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Simulation-based support for product development of innovative building envelope components

R.C.G.M. Loonen✉, S. Singaravel, M. Trčka‡, D. Cóstola§, J.L.M. Hensen

Building Physics and Services,
Eindhoven University of Technology, the Netherlands

e-mail: r.c.g.m.loonen@tue.nl

Abstract

A need for innovation in building envelope technologies forms a key element of technology roadmaps focusing on improvements in building energy efficiency. Many new products are being proposed and developed, but often, a lack of insights into building integration issues is an obstacle in typical product development processes.

The main objective of this paper is to demonstrate the potential of expanding the application area of whole-building performance simulation and analysis towards decision-making support in the domain of research and development of such innovative building products. We propose a simulation-based approach that can help overcome several of the existing limitations.

The methodology combines building performance simulation together with sensitivity analysis and structured parametric studies to provide multi-scale, multi-disciplinary information about the performance of different product variants. The strength of this computational approach lies in increased opportunity for analysis and informed decision-making on the basis of whole building performance information, and therefore less dependence on trial and error procedures.

This methodology is illustrated in an application example of a new type of switchable glazing where we give recommended directions for improved product specifications.

Keywords:

Product development; building performance simulation; decision support; smart windows; indoor environmental quality; energy efficient buildings

1. Introduction

The present and future of sustainability in the built environment is influenced by two opposing factors. From an environmental perspective, there is the need to reduce building-related CO_2 emissions [1]. However, at the same time, the importance of high levels of indoor environmental quality is well-recognized [2], and comfort expectations continue to rise [3, 4]. As technological solutions in response to this challenging situation, many innovative building technologies and components have recently been proposed [5, 6, 7, 8]. In particular, the integration of active and passive design elements in the building envelope is increasingly receiving attention from the research and development community [9, 10, 11].

Diffusion of new technologies into daily construction practice is a challenging but essential step towards realizing effective contributions of these innovations in terms of sustainability goals [12, 13, 14]. Wide-scale applicability and competitive cost-benefit ratios are both identified as essential conditions for making such impact happen. [15, 16].

In this paper, the application of building performance simulation (BPS) and analysis techniques is put forward as a useful additional tool in the product development of innovative building envelope components, to make the process more efficient and effective. This is done by proposing and testing a methodological framework that aims at overcoming some of the existing limiting elements in product development processes.

The paper is organized as follows. Section 2 continues with an overview of recent innovative building envelope components and identifies some of the barriers and limitations that are faced in the innovation process. In Section 3, this is followed by a short review of the current role of modeling and simulation in product development of new building envelope components. In Section 4, we propose a methodological framework for more effective use of BPS throughout multiple stages of the product development process. This method is then applied to a case study of a new type of switchable glazing in Sections 5 and 6. After reflecting on findings from the case study, the paper is concluded in Section 7 by discussing how BPS can help overcome some of the limitations we identified.

2. Barriers in product development of innovative building envelope components

From discovery to deployment as a marketable product, new products go through several stages of the research and development (R&D) process [17]. Figure 1 presents an overview of characteristic phases that a new product typically undergoes in product development cycles of innovative building envelope components.

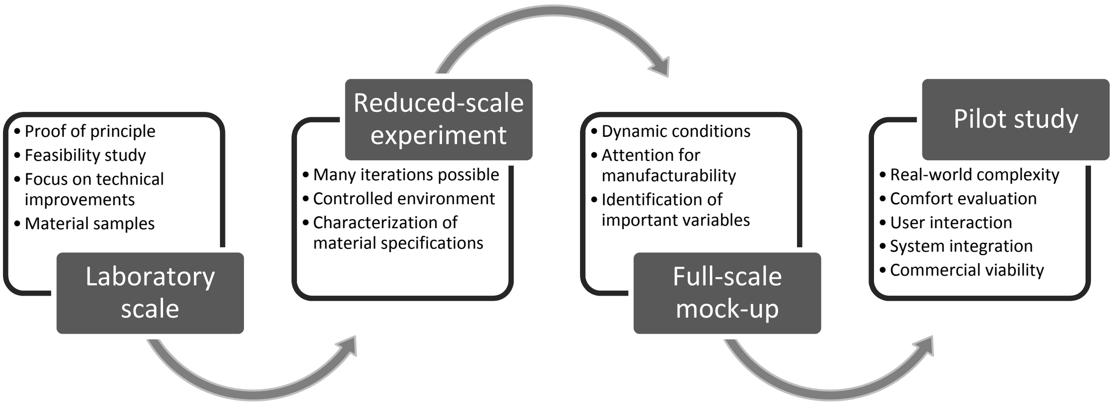

Figure 1: Characteristic phases in product development of innovative building envelope components.

In Figure 2, recent publications describing R&D steps of various innovative adaptable building envelope components are classified according to these phases [18-44] .

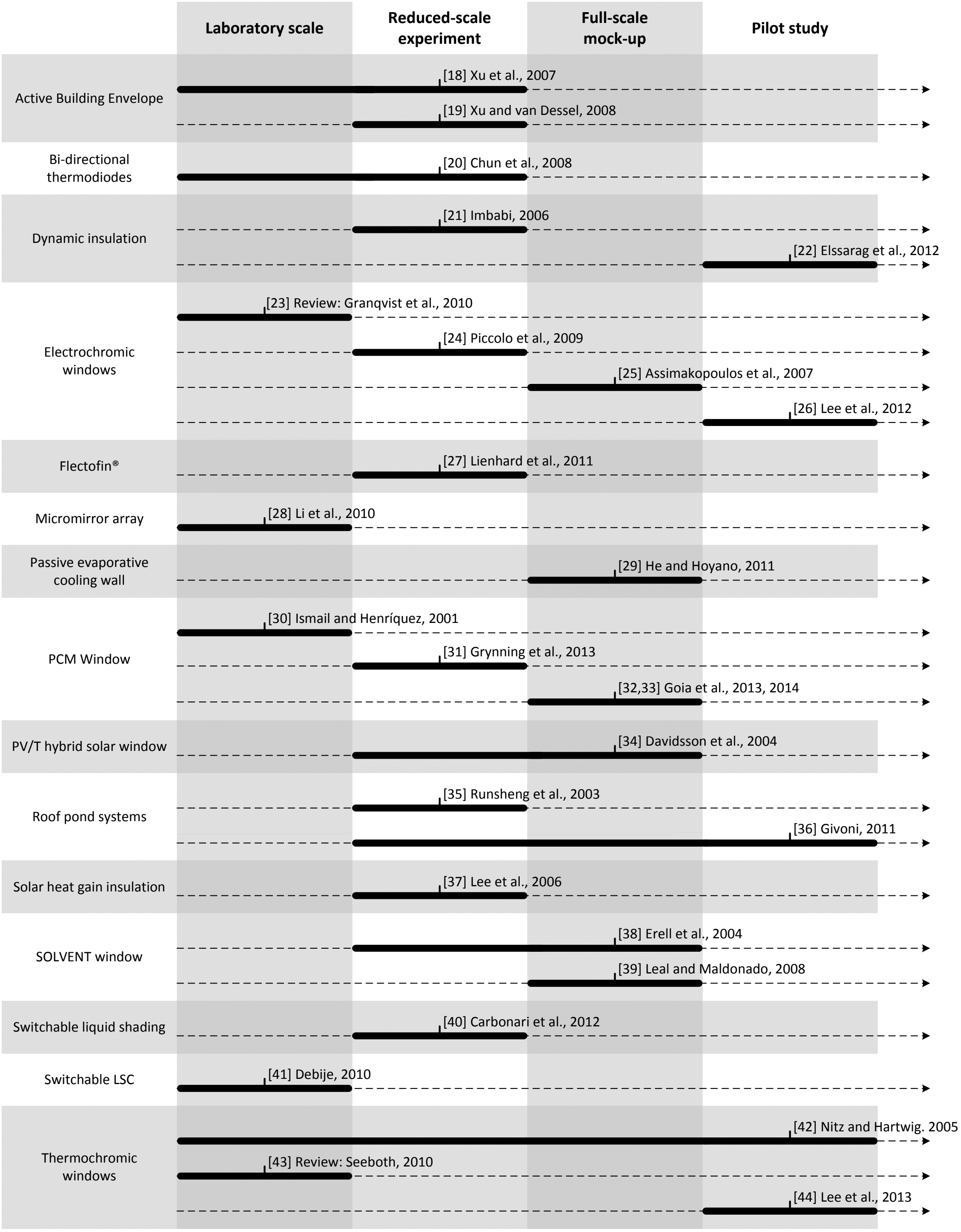

Figure 2: Classification of building envelope R&D publications in relation to the characteristic phases from Figure 1.

The success or failure of innovations in the construction industry is influenced by numerous factors. The ability of innovation teams to show that their new product will reduce cost and enhance quality or performance, has been recognized as one of the key enablers for success in this context [17]. A lack of effective communication about performance aspects, by contrast, was identified as one of the significant barriers hindering technical innovation [45].

Considering these drivers and barriers for innovation, a number of inefficient elements in the R&D process were identified from the studies summarized in Figure 2:

- **Mismatch between information need and availability:** Product development of building envelope components often takes an iterative, but linear problem solving approach (Figure 1) [46, 47]. Decisions in the early stages have highest impact on the end result, but in the absence of detailed whole-building performance information, tend to be based on intuition rather than analysis. Because only limited performance information is available, it is difficult to set goals, and measure whether they are achieved. Moreover, early-stage identification of most promising directions for further development is a challenging task.
- **Disconnection between material science and building scale:** Multiple stakeholders with diverse interests are involved in the product development process. As a result, there is a need for objective performance information to assist in decision-making. The innovation process moreover typically spans across multiple engineering disciplines. The expertise required for contributing to progress in technology development tends to be in a different domain than the expertise required to assess what impacts this has on the built environment. In the existing workflow, material scientists have limited guidance as to which properties are optimal [44], and it may not be straightforward to appraise how modifications on the material scale affect performance aspects on the building level. There is a demand for integrated, multi-scale, multi-disciplinary tools to provide such complex insights.

- **Lack of information on building integration issues:** Annual performance of building envelope components is strongly coupled to building-specific design attributes (e.g. glazing percentage, orientation) and dynamic disturbances (e.g. climatic conditions, occupants' behavior). Component-level performance metrics like U-value and solar heat gain coefficient, which are determined under a single set of standard test conditions, can capture this type of complexity only partially [48, 49]. In many situations, good design solutions are those that find a balanced trade-off point considering the multitude of competing performance criteria over the whole building life cycle [50, 51]. Pushing component-level properties such as visible transmittance towards either high or low extremes might therefore not always be the best solution, but a more thorough analysis of building performance issues is needed to make well-informed decisions. Moreover, an increasing number of innovative components make use of materials with controllable, dynamic properties. In such cases, considering the adaptive behavior under transient conditions is fundamental for evaluation of the performance [11].
- **Limitations of experiments:** The task of obtaining reliable performance information on the basis of experiments is not always straightforward. This holds for measuring the different building energy flow paths [52], and also applies to objective quantification of thermal [53] and visual comfort perception [54]. Moreover, conducting series of experiments with different product variants is a time-consuming and labor-intensive activity. Because of planning and budget constraints, the number of product iterations often needs to be kept as low as possible.
- **No what-if analysis:** In the conventional product development process, only a limited number of scenarios, related to such factors as orientation, building typology and climate can be examined. It is difficult to make projections of performance outside the range of tested conditions on the basis of this

> bounded and incomplete knowledge. Technological product development can also be hampered by the state of innovation itself. The envisioned directions for further development may be clear, but the technology is still immature, or evaluated on the basis of semi-functional prototypes [44]. Test output from experiments may consequently give a distorted view of reality, and thereby introduce the risk that the actual performance of the end product is misinterpreted [55]. Physical tests thus provide only limited insights into possibilities of products with specifications that push the edge of what is possible. To explore future directions, it can sometimes be worthwhile to assess the performance of visionary, hypothetical product variants with properties that cannot yet be manufactured [56]. The virtual world of computer simulations is well-suited for supporting this type of analyses.

Considering these limitations in existing product design and development processes, it is expected that some emerging building envelope technologies do currently not reach their full potential. This situation potentially leads to sub-optimal solutions which have negative impact on the competitive position of product developers, but is also a missed opportunity for the innovations to contribute to sustainability goals.

3. The role of simulation in new building product development

BPS takes into account the dynamic interactions between building design, climatic conditions, and user behavior, and is therefore considered as a valuable resource in the process of refining building performance. These attributes are the reason why BPS is routinely used for supporting informed decision-making in the building design process [57], and make that BPS is also gradually being introduced in the building’s operational phase [58]. In relation to innovative building envelope components, the dominant use case of BPS is in the performance evaluation of specific building design concepts [59, 60, 61]. Thus far, the systematic application of BPS for decision-making support in the process of product specification development remained largely unexplored. Strachan (2008) [62] argues that the application of BPS can “offer the bridge between outdoor tests and full-scale building performance prediction”, and presents a number of applications in this last phase of product development. A methodology for using BPS as an explicit R&D tool in the earlier stages of the process has not been proposed before. The calculations or simulations being used in these stages typically focus on the component-level only, and tend to be limited to steady-state conditions for typical or extreme cases. Nevertheless, BPS has occasionally been associated with terms like virtual laboratory [63, 64, 65], and conducting of virtual experiments [66]. In the following sections, we take this notional concept a step further, by presenting an approach that can be implemented throughout all stages of the product development process.

4. A methodology for BPS-based support in product development

Product development processes of new building envelope components are not easily captured in generally-applicable workflows or process diagrams. The reason is that there are many case-specific characteristics that can be unfitting for other product development processes. For example, the innovation can be (i) industry- or university-driven, (ii) autonomous, or part of a family of (existing) products, or (iii) with or without availability of prototypes, or access to testing facilities. Moreover, each process has its case-specific stakeholders, performance aspects (conflicting or not), constraints, time-lines, etc.

To add structure to the role of simulation in this process, without being too prescriptive, we propose the following seven-step procedure for effective use of BPS in the product development process of innovative building envelope components (Figure 3).

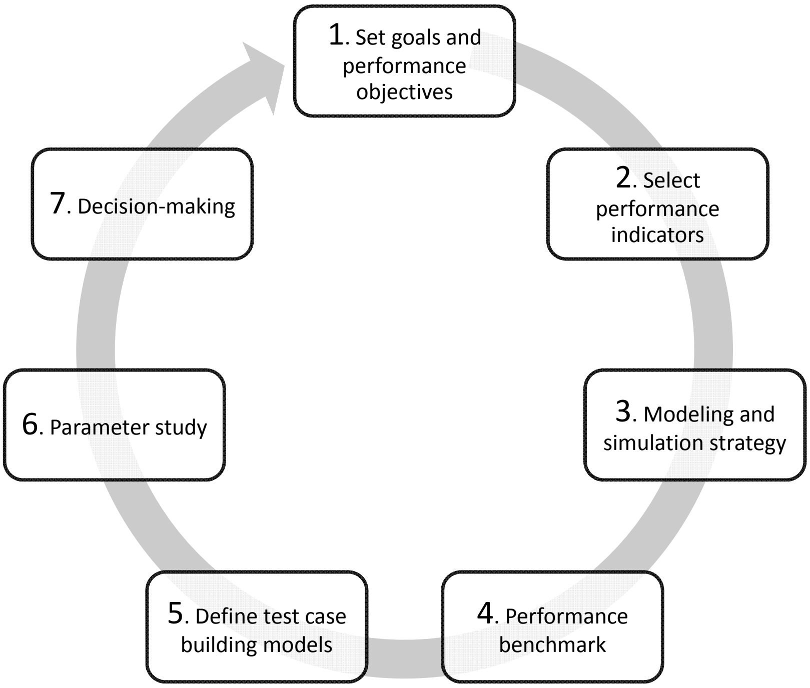

Figure 3: Simulation-based methodology for decision-support in R&D of building envelope technologies

1. **Set goals and performance objectives.** Before beginning the analysis, it is important to determine the intended purpose of the simulation study. In parallel, the performance objectives that have to be achieved by the innovative component need to be established. It is necessary to identify the multiple performance aspects that together contribute to the success or failure of the product, and to reach consensus about their priorities [13, 27]. Such a performance-based approach, with clearly defined objectives, can guide the team in decision-making through the various stages of the development process. This first step should additionally help in defining focus by specifying boundaries in terms of climatic conditions, building typology, technical constraints, etc.
2. **Select performance indicators (PIs).** Performance of different product variants can be evaluated and compared after identification of appropriate PIs in line with the objectives. The set of PIs should address the innovative component's ability to influence the building's environmental, economic and social impacts. Note that

improper selection of PIs may lead to insufficient insight for decision-making throughout the development process.

3. **Develop a modeling and simulation strategy.** The aim of this step is to transform the component's observed behavior into models that can be embedded in whole-building simulation programs. This model development should capture all relevant physical principles and address the PIs at an appropriate level of detail, by finding a right balance between model complexity and resulting accuracy [67, 68].

   Measurements form an essential part of this step. On the one hand, they are used to complement the model development and for parameter identification of building envelope characteristics. On the other hand, they can help build confidence in model outcomes by means of empirical validation studies.

   It should be realized that many of the product development processes are at the forefront of technology (Figure 2). As a result, off-the-shelf simulation tools may have limited modeling capabilities to support adequate performance prediction of such innovative concepts [69]. To avoid time-consuming development of new computational models from scratch, rapid virtual prototyping [70, 71] or co-simulation techniques [72] may become interesting options.

4. **Performance benchmark.** This step provides the R&D team with information about performance of the product in its present state. The analysis can be done by comparing performance of the innovative component with (i) direct competitors, or (ii) other technologies that fulfill similar roles. To perform this study, one or more reference buildings with simple building and system features are modeled in the selected BPS tools. As such, this phase serves to give an indication of the scope for improvement, and builds awareness of the strengths and weaknesses of the product.

5. **Define test case building models**. One of the differences between simulation support in building design versus product development is the inherent degree of variation in potential future applications in the latter case. As a general rule, the R&D team seeks to develop products that can accommodate a wide range of building designs. In product development, it is therefore important not to focus on the specifics of one building, but instead, to explore a variety of possibilities. Sensitivity analysis [73, 74] can act as a tool for defining test case buildings with different design attributes in an appropriate way. In the BPS domain, sensitivity analysis is normally used for identifying the set of variables which have most significant influence on simulation outcomes [75]. In the present context, sensitivity analysis is used to adequately define test case building models, based on the ranking of design variables with respect to differences in comfort and energy performance. The test case building models represent more extreme cases than the reference building used in step 4. This distinction is made with the following three goals in mind:
    - Accentuating differences in performance, and ensuring that they can be attributed to variations in product specifications.
    - Identifying the need for one common product, or a family of products, to be customized to the needs of different applications [76].
    - Targeting the market niche with the highest potential for early applications.
6. **Parameter study**. To identify the best performing product variants, or directions for improvement, a simulation-based parametric or optimization study is performed, with the innovative component integrated in the previously defined test case buildings. Whereas the previous step focused on differences in building design aspects, this step considers performance

effects related to parameter variations of the envelope component itself. It is important to note that virtual prototyping experiments [77, 78, 79, 80] can be performed, with product specifications that may not yet be feasible in practice. In addition, a check for performance robustness, or "what-if" analyses can be performed at the end of this step by considering a range of different use scenarios or ambient conditions.

7. **Decision-making.** In this final step, simulation outcomes are compared to the goals and requirements from step 1. The results can be used for decision-making regarding e.g. most-promising product specifications, outlining material science development objectives and directions, and communicating performance benefits to stakeholders. The simulation process can be repeated in loops, to represent different product generations throughout the development process.

To illustrate the use of BPS in the integrated development process of innovative components for the building envelope, the methodology as outlined above is applied and examined for a new type of switchable window that is described in the following section.

5. Application example: new switchable window technology

For many years, switchable window technology holds the promise of becoming a significant player in energy efficient building design [81]. Progress over the last years has led to many advances, and recently resulted in a first generation of commercially available switchable glazing products [82, 83]. Despite this progress, widespread application still seems to be a few steps away. To make switchable glazing more competitive with conventional types of solar shading, ongoing R&D efforts are focusing on several different aspects, including: tuning of spectral properties [84, 85], improving thermal performance of the window [86], reducing switching times [87], enhancing long-term stability [88], and optimizing operation strategies [89].

The work presented in this application example is part of these developments. More specifically, it is embedded in a new line of research that aims to unite the complementary positive aspects of liquid crystal switchable windows and luminescent solar concentrators [41, 85, 90]. A key advantage of such a window lies in the potential to generate the electricity that is required for its own operation. Because no external power supplies are needed, this opens up interesting opportunities in renovation projects.

5.1. Description of the initial situation

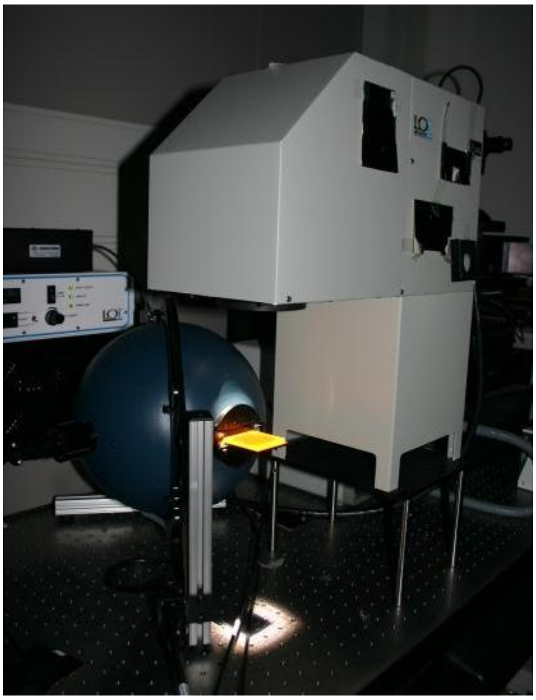

Figure 4 Overview of experimental set-up for characterization of material properties

Measurements on reduced-scale samples were carried out to characterize optical properties of the switchable window according to ISO 9050 (Figure 4). The switchable window properties shown in Figure 5 (black dots for dark (D) and bright (B) states) represent the state of development after proof-of-principle, but prior to the simulation process, and contrast these to all other optical properties (grey dots) in the international glazing database (IGDB) [91]. Compared to the more mature, state-of-the-art electrochromic materials, the technology shows a relatively restricted switchable range [83]. But as the technology is still in the earlier stages of development, there is sufficient scope for adjustments. For the purpose of this study, we assume that the window can only be switched in two states; the bright and dark states respectively. As opposed to the switching delays observed in e.g. electrochromic window systems, this type of window is able to switch instantaneously.

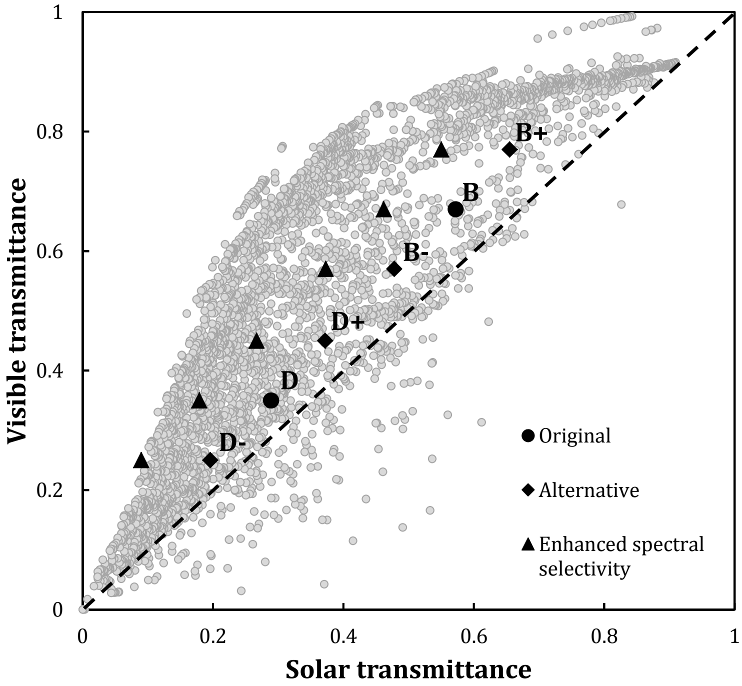

Figure 5 Relationship between solar and visible transmittance for the switchable window states in relation to other glazing types in the IGDB (grey dots). Black dots indicate the current situation for bright (B) and dark (D) state. Diamonds and triangles are only used in Section 6.6. Diamonds indicate options for the parametric study (Section 6.6) with the same light-to solar-gain ratio but more (+) or less (-) transmission; triangles indicate options with enhanced spectral selectivity (Section 6.6.2).

6. Results

In this Section we present the results of simulation studies which were performed to assist decision-making during product development of the new switchable window type. The results are described by following the same steps as outlined in the framework of Section 4.

6.1. Goals and performance objectives

Dynamic optical properties of switchable windows have a direct influence on both energy performance and indoor environmental quality of a building. Depending on the window’s state, the positive and negative aspects of incoming solar radiation can be modulated over time. Switchable windows with a large dynamic switching range have, in theory, the highest potential for reducing heating and cooling energy consumption [44, 92]. In addition, a low-transparent dark state works well for reducing glare, whereas high transparency in the bright state is beneficial for daylight utilization and view to outside. Determination of these advantages is, however, not always straightforward because savings may be offset by other PIs, such as increased electricity consumption for lighting. Moreover, from the point of view of material development, it is not realistic to focus on all aspects at the same time. The goal of this simulation-based study therefore is to identify priorities for further development of the switchable glazing product based on integrated comfort and energy performance considerations.

For successful integration of the new switchable window technology in building envelopes, the following requirements should be met:

- Low energy consumption for lighting, heating and cooling;
- High degree of daylight utilization;
- Low occurrence in perception of daylight glare;
- High levels of thermal comfort.

6.2. Performance indicators

Recently, a number of studies had the goal to investigate the interrelationships between thermal, visual and energy performance indicators in the context of: window design optimization [50], computer-based daylighting analysis [93], solar shading systems [94], and smart windows [95]. Based on findings from these studies, and in line with the objectives of step 1, the PIs in Table 1 were selected for the performance assessment. Table 1 makes a distinction between absolute and relative PIs. Absolute indicators allow for generic comparisons, whereas the relative PIs specifically focus on the difference with a reference or benchmark case. To compute primary energy consumption, we assume that the seasonal heating efficiency = 0.9, cooling COP = 3, and the primary energy conversion factor for electricity = 2.5.

Table 1: Overview of performance indicators

Absolute	**Relative**
Total primary energy demand [kWh/$m^2_{\text{floor area}}$]	Total energy savings [%]
Useful daylight illuminance (UDI) [-]	Improvement in UDI [%]
Daylight glare probability (DGP) [-]	Reduction in glare [%] or daylight glare hours [hr]
Overheating hours [hr]	Reduction in overheating hours [%]

6.3. Model development and simulation strategy

Compared to BPS models for performance prediction of conventional facade systems, two additional requirements apply for the case of switchable windows:

- Flexibility in input of new window properties;
- Possibility to change and control window properties during simulation runtime.

Because of these requirements, special attention needs to be paid to the selection of BPS tools. Various simulation approaches have previously been used for analyzing the performance of switchable glazing products (e.g. [25] [89] [95] [84]). In this research, we adopt a high-resolution, coupled simulation strategy which is outlined in

Figure 6. Daylight simulations were first conducted in a preprocessing stage for all window states independently. DAYSIM [96] is used to calculate annual time-series of five-minute luminance and illuminance data and daylight glare probability (DGP) values at specific sensor-points. This data is then supplied to TRNSYS [97], which selects the right data during run-time corresponding to the operational logic in the window controller. The integration of thermal and visual domains is accomplished by feeding internal gains for lighting from DAYSIM to TRNSYS type 56 and basing window state on either thermal or lighting considerations [98].

Throughout the model development process, it was assumed that the behavior of the switchable window can be modeled using the default set of input parameters and physical relationships for specular glazing systems. The validity of this assumption was demonstrated in experiments with the liquid crystal window integrated in reduced-scale prototypes exposed to atmospheric boundary conditions. Details of this validation study are reported in [99].

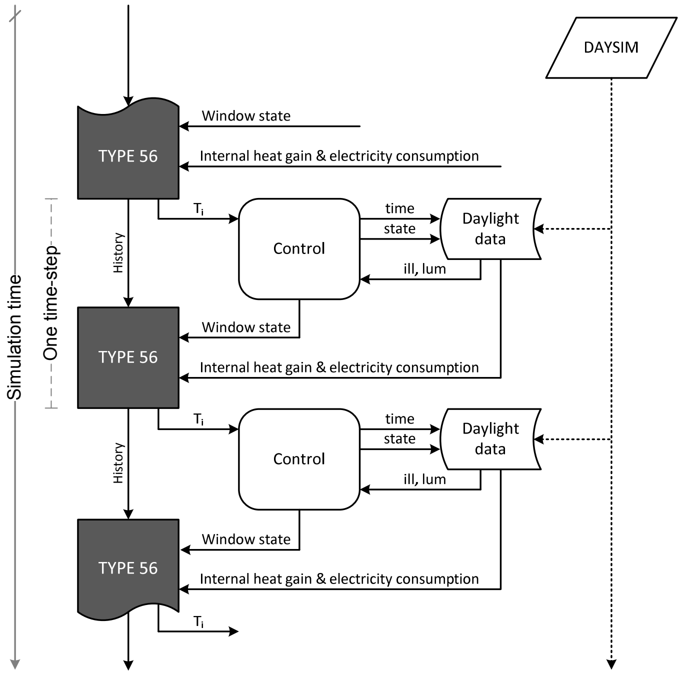

Figure 6: Coupled simulation approach using TRNSYS and DAYSIM

6.4. Performance benchmark

The analysis in this part of the study focuses on a four-person South-facing perimeter office zone, situated at an intermediate floor, and surrounded by identical office spaces (Figure 7). Representative values for a Dutch reference office building [100] were taken for other construction details. The office zone is occupied from 9 am to 5 pm, and results are evaluated with ambient conditions for Amsterdam, the Netherlands.

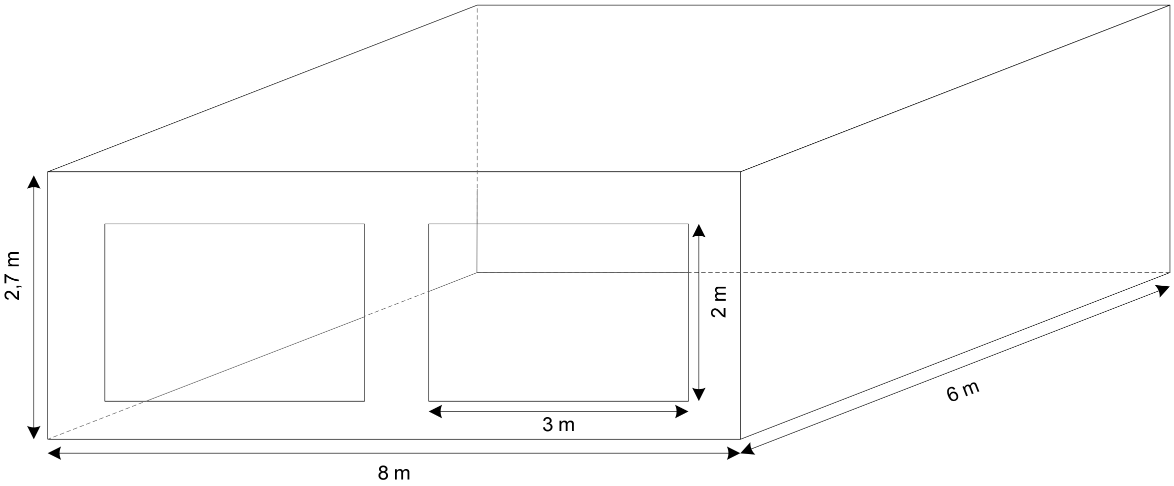

Figure 7 Office room used for the benchmarking study

Previous studies show that the performance of switchable windows is strongly linked to the window control strategy that is used for their operation [25, 89]. Before doing comparative analyses on the product level, it is therefore important to examine these control aspects first. Six different operation strategies were analyzed in this study; five strategies using automated control, and one using manual operation as a reference strategy (Table 2).

Table 2: Overview of the operation strategies

Reference operation strategy	window operated with control strategy that resembles manual operation of venetian blinds (Lightswitch) [101]

Operation strategy 1	window switches to dark when daylight illuminance on the workplane > 500 lx
Operation strategy 2	window switches to dark when exterior illuminance on the window is > 20,000 lx
Operation strategy 3	window switches to dark when room air temperature > 24°C
Operation strategy 4	window switches to dark when outdoor air temperature > 24°C
Operation strategy 5	window switches to dark from 1 May until 30 September

Figure 8 shows the results for each of the different automated window operation strategies, relative to the reference strategy with manual control. It can be observed that only the control strategy based on indoor daylight illuminance (strategy 1), results in an improvement in all four performance aspects. Therefore, this strategy is selected for use in further analyses in this paper.

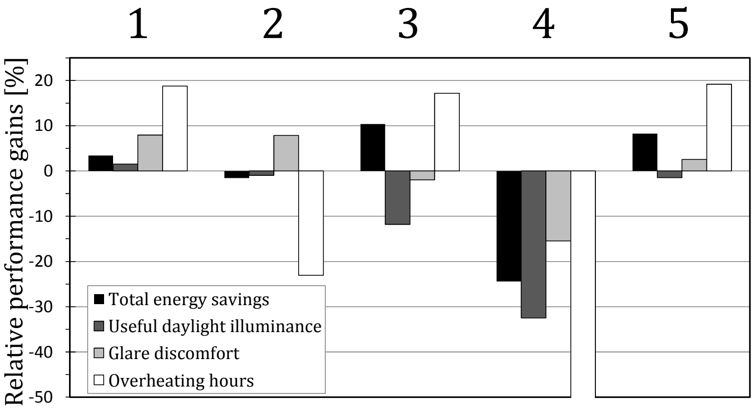

Figure 8 Performance of the switchable window for different window operation strategies

As switchable windows could replace conventional types of solar shading, it is also important to position their performance with respect to competing technology options. To this end, a benchmark study was performed by comparing performance aspects of the switchable window to cases with conventional double glazing, using the same U-value, combined with solar shading in the form of (i) a 50 cm horizontal overhang and (ii) internal venetian blinds. From the results presented in Table 3, it can be observed that the switchable window is the most favorable option when it comes to energy demand and thermal comfort. However, there is still room for improvement in the windows' ability to reduce the occurrence of glare, while proving sufficient levels of daylight in the occupied space.

Table 3: Results of the benchmark study, comparing and ranking the switchable window with an overhang and venetian blinds.

			Overhang	Venetian blinds	Switchable window
Energy		kWh/m^2	113.5	127.9	101.2
		Rank	2	3	1
Overheating		hr	277	78	48
		Rank	3	2	1
UDI	<100 lux	%	6.3	18.8	6.8
	100-2000 lux	%	79.1	80.9	72.5
	>2000 lux	%	14.6	0.3	20.7
		Rank	2	1	3
DGP	Imperceptible	%	92	98	89
		Rank	2	1	3

6.5. Definition of test case building models

A single-variable sensitivity study was performed to define the test case building models that are used in the parametric study. This was done by modifying the parameters of a base case model over the ranges indicated in Table 4. The outcomes of the sensitivity study were post-processed using the elementary effects screening method [102, 103]. In this analysis, the sensitivity indices are calculated relative to the performance of the base case with switchable glazing. As such, we do not evaluate the absolute merits of applying a switchable window, but shift the attention towards differences with the existing product variant.

Table 4: Parameter values and samples for the sensitivity study

Parameter	Unit	Base case value	Range	Samples

Window-to-wall ratio	[-]	0.5	0.15 – 0.95	0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95
Window orientation	[-]	south	-	north, east, west
Window position	[-]	center	-	top, bottom, left, right
Room depth	m	5.40	3 – 7	3, 4, 6, 7
Wall insulation	$W/m^2 K$	0.3	0.1 – 0.5	0.5, 0.4, 0.2, 0.1
Thickness of thermal mass layer	cm	4	1 – 8	1, 2, 3, 6, 8

Table 5 shows the parameter ranking as outcome of the sensitivity analysis. Because building performance is most sensitive to the parameters ‘window-to-wall ratio’ and ‘window orientation’, it is worthwhile to investigate to what extent different fenestration properties affect the performance under a wider range of values for these two design attributes. To this end, eight variants of the reference office space are defined as test case buildings for further analyses. These test case buildings have a window-to-wall ratio (WWR) of 25% and 95%, and are evaluated in all four cardinal orientations.

Table 5: Ranking of the influence of different building parameters on performance

Rank	Total energy savings	Increase in UDI
1	Window orientation	Window area
2	Window area	Window orientation
3	Room depth	Room depth
4	Window position	Window position
5	Insulation	Insulation / Thermal mass
6	Thermal mass	

6.6. Parameter study

6.6.1. *Influence of orientation and window-to-wall ratio (WWR)*

Figure 5 gives an overview of the range of dynamic solar-optical window properties which are tested in the parametric study. Black dots correspond to the original window properties in the bright (B) and dark (D) state. Black diamonds represent alternative sets of optical properties. For both states, alternative variants with more (+) and less (-) transparency are tested with similar light-to-solar-gain ratio. In total, this leads to nine different combination sets of glazing properties.

Table 6 shows results in terms of energy performance and UDI for every orientation and WWR. The results are ranked in such a way that 1 represents the best, and 9 represents the worst-performing alternative. By doing this, it is relatively easy to observe performance trends in the simulation output. The results for this example show that combinations with B+ and D- tend to lead to the highest performance. The product can therefore be improved by extending the range of operability between bright and dark states. Further examination of results shows that for buildings with small WWRs, higher light transmittance of the bright state has more influence on the building performance, whereas for buildings with large WWRs, lower light transmittance of the dark state leads to a more positive effect.

Table 6: Ranking of results for different orientations and window-to-wall ratios.

Orientation		South		West		East		North	
WWR		0,97	0,25	0,97	0,25	0,97	0,25	0,97	0,25
B-	**D+**	*8*	*8*	*8*	*8*	*3*	*8*	*9*	*7*
B-	**D**	5	5	5	5	4	4	5	5
B-	**D-**	2	3	2	4	9	**1**	2	4
B	**D+**	9	9	9	9	8	9	8	9
B	**D**	6	7	6	7	7	7	6	8
B	**D-**	3	4	3	6	5	5	3	6
B+	**D+**	7	6	7	3	6	6	7	2
B+	**D**	4	2	4	2	2	3	4	**1**

B+	**D-**	**1**	**1**	**1**	**1**	**1**	2	**1**	3

These findings suggest that perhaps it is not wise not to invest all time and effort in developing just one product with the widest modulation range possible. Instead, the development of customized windows, with a relatively narrow switching range, but tuned to the demands of different applications, seems to be a more promising approach.

6.6.2. *Influence of spectral selectivity*

As a potential improvement to the current glazing specifications, another set of properties with enhanced spectral selectivity is analyzed, i.e. having a higher visible light transmittance for the same solar transmittance (indicated with triangles in Figure 5). Because these alternative window sets have a higher light-to-solar-gain (LSG) ratio [104], it is expected that, in the cooling-dominated office, they lead to a more favorable tradeoff point in the interaction between solar gains and daylighting. In terms of daylight utilization and glare, no differences in performance are observed. However, as Table 7 shows, the performance gains in terms of reduced energy demand are significant. Especially for applications with large WWRs, the switching of optical properties in the near-infrared range is a direction that warrants further exploration.

Table 7: Energy performance improvement relative to the case regular light-to-solar-gain ratio. The results are shown as improvements in percentage points.

Orientation		South		West		East		North	
WWR		0,97	0,25	0,97	0,25	0,97	0,25	0,97	0,25
B-	**D+**	9.3%	4.2%	6.8%	2.7%	6.2%	2.3%	4.4%	1.1%
B-	**D**	9.8%	3.9%	7.3%	2.8%	6.2%	2.2%	4.4%	1.1%
B-	**D-**	9.0%	3.2%	6.7%	2.7%	6.0%	1.5%	3.7%	1.0%
B	**D+**	9.3%	4.3%	6.8%	2.9%	6.6%	2.4%	4.4%	1.2%

B	**D**	9.8%	3.9%	7.3%	2.9%	6.9%	2.3%	4.4%	1.2%
B	**D-**	9.0%	3.2%	6.7%	2.6%	6.7%	1.6%	3.7%	0.9%
B+	**D+**	9.2%	4.2%	6.7%	2.8%	6.4%	2.3%	4.4%	1.1%
B+	**D**	9.7%	3.7%	7.2%	2.8%	6.9%	2.2%	4.4%	1.1%
B+	**D-**	9.0%	3.0%	6.7%	2.5%	6.9%	1.9%	4.3%	1.0%

6.7. Case study conclusion and reflection

Identifying priorities for further development of the switchable glazing product was specified as the main goal at the beginning of the simulation study. Because the computational approach uses high-resolution models that effectively take into account the mutual interactions between daylighting and thermal effects, we were able to analyze the performance of various switchable glazing alternatives at a high level of detail. Our results show different areas for improvement compared to the existing product variant, translating into a challenge that can be addressed in two different ways. One option is striving for the largest switching range possible, which coincides with the direction that tends to be pursued by most material scientists in this field [44, 92]. Analysis of our results, however, suggests that, for the conditions we investigated, it is more interesting to tune window specifications in response to the requirements under different design scenarios. For certain buildings it would be better to have high visible transmittance in the bright state, whereas in other applications low solar transmittance in the dark state is the key to obtaining higher performance. For the short-term development goals towards early market introduction, these divergent requirements are therefore treated in the form of two different variants of the same product family. Results from our simulations moreover show the importance of spectral selectivity and development of advanced control strategies that can respond to the multi-criteria nature of solar shading control.

This computational study served the main purpose of demonstrating the proposed simulation framework. It explored only a limited subset of possibilities for variable window properties, and is limited in scope, but nevertheless provided valuable information to the product development team, and worked well as a medium for discussion and communication. Simulation-based research continues to be used in the R&D process for investigating the potential of windows with e.g. intermediate states in transparency, or further refined spectral selectivity, and for testing the robustness of our findings in different climates. Future research could additionally focus in more detail on the window control aspects and could make use of optimization algorithms to more efficiently explore the design option space.

7. Discussion and conclusions

In this paper, we proposed a simulation-based approach to assist decision-making in the process of innovative building envelope product development. By taking advantage of whole-building performance predictions in combination with sensitivity analyses and structured parametric studies, the method is able to provide insight into building integration issues of such components at an early stage of the R&D process. Through iterative evaluation of multiple product variants, the integration of simulation allows for strategic decisions that acknowledge high-potential directions in the development process and may therefore help creating competitive advantage by improving product performance or time-to-market in a cost-effective way. Moreover, the method also allows for multi-scale, quantitative, analysis of effects that are not easily captured in pilot studies or field test experiments, such as what-if studies and robustness evaluation of the solutions with respect to different occupancy scenarios, performance indicators, or climatic contexts.

The simulation-based approach does, however, not intend to replace the role of experiments. Yet, it can help give priority to test those candidate solutions with higher chances of success. Simulations can furthermore be used for exploring the potentials of systems with properties that do not yet exist. This is something one can accomplish only through virtual experiments.

8. Bibliography

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