreadsheet and interacting with other variables engages a discussion on the use of materials early in the design process. Indeed, glass is not always as transparent as we sometimes may think, especially when we apply coefficients such as transmittance, earlier mentioned. Ordering spatial typologies into a graph (Fig. 9) also constitutes an invaluable pedagogical tool to discuss the variables that affect daylighting.

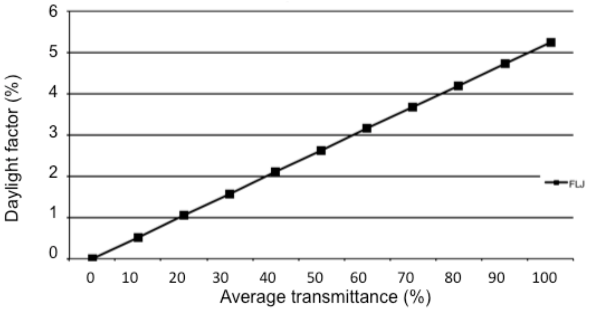


Figure 4: Daylight factor variation in relation to transmittance.

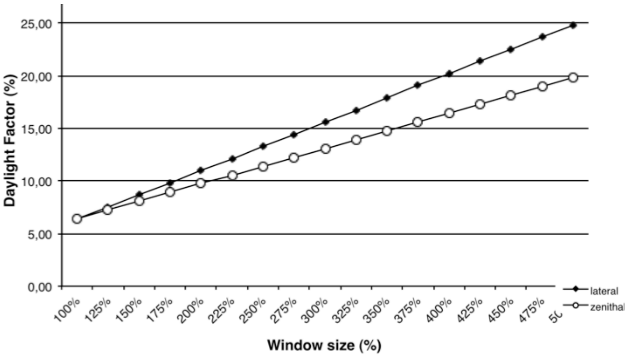


Figure 5: Daylight factor variation in relation to lateral and zenithal size of apertures (windows and skylights).

Associated with the notion of transparency comes along the importance of the architectural section. A section reveals the internal structure of a building and expresses the balance between opacity and transparency, allowing the evaluation of the skyview angle and providing an insight into the design process in terms of space composition. In fact, the importance of having a view to the overcast sky from a given point of a space to monitor if daylighting is sufficient [6], is one of the most intuitive rule of thumb. Working with an architectural section, LUMcalcul takes into account the thickness of the contour of an aperture as well as the location of external obstructions. The notion of the skyview angle, such as illustrated in figure 1, 6 and 7, represents the availability of daylight at ground level of an exterior space. Figure 6 illustrates a section of the initial design configuration of the horticultural pavilion, showing the different angles considered within LUMcalcul to calculate the average daylight factor. In figure 7, most areas of glass are located on a single side of the space, allowing the roof to be sloping. The design variation with a sloping roof, shown in figure 7, is offering a much greater aperture towards the sky and is more suited to limit northern snow accumulations, which could obstruct windows at roof level. This latter configuration provides an average daylight factor of 7,56% in the upper space (Fig. 7) instead of 2,24% obtained in the base case (Fig. 6) for a similar total area of glass.

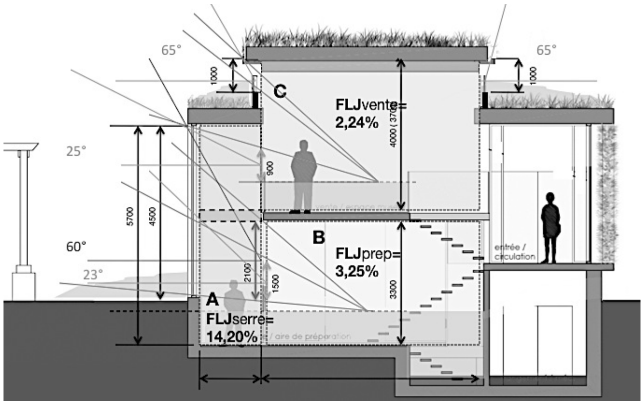


Figure 6: Initial design proposition: skyview angles and daylight factor results obtained with LUMcalcul.

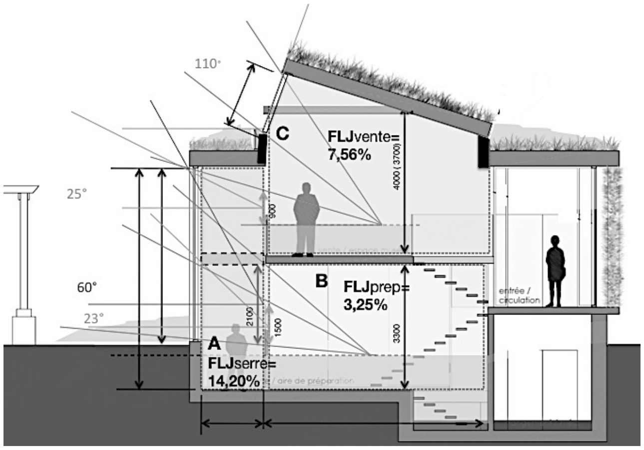


Figure 7: Sloping roof alternative: skyview angles and daylight factor results obtained with LUMcalcul.

Other design alternatives were explored, compared and represented in the graph of figure 9. The direct proportionality that lies between the skyview angle and the daylight factor expressed in the equation reinstates the importance of working early in the design process with the architectural sections together with calculation methods such as LUMcalcul. Whilst three-dimensional modelling software provides immediate daylight factor results after the model is built, skyview angles need to be entered manually in LUMcalcul from section drawings. In fact, this act of working with an architectural section is advantageous for architects as they become more aware of the importance of each variable in the development of their architectural details, having a certain knowledge of the implication of their decisions on daylighting potential of a design. For instance, the greater skyview angle of the skylight (Fig. 8) produces a higher mean daylight factor than the other illustrated strategies (Fig. 6 and 7).

The complexity of an architectural section should contribute to less accuracy in the evaluation of the daylight factor using LUMcalcul. A particular shape and location of a reflector, such as a sloping ceiling (Fig. 7), may therefore result in an underestimation of the actual lighting levels of a design proposal. In a more simple rectilinear space, previous results have shown that an error of about 3,5% was recorded between LUMcalcul and a simulation using photocells measurements of a physical model under an artificial sky [2]. Calculations for the example shown in figure 6 and 7 and 8 implied that the three analysed spaces illustrated in section were separated as if they were independent. In fact, their relationship lies in the interpretation of the sky view angles and obstructions created by their proximity.

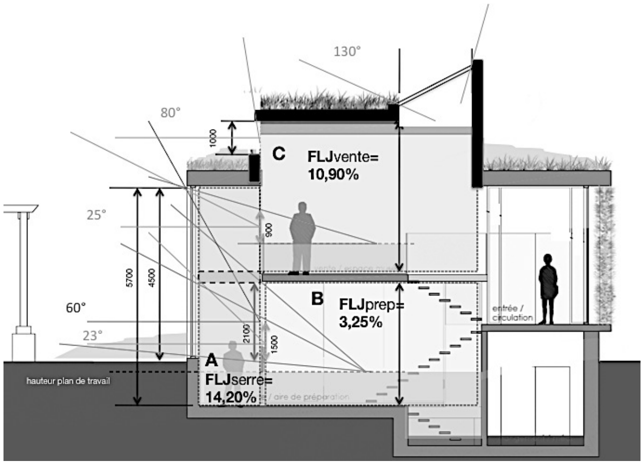


Figure 8: Skylight alternative: sky view angles and daylight factor results obtained with LUMcalcul.

DAYLIGHING PRELIMINARY RESULTS

This research has shown that hand calculations, hereby facilitated with LUMcalcul, provide a relevant basis for determining an appropriate sequence of experiments that might be needed when further modelling is desired. In this regard, figure 9 represents average daylight factor results obtained from LUMcalcul for different typologies of apertures tested for the upper space of the horticultural pavilion, including the strategies illustrated in figure 6, 7 and 8. Interestingly, they all include the same area of glass except for the last tested typology, which records the highest mean daylight factor. Those typologies that have similar parameters however produce significantly different daylight factor results, enabling the architect to consider an alternative design proposal (Fig. 9) than the initial idea. It is assumed that more precise simulation tools should complement the information provided by LUMcalcul, notably regarding daylight distribution, brightness location, glare evaluation and other qualitative aspects related to the visual ambiance of the space.

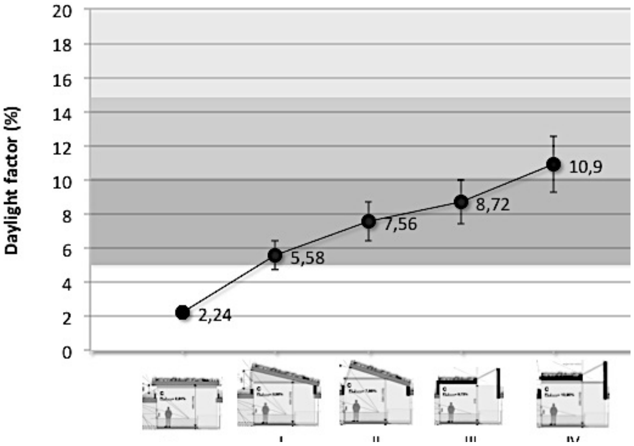
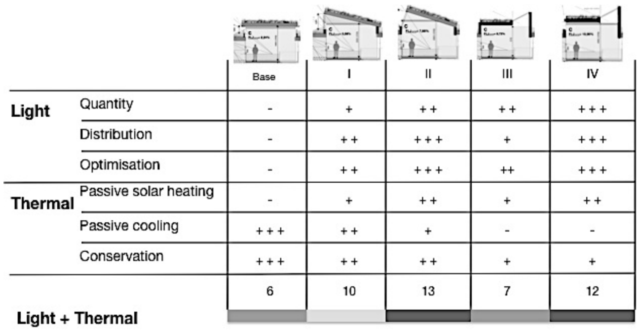


Figure 9: Comparative daylight factor results between different section configurations using LUMcalcul.



		Base	I	II	III	IV
Light	Quantity	-	+	+ +	+ +	+ + +
	Distribution	-	+ +	+ + +	+	+ + +
	Optimisation	-	+ +	+ + +	++	+ + +
Thermal	Passive solar heating	-	+	+ +	+	+ +
	Passive cooling	+ + +	+ +	+	-	-
	Conservation	+ + +	+ +	+ +	+	+
Light + Thermal		6	10	13	7	12

Figure 10: Lighting and thermal potential of design solutions.

The experimental plan devised for more detailed evaluations therefore included predictions relative to the thermal behaviour of the analysed solutions. Figure 10 shows that not only daylighting was considered but also the thermal potential of a design proposal. Since the aim of a more detailed simulation is to achieve certain quantitative and qualitative design targets, an analysis (Fig. 10) therefore identifies the daylighting potential in terms of quantity, distribution and optimisation. On the thermal aspect, the concepts of passive solar heating, passive cooling and conservation become key elements relating to apertures and areas of glass that need to be addressed. A score is attributed to each variable, based on rules of thumb and past performances relating to similar architectural precedents. Figure 10 shows the total score for a particular typology in terms of daylighting performance and the related thermal implications. A code is devised to communicate the results to the design team and confirm further developments in the design. The lighting + thermal result is translated into numerical data (Fig. 10), whereas the highest scoring typologies correspond to the most promising alternatives. Such interpretations generate global hypothesis, which would need further investigation and modelling [2]. Perhaps the most important aspect of this table (Fig. 10) is to provoke a discussion about the thermal and daylighting balance of a design solution between building professionals.

In the studied building section, the upper area of the building supports activities related to plant sales and horticultural workshop. In that respect, daylighting objectives are much more critical when plants are considered in the design. The daylighting required within a plant sale area is lower than it would be to maintain them on the long term though. A plant can be kept in an area that is approximately 300 lux for about 3 weeks. Under the Canadian Nordic climate, this would translate into a daylight factor of 10% to 15% to maintain this lighting level for 95% of the time between 9h and 17h [1]. Preliminary calculations were including an extensive use of wood, a client's preference for most internal surfaces except for the ceiling, and thus, an average internal reflectance of 55% was initially considered. The location of the high reflectance surfaces should much improve the results. Also, since the values obtained with LUMcalcul approach the required values for plant sales, we decided to use more white surfaces than it was initially discussed to obtain higher daylight factor values where required. LUMcalcul result for the sloping roof typology provides a 11,4% daylight factor when using this higher internal surface reflectance of 65%. The daylight factor formula does however not consider the location of the brighter surfaces.

FURTHER DESIGN VALIDATION

A qualitative and quantitative analysis involving physical scale modelling was completed to verify the potential of the design to support the activities related to plants such as public sales and educational workshops.

The analysis also involved photometric data obtained from calibrated CIE photocells in a physical model under a mirror-box type of artificial sky (Fig. 11). The physical modelling for instance confirms that the sloping roof typology (Fig. 12) constitutes a viable solution to respond to the needs expressed by users concerning horticultural activities. The average daylight factor of the modelled sloping roof space is 10,69%, an error margin of 6,6% compared with the 11,40 % result obtained with LUMcalcul using identical parameters. A similar experiment was undertaken with other configurations. LUMcalcul prediction using identical average reflectance values as for the physical model indicate an average daylight factor of 15,56% compared with 17,76% for physical modelling. This difference constitutes a 12,3% error factor, considerably higher than for the sloping roof configuration. In the skylight configuration, the location of the vertical white wall on the right acts as a particularly advantageous reflector of light. The photographic representation also emphasises the high brightness of that vertical wall, which receives an excellent exposure to the light from the sky. The horizontal distribution of lighting levels in the skylight configuration offers higher levels of contrast. The three-dimensional distribution of daylight factor data indicates an important peek along axis A, immediately under the skylight. The lighting distribution expressed in the three-dimensional graph of the sloping roof configuration is more even, suggesting a rather uniform lighting distribution.

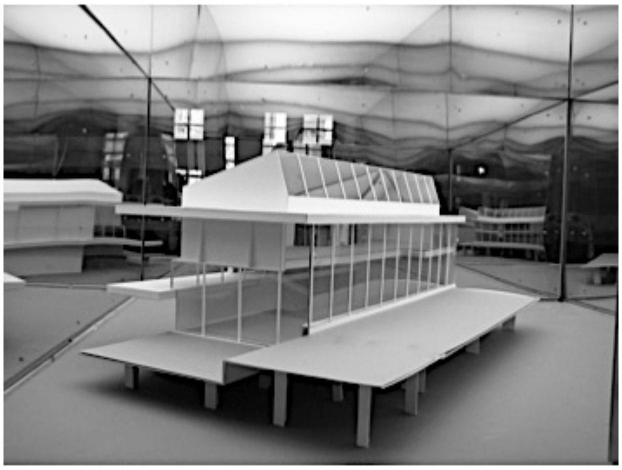
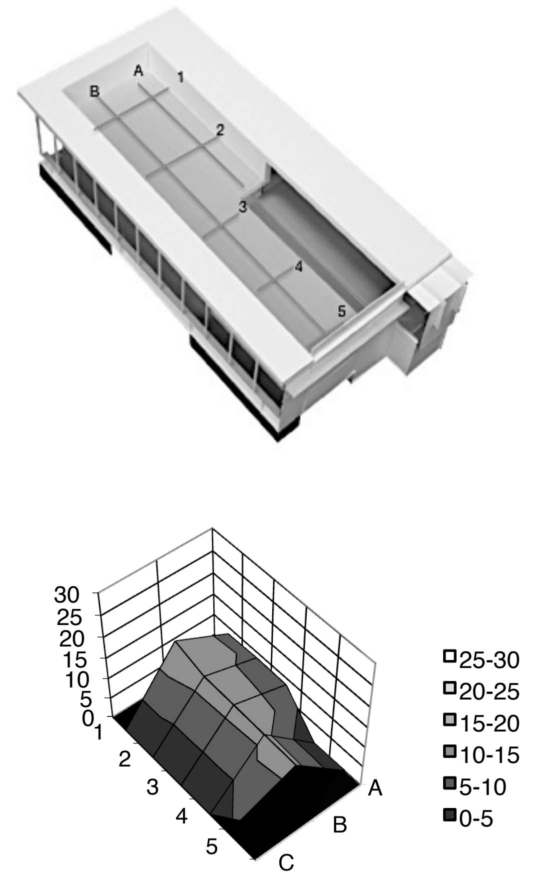


Figure 11: Physical model in Laval University's artificial sky.

These results emphasise the fact that not only the presence of reflectors in a space influence the validity of calculation methods, but it also appears that the non-uniformity of the lighting distribution, in that case offered by a skylight located along a vertical wall, accentuates the unevenness of the results, added with the use of an excellent reflector of light.



	1	2	3	4	5
A	8,24	8,54	8,31		
B	14,35	12,13	11,84	11,47	11,15
C					6,61

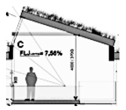


Figure 12: Photocell CIE calibrated measurements of physical modelling of sloping configuration in the artificial sky.

CONCLUSION

This research has shown that hand calculations, hereby facilitated with LUMcalcul, provide a relevant basis for determining the appropriate sequence of studies that are needed when advanced modelling is desired. LUMcalcul, although schematic to represent the distribution of lighting levels, remained relevant in the initial design stages to accelerate to decision process and provide a discussion on the variables that affect daylighting. Moreover, it affords a more direct interaction between input data and results than most tools, making it an ideal basis for discussing daylighting with all team members of the Integrated Design Process.

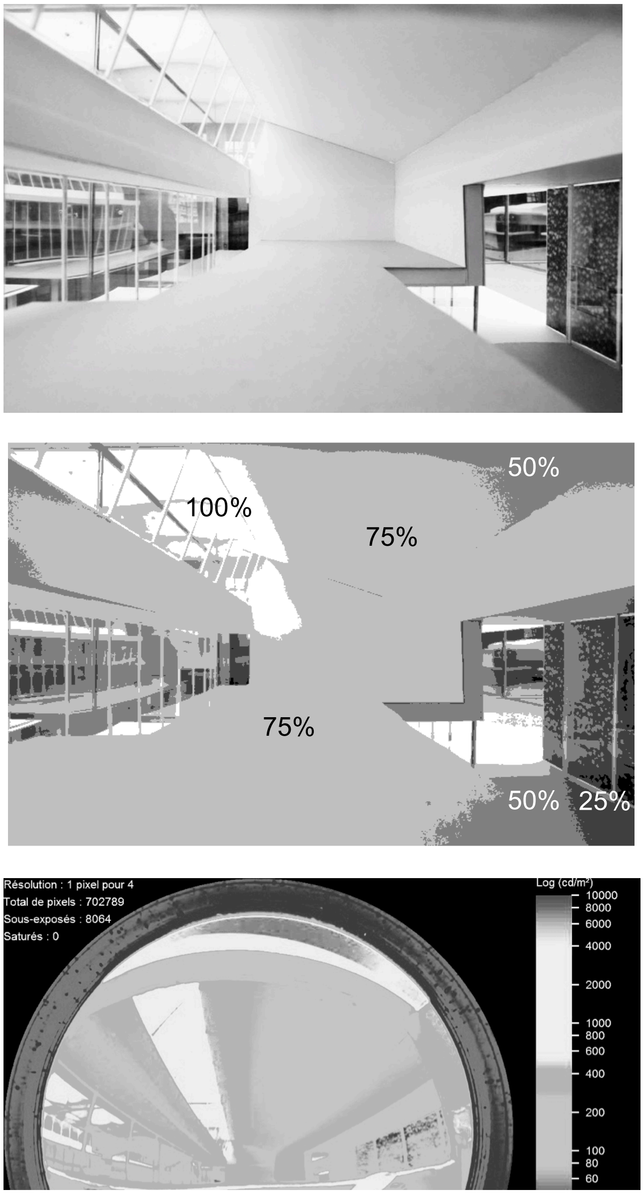


Figure 13: Physical modelingl with sloping roof configuration in the artificial sky: interior view captured with High Dynamic Range (HDR) digital imaging photography (top) using Photosphere, greyscale image brightness separation (middle), and Photolux software (bottom).

It is assumed that more precise simulation tools should complement the information provided by LUMcalcul as the design evolves, notably regarding daylight distribution, brightness location, glare evaluation and other qualitative aspects related to the visual ambiance of the space. For instance, High dynamic range digital imaging has further developed the discussion on the overall daylighting of the design solutions, providing the necessary visualization of brightness distributions to develop the design of the space after LUMcalcul predictions were initially used. Figure 13 shows the complementarity HDR/Photosphere and Photolux renderings to evaluate the sloping roof configuration of the design, which provided the evaluation of the distributive advantages offered by each design proposal. The complexity of an architectural section cannot be fully acknowledged in the evaluation of the daylight factor using LUMcalcul. However, the error factor of 6,6 to 12,3% relative to complex design solutions appears to have provided relevant initial guidelines, which were necessary in beginning design. LUMcalcul proved to be an appropriate interactive tool to discuss the notion of transparency and opacity with architects. A clear advantage of the tool is the recognition that a more intuitive relationship with design sketches and representation tools such as architectural sections is desirable. It therefore corresponds to the immediate needs of discussing lighting concepts within the design process without the need to process complex spatial data.

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