Dynamic shading systems: A review of design parameters, platforms and evaluation strategies

AL-MASRANI, Salwa M. and AL-OBAIDI, Karam <http://orcid.org/0000-0002-4379-6964>

Dynamic shading systems: A review of design parameters, platforms and evaluation strategies

Salwa M. Al-Masrani[a] , Karam M. Al-Obaidi[b,*]

[a] Faculty of Engineering and Built Environment, SEGi University, Petaling Jaya, Selangor, Malaysia

[b] Department of the Natural and Built Environment, Faculty of Social Sciences and Humanities, Sheffield Hallam University, Sheffield, UK

Corresponding author

E-mail addresses: k.al-obaidi@shu.ac.uk; karam_arc@yahoo.com (K.M. Al-Obaidi)

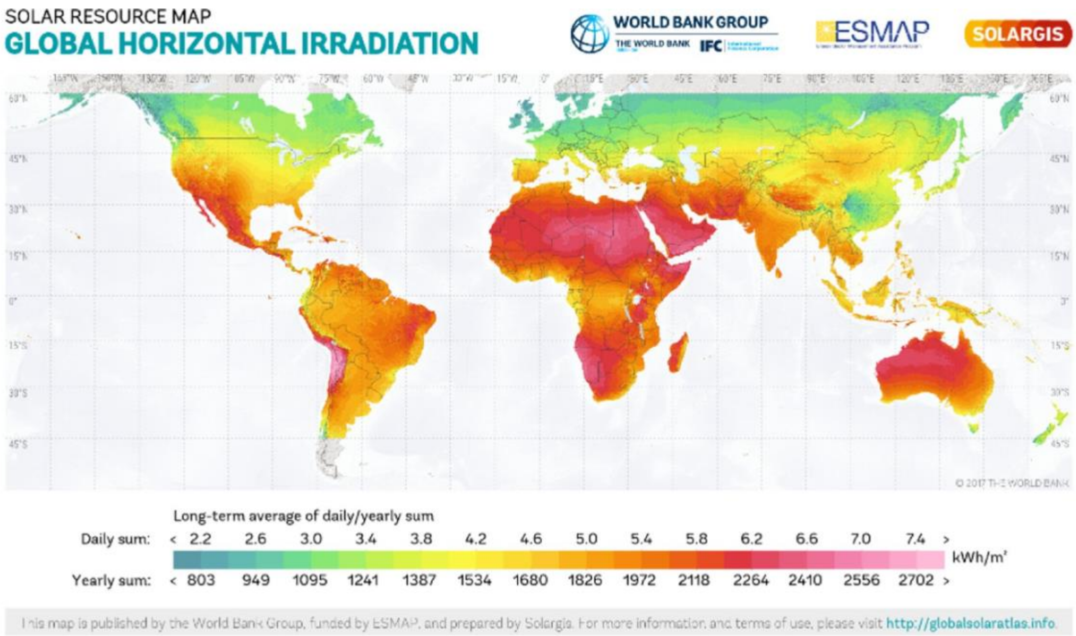
ABSTRACT

The advancements in software and hardware technologies provide opportunities for solar shading systems to function dynamically within their context. This development has helped dynamic shading systems respond to variable environmental parameters such as sun angles and solar insolation. However, the technical under- standing of system design, mechanism and controlling methods presents a challenge for architects and designers. Therefore, this study aims to review the current applications and trends of dynamic shading systems to clarify the potentials and limitations in enhancing system performance based on integrated design objectives. This study assessed several systems on the basis of a critical review to identify different models, applications and methodologies. This study is divided into two main sections: (i) design elements and platforms that engage with specific methods in creating a dynamic shading system and (ii) evaluation strategies to examine system performance. The systems were investigated based on the multiplicity and integration of the parameters involved through various components, such as architectural, mechanical, operational and automation components. The review analysed various studies on the following two bases: (1) geometric-based analysis, which distinguishes between simple and complex shading models, and (2) performance-based analysis, which assesses the shading systems based on two groups of methodologies, namely, theoretical and experimental. The outcome of the review reflects a clear classification of shading models and a comprehensive analysis of their performance. This study generally provides a systematic framework for architects based on thorough research and investigation. Finally, the study introduced several findings and recommendations to improve the performance of dynamic shading systems.

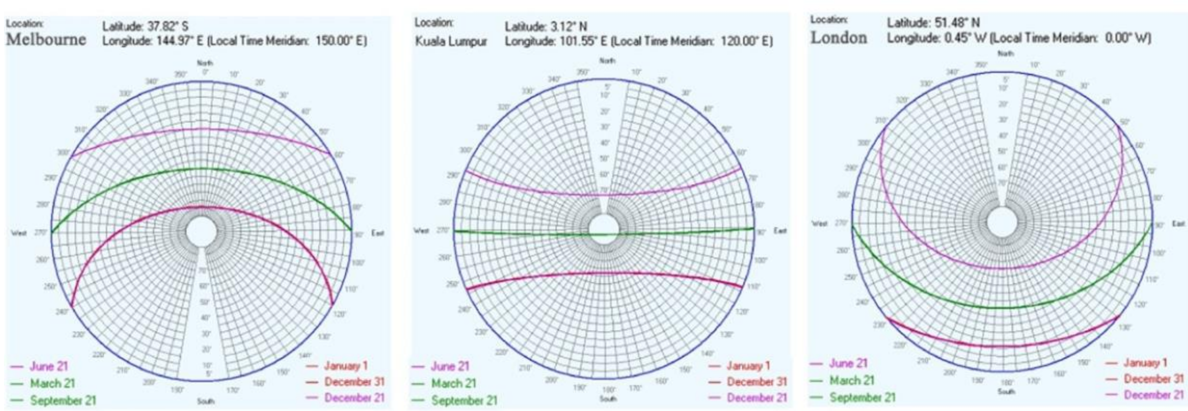
1. Introduction

Energy depletion and climate change are global issues that have gained growing interest, particularly in the construction industry. Kibert [1] indicated that a sustainable construction tends to conserve energy based on efficiency and/or using renewable energy sources. COAG [2] stated that using a sustainable building envelope could help control over 50% of the total energy consumption, which could be achieved by the integration between passive design modules and technological solutions. The current advancements in software and hardware technologies urged designers to merge climatic needs and technology into one platform to develop dynamic building envelopes that respond to different climatic parameters [3,4], such as sun angles and solar levels that differ according to the geographical location and site conditions, as shown in Fig. 1. The utilisation of climatic variables in the design of dynamic façade systems is crucial to regulate the flux of solar loads, enhance building performance and ensure human comfort [6–9].

Solar shading systems generally represent one of the passive design strategies globally employed to protect buildings from intensive solar radiation, especially during peak hours [10]. According to the literature, employing passive shading systems is an effective bioclimatic practice to maintain the balance between visual and thermal demand [11]. However, studies showed that static shading elements are notably incapable of completely responding to variable climatic conditions [12–14]. In addition, studies showed limitations in attaining a required daylight condition, thereby increasing lighting demand [7,15,16]. In fact, the system interaction with climate is only optimal at a specific time and date over the day and the year. Consequently, static systems are no longer favourable in terms of control flexibility and energy efficiency.



(a)



Melbourne/Australia Kuala Lumpur/Malaysia London/United Kingdom

(b)

Fig. 1. (a) World map of global horizontal irradiation [5] (b) Sun path diagrams in three different latitudes generated by IES VE software.

Concurrently, rapid advancement in construction and information technology over the last twenty years [17] has permitted drastic changes in façade design, which shifted from the conventional style of rigid blocks towards lightweight, transparent and multi-layered skin [18]. This advancement allows for the use of dynamic elements that automatically regulate the penetration of light and heat [19]. Recent studies found that the current restriction of conventional systems cannot be improved without static to dynamic transition and responsive design elements [20,21]. Therefore, a new tendency is to shift from 'single function, single behaviour' to multifunctional and integrated technologies [21].

A dynamic shading system is composed of moveable elements that work within an algorithm. The definition of dynamic shading system can be associated with intelligent façade applications, which have been proven to increase inhabitants' comfort [22] due to their interaction with the external and internal environments [23]. Therefore, the term 'dynamic' refers to continuous and developing change, along with frequent updates, which can be based on the following two aspects: (1) the continuous interaction between the system and its environment [24,25] and (2) the cause-and-effect interrelation between forces and movements within specific periods [26]. Thus, dynamic shading devices are intelligent systems automatically operated in response to outdoor or indoor weather parameters in favour of high comfort level and energy performance [27]. Dynamic shading devices generally comprise several layers that are engaged to create the intelligent system, starting from the transformative skin layer and ending with the operation and management of different facilities [17,28]. The automatic response presents the key feature of dynamic shading systems [20], where its implementation involves three components: sensor network to obtain data, controller to determine the suitable action and a few mechanical actuators [29].

Investigating the design, establishment, mechanism and control of the dynamic system is necessary to provide a systematic process for architects. Therefore, this study aims to highlight the parameters involved in the design of dynamic shading systems, including their technical establishment and the methods followed for their performance evaluation. In addition, the review will classify various models of dynamic shading based on their geometric and motion design to explore their influence on environmental and energy needs. Hence, in addition to distinguishing the role of these factors in meeting the cri- teria for a proper design, defining the dynamic shading as a system that has models, components and mechanisms with different evaluation strategies is crucial. However, issues related to cost, maintenance and technical installation are not addressed in this paper.

2. Solar shading design

2.1. Sunlight control and shading mechanism

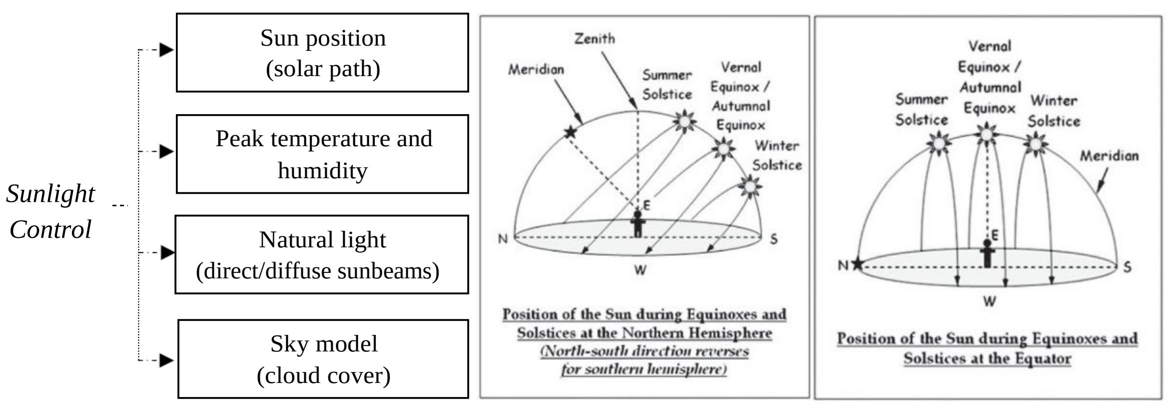
The aim of a shading device is essentially to shelter a building from undesirable solar radiation, especially in severe conditions and orientations [13]. The mechanism of a shading system functions on converting direct solar radiation into diffuse light [30] and modulating the amounts of light penetration [31]. The environmental performance of shading systems involves two primary objectives: (i) visual performance, which is solely about preventing glare and maintaining adequate indoor illuminance [31], and (ii) providing acceptable thermal conditions by controlling solar heat gains accompanied with direct and diffuse sunbeams [102]. The adaptive behaviour of advanced shading applications, such as dynamic systems, has promoted consistent criteria [32]. Thus, the functionality of dynamic shading should be determined by the control effectiveness of sunlight levels that penetrate a building daily and yearly [12,33], especially at different sun angles [34], as shown in Fig. 2(b).

Therefore, a proper dynamic shading design necessitates an accurate understanding of the sun movements in a specific site considering several parameters, as illustrated in Fig. 2(a). The first parameter is the sun position in the sky during different seasons in terms of altitude and azimuth angles as shown in Fig. 1(a).

2.2. Selection criteria of dynamic shading systems (user requirements)

The resilient behaviour of dynamic shading systems permits for potent control over solar gains in different seasons [39]. Prowler and Bourg [35] stated that in nearly all climates, diffusible and regulatable natural light will sustain good daylighting; however, heating and cooling loads will be different. Therefore, the criteria for selecting a suitable shading system should be created based on the understanding of the system behaviour in different climates. In warm and hot climates, excess sunlight may generally result in high cooling demand [40]. In cold and temperate climates, cooling loads have been proven to be frequently higher than heating loads [41], whilst sunlight can positively contribute to passive heating during winter [33–35]. Thus, in moderate or cold climates, dynamic shading can contribute considerably to reducing the overheating and cooling energy in summer [42,43], whilst it might result in conflicting loads in winter in particular spaces, such as offices or classrooms, where the visual task is priority [44]. However, excluding the overflow of natural light will increase heating demand [38,45]. In the tropics, the positive correlation between visual and thermal performance [37] ensures that dynamic solar shading has an affirmative impact throughout the year [36]. Therefore, space activity and climate characteristics should be considered along with energy concerns to find an optimum design solution.

Apart from environmental performance, other requirements can be influential when choosing a suitable design, such as aesthetics, maintenance, safety, cost, and privacy [39], in addition to other considerations defined likely by owners or facility managers, such as constructional or economical restrictions [46]. Thus, technical design aspects (geometric design, control strategy and automation technology) of the system can be derived based on elaborated criteria determined by stakeholders and a strict guideline defined by the designer on the basis of the system climatic behaviour, as presented in Fig. 3.



(a) (b)

Fig. 2. (a) Climatic parameters considered in shading design for controlling the flow of sunlight. (b) Position of the sun during equinoxes and solstices at the Northern Hemisphere and at the Equator (www.mydarksky.org).

The second parameter is the peak temperature and insolation [9,35]. The third parameter is the solar flux of direct and diffuse light in a year, including intensity, peak values and fluctuation rates. The fourth parameter is sky models identified by cloud cover and the frequency of cloud formation, which affects the availability of direct sunlight [30]. Hence, understanding these para- meters could control light and heat loads in buildings [36], which lead shading devices to achieve high performance [37,38] and help provide productive conditions [7,12].

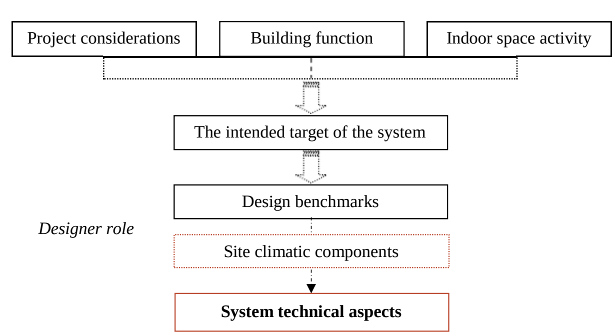


Fig. 3. Flowchart of steps through the design of a dynamic shading system.

3. Methodology

This study presents a critical review of the current applications of dynamic shading systems based on evidence and uses an observational survey to explore developments and trends. The research reviewed a wide range of studies and evaluated different systems. Konstantoglou and Tsangrassoulis [29] reviewed dynamic operation of building skins using three levels of analysis include (i) system level that covers the performance of dynamic shading systems, (ii) control strategies level that covers electronic and digital aspects and (iii) building level that examines how dynamic systems affect the buildings energy balance and occupants comfort as shown in Fig. 4(a). Hofer et al. [47] presented a modelling framework that represents ways to optimise geometry, motion control, and electrical design parameters based on system performance as shown in Fig. 4(b).

Therefore, the study is divided into two main sections as shown in Fig. 5. The first section covers the principal aspects related to the design of dynamic shading systems. It introduces a comprehensive background about the design of dynamic shading devices where it focused on two main aspects; (1) design parameters integrated with the technical elements (architectural, mechanical and operative) as well as digital electronics (automation and control) and (2) platforms and methods (tools and techniques). These aspects were discussed based on various theoretical and experimental evaluations. The second section presents an analytical evaluation of several shading systems through the presented literature, the design aspects presented in the first section form an essential guideline that was involved to analyse different systems and methodologies.

The first section of review focuses on the physical and digital aspects engaged in the system design. The physical aspects cover the following specific modules: (i) architectural components that focus on the architectural features of shading skin, including the geometrical shape and motion layout; (ii) mechanical components that address the kinetic design and mechanical tools; and (iii) electrical components based on the possible energy sources required for the system operation. The digital electronics cover the automation components that underline the essential hardware and software constituents, such as control systems, analytical schemes, protocols and characteristics as well as control scenarios with its potentials and limitations. In addition, this section discusses several design platforms and methods followed in different methodologies to investigate the system functionality, performance and tools. The second section evaluates the systems by using two types of analysis. (i) geometric-based analysis which is grounded on the model design intricacy that was investigated on the basis of architectural and kinetic aspects, i.e., geometric design and motion layout (mechanical concept). (ii) performance-based analysis that assesses the impact of the presented systems on the built environment and energy through different types of methodologies, this type of analysis highlights important issues, such as the responsive mechanism, control systems, control strategies and the influence of these factors on the system's environ- mental and energy performance.

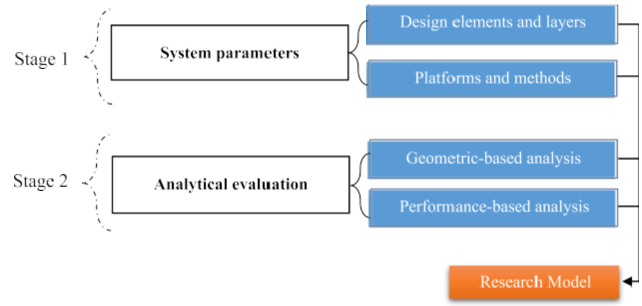


Fig. 5. Review framework for studying a dynamic shading system.

4. Design elements, platforms and methods of dynamic shading systems

The design of a dynamic shading system involves multiple layers and parameters which require processes and methods to assess its performance in terms of reliability, validity and effectiveness to reveal the potentials and shortcomings of the system. The establishment of a dynamic shading system is accomplished through different components, as illustrated in Fig. 6. This process involves a multidisciplinary approach [48], which is called mechatronics [49], incorporating fields such as architectural, mechanical, electrical and software engineering [50]. These aspects will be discussed in detail in the following sections.

4.1. Design elements of dynamic shading systems

The shading skin of a system is composed of physical layers which design incorporates two main components: static parts (shading elements) and mechanical parts, such as gear wheels and rails [48]. The design of these layers requires architectural and mechanical understanding. Meanwhile, the operational layer addresses the required power utilities to run the system [51]. These layers incorporate several design parameters that affect the environmental and energy

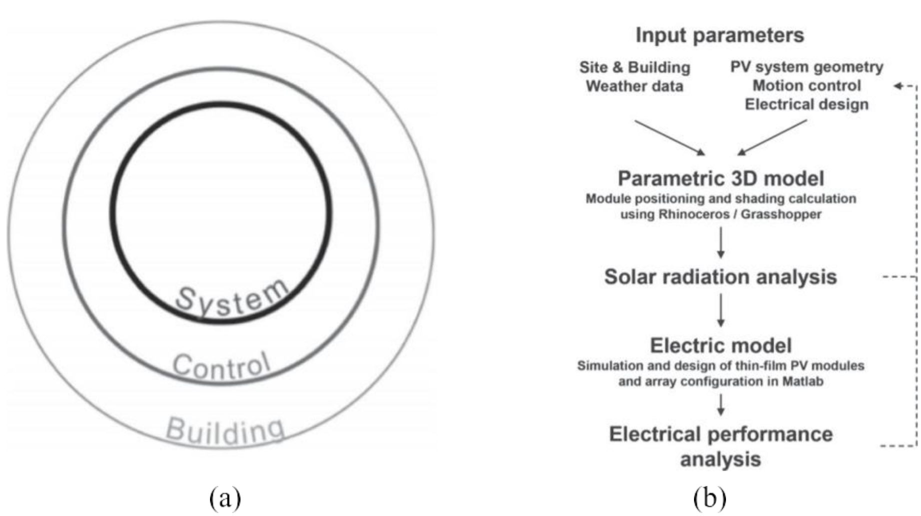


Fig. 4. (a) Diagrammatic representation of the three analysis levels for dynamic operation building skins [29]. (b) Modelling framework that represents ways to optimise geometry, motion control, and electrical design parameters based on system performance [47].

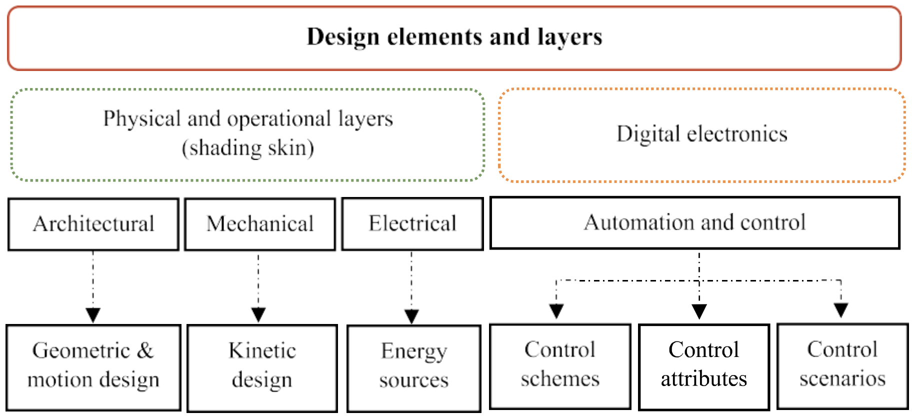


Fig. 6. Components engaged in the design of dynamic intelligent shading system.

performance of a system [48]. Thus, these aspects will be further elaborated individually.

4.1.1. Architectural components

The architectural design of a dynamic shading system starts from identifying the geometric shape of the device or the structure [48], along with a clear perception of the movements performed by its elements. These aspects must reflect the site requirements and respond to various climatic data, such as sun angles [52,53] or incident solar radiation daily and yearly [38]. Moloney [54] specified three primary forms of motion established for any single movement in space: (i) translation, which is the linear shift parallel to the coordinate axes; (ii) rotation, in which the object's orientation in space is changed by rotating around the coordinate axes; and (iii) scaling, which is the increment or diminution of the unit size, as illustrated in Fig. 7(a). However, different typologies (architectural types) can be produced from every type of movement based on the degree of freedom related to geometrical restrictions, such as the number of coordinate axes[55,56], as shown in Fig. 7(b & c). Three degrees of freedom can be identified for each type of these motions based on the form of change in position or orientation with respect to one, two or three axes [56]. For example, rotation can produce three different typologies: swivel (restricted rotation), revolving (free rotation) and swing (off-centre rotation flap) [55]. Moreover, a combination of two basic movements, such as translation and rotation, can generate other typologies, such as expanding, contracting, folding [56], directional twist or rolling [57], as shown in Fig. 7(b). On the basis of these rules, many models can be designed and then analysed through a climate-based study to determine the effective shading configurations.

4.1.2. Mechanical components

The mechanical studies address the kinematic and kinetic design of

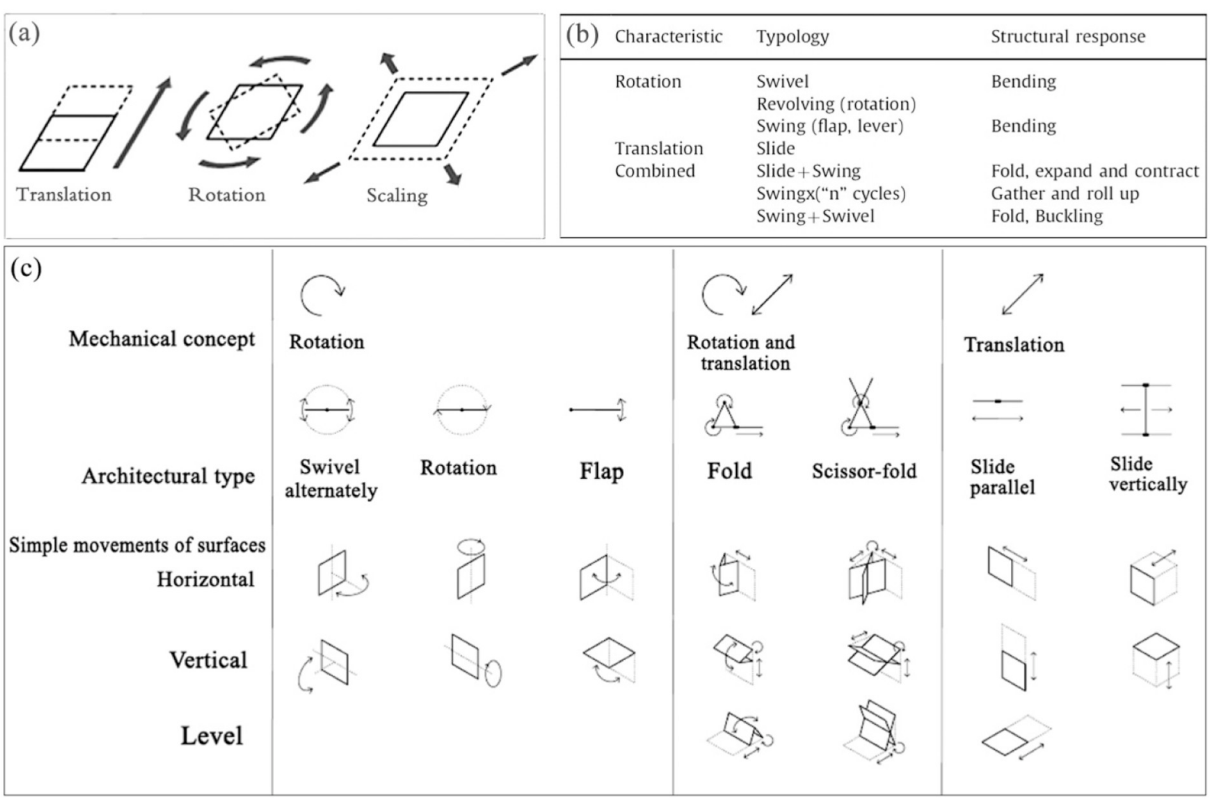


Fig. 7. (a) Forms of spatial geometric transformation of rigid bodies [54]. (b) Typologies of movement breakdown [55]. (c) Movements of rigid building elements [56].

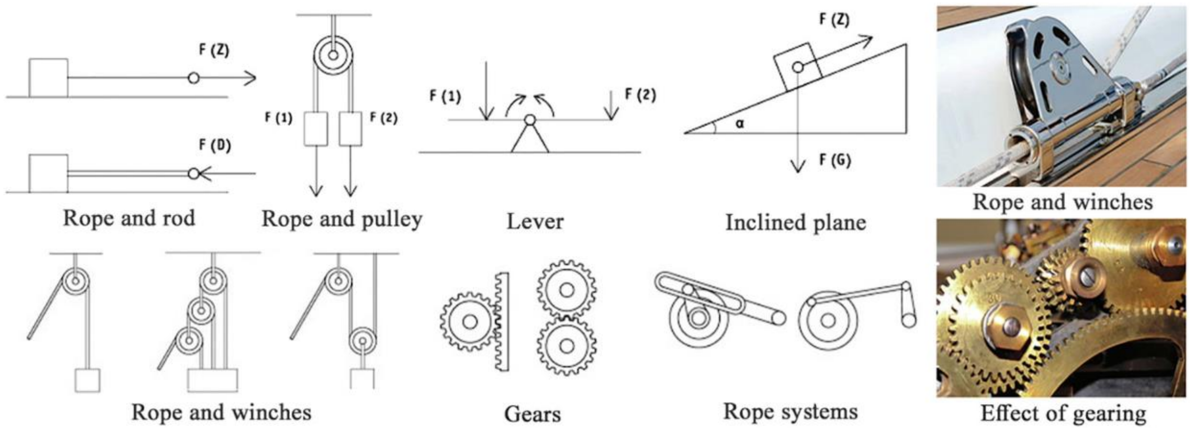


Fig. 8. Some mechanical devices employed for actuating mechanism [56].

the device based on the architectural concept, which presents moving elements as a whole at the macro level. Schaeffer and Vogt [56] stated that moveable elements are composed of rigid bodies connected by hinged joints, in which a complex chain of movements occurs to produce motion. In many cases, the movement of architectural elements in space is different from the sequential and geometric movements running at the detailed level [56]. The mechanical movements can always be reduced to two basic movements, that is, translation and rotation, or a combination of the two, as indicated in Fig. 7(b & c).

The motion of rigid bodies can be presented in two scales: kinematic and kinetic. *Kinematics*, as stated by Schaeffer and Vogt [56], 'refers exclusively to the temporal process of motion and involves recording the geometric displacement of one or more bodies over time'. In addition to other key parameters, such as duration, velocity and acceleration, *kinematics* helps determine the distance travelled. Meanwhile, the term *kinetics* refers to the relationship between motions and its origins, as well as forces and torques [58], given that any movement is inter- preted through methods of analytical dynamics, where the magnitude and the point of application or the direction of an applied force are organised by mechanical devices called the machines (actuators). This approach can vary between simple and compound models [56]. McCarthy and Soh [59] described machine as a 'system that generally consists of a power source and a mechanism for the controlled use of this power'. As shown in Fig. 8 [56], this mechanism employs various devices and accessories, such as bars, ropes, pulleys, levers, winches and gears, to achieve the desired output of forces and movements.

The actuators, which are generally presented as valves or motors [60], are responsible for the direct activation of the process [61]. Different types of actuators can be used to move shading elements based on several aspects, such as motion type, degree of freedom, size and weight of shading elements and façade coverage area [56]. Different examples of frequently used actuators are available, such as linear actuators for moveable louvres and slat adjustments, heavy-duty rack actuators for large façade areas and linear actuator arms for folding mechanism, as illustrated in Fig. 9.

4.1.3. Electrical components

Electricity is an immanent part of the operation of dynamic shading systems. In addition to other sources, such as pneumatic or hydraulic energy [51,60], electricity is frequently a source of power necessary to activate the actuator mechanism [59]. Several factors can affect the required energy input to move shading elements, such as the direction of movement in relation to the direction of gravity, the self-weight and bearings of the objects, as well as the actuator choice and its structural allocation [59]. Karanouh and Kerber [20] stated that the central linear actuator of each origami screen used in Al-Bahr Towers uses less energy than a regular light bulb; each screen has a height of 4.2 m, a width of 3.6–5.4 m and an approximate weight of 625 kg, as shown in Fig. 9. In addition to pneumatic energy [62], several resources of alternative energy have been successfully employed to run active dynamic systems, such as electricity generated by solar panels [20,63] or by photovoltaic cladding integrated with shading elements [7,64], as shown in Fig. 10.

4.2. Digital electronics of dynamic shading systems (automation and control strategies)

Dynamic shading systems respond to external data through rule-based automation [20], which incorporates hardware and software

Fig. 9. Some models of linear actuators used for active façade systems (https://www.elerolinear.com) and screw-jack linear actuator used in folding screens of Al-Bahr Towers in Abu Dhabi [20].

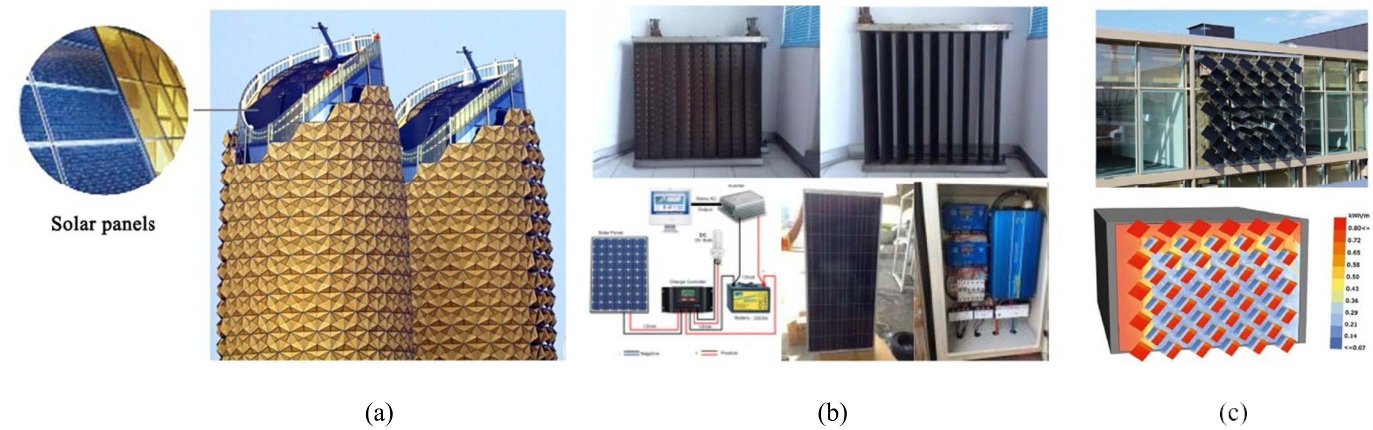


Fig. 10. (a) Solar panels employed to generate electricity to operate origami shading screens [20]. (b) Dynamic vertical fins [63]. (c) Adaptive BIPV shading system [64].

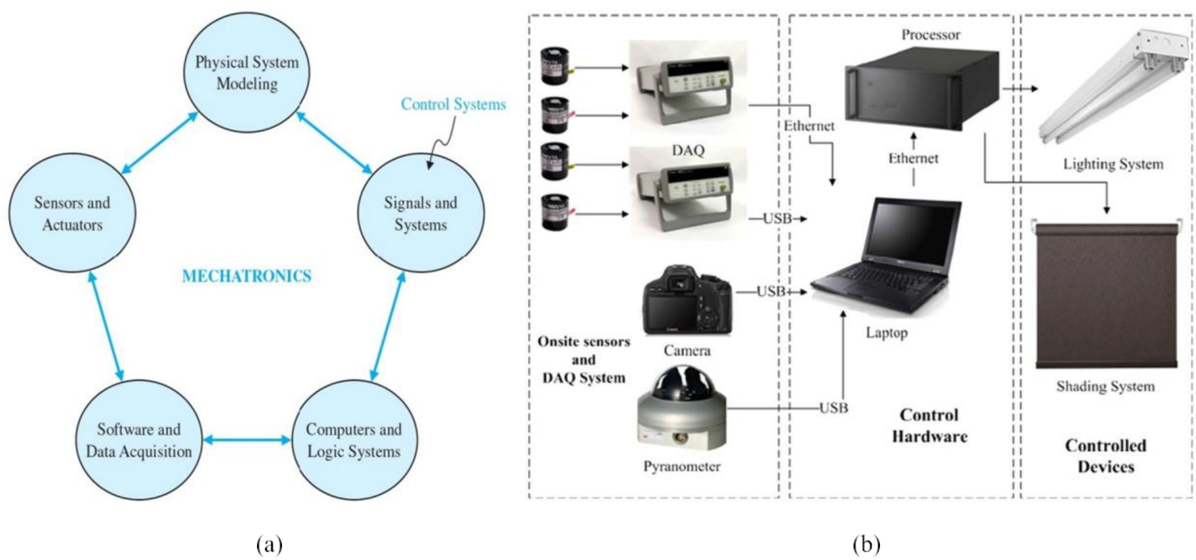


Fig. 11. (a) Components of a typical control system [49]. (b) Electronic apparatuses and control hardware utilised with dynamic roller shade [66].

layers that comprise a series of apparatuses, such as sensors, controllers and logic units [49], along with a control system, which sends commands to other engaged tools to perform the desired action [65], as shown in Fig. 11. The design of a control system requires comprehensive knowledge of the targeted process and the mechanism of engaged sensors and actuators, which are mostly linked to a communication network [60]. The basic concept of control systems converges with the study of dynamic behaviour [67]. Mughal [24] described the dynamic system as having a memory where the input value at a certain time affects the output, thus interacting with its environment through variables and environmental disturbances. This linear progress reflects a dynamic cause-and-effect relationship within the process, as presented in Fig. 12 [24,50,67]. The control system can be split into two main parts: inputs and controllers [51]. The inputs provide all the required data to fulfil the purpose of the system [65]. They detect the

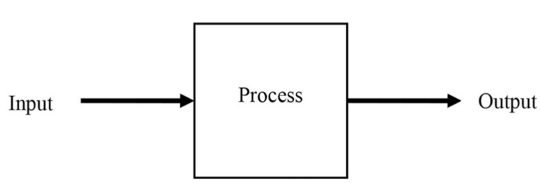


Fig. 12. The input–process–output (IPO) model (block diagram) [50].

information from the surrounding environment and convert it into instructive signals, taking different forms, such as manual input method, sensors, restored information, manual programming or internet [68]. The controller acts as an interface between the input means and the actuators, and is driven by computation, a software unit or a computer [51], as shown in Fig. 11(b).

4.2.1. Control strategies (analytical schemes of control systems)

Two types of control systems can be formulated: open-loop (feed-forward) and closed-loop (feedback). An open-loop system can control the process by directly activating the actuator without using feedback, as shown in Fig. 13(a). A closed-loop system uses a comparison of the actual output with the desired output response (reference) as a feedback signal to constantly reduce the variation (error), as demonstrated in Fig. 13(b) [24,50,69]. Therefore, the controller in the feedback systems has two inputs (the measured and the reference signal) and one output (controller signal) [60], which helps improve the system performance, continually correcting the eventual action [60]. Closed-loop control is the preferred scheme for the dynamic operation because it is capable of rejecting the unavoidable external disturbances; moreover, it can improve the measurement noise attenuation because the two external signals affect the result and must be considered in the practical implementation [60]. Haugen [70] defined the measurement noise as a random signal proliferated by the controller, leading to variations in all variables in the control path. By contrast, the disturbances are described by Dorf and Bishop [50] as 'unwanted input signal that affects the output signal'. Practically, all control systems are prone to disturbances [71]. According to Åström [60], disturbances can take two main forms: (1) measurement noise and (2) load disturbances, which can misguide the system out of its aimed behaviour. Many types of disturbances can virtually enter the system from various resources [60]. These disturbances might take several forms: (1) change in the desired variable's value (set point); (2) change in supply, representing any variation in the energy inputs to the process; (3) change in demand, which is a disorder of the output energy flux; and (4) environmental changes, such as atmospheric pressure or ambient temperature [72]. In the end, the presence of disturbances is the main motivation for adopting the feedback systems, in which errors are constantly corrected by the controller [60], as illustrated in Fig. 13(b).

employ an open-loop protocol driven by various stimuli, such as the angle of incident sunlight [38,69], outdoor illuminance levels [78], or hourly sky condition [79]. However, despite the restricted capabilities of reactive system controller, it can still generate some modifications, such as amplifying, minimising or speeding up [73]. The responsive control system was applied in Al-Bahr Towers in Abu Dhabi in 2012, where foldable shading screens change their configurations in response to sun angles [20], as shown in Fig. 10(a).

Automated shading systems can be labelled as *interactive* when they control climatic response and user needs [73]. Thus, they can perform a double mission, that is, responding to environmental changes by regulating sunlight flow and meeting the needs of the inhabitants by fulfilling different tasks and preferences [80]. In this case, a closed-loop or feedback protocol can be employed to sustain adaptive behaviour [81]. Creating a real-time interaction between the system and the user

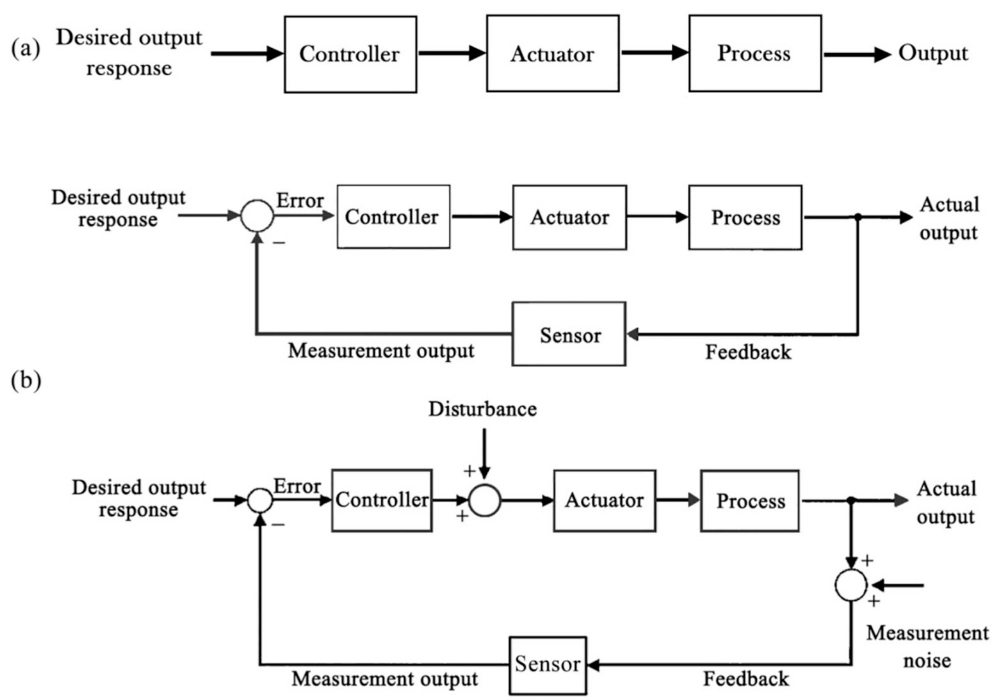


Fig. 13. (a) Open-loop control system without feedback; (b) Closed-loop (feedback) control system and closed-loop control system with disturbances [50].

4.2.2. Control technological attributes (automatic control characteristics)

Most dynamic systems are controlled in a fully automatic mode [24], in response to the outdoor or indoor environment [27]. Apart from a series of fine-tuned sensors and actuators [24,67], dynamic systems utilise software (control systems) and hardware tools (controllers). The controller constitutes the most important component in the automation cycle, and its properties and capabilities can offer various behaviours. Achten [73] labelled the sophisticated levels of responsiveness by interactivity based on the controller capabilities and the user role in the automation process, as illustrated in Fig. 14. In this context, Loonen [74] differentiated between two control methods, namely, automatic and automated, which can be adjusted or modified by users. Thus, on the basis of the control system layout, the controller characteristics and the participation of a third party (agent), two classes of systems, namely, reactive and interactive systems, can be distinguished [73].

Dynamic shading system is generally referred to as responsive or reactive when it automatically responds to the exterior environment [20] by receiving data from its surroundings and providing a reactive response without an agent. In other words, users cannot interfere in its responsive manner [75]. The reactive system directly responds to some stimulus within a predetermined manner [76], to regulate the flow of natural light and heat at the level of building façades [77]. Thus, it can

through an agency is possibly the most striking feature of interactive systems [75]. A similar approach can be observed through mixed-mode control, which can override the automatic mode to manual control. One example is the dynamic foldable screens of Kiefer Technique Showroom [82], which can react to outdoor and indoor variables whilst allowing the occupants to customise their needs with a user control option [83]. Achten [73] distinguished two types of interactive systems: (i) autonomous system, in which logic unit can independently determine the suitable response (output) based on multiple inputs, and (ii) agent system, in which the programming method helps predict users' preferences without any direct interference by contacting other systems, as shown in Fig. 14. Therefore, the contact between the user and the system can be observed in the following two forms: (1) active relation, in which the user directly initiates the system through a physical action (e.g. holding a button), and (2) passive relation, where the system at- tempts to identify what the user wants without any request [73].

In this context, Sherbini and Krawczyk [68] distinguished four types of indirect control: (1) input control, (2) multi-input control, (3) ubiquitous multi-input control and (4) intelligent multi-input control. This form of controlling technology conforms with grid-based and para- metric shading models, where each shading element can perform an individual responsive movement. Yekutiel and Grobman [84]

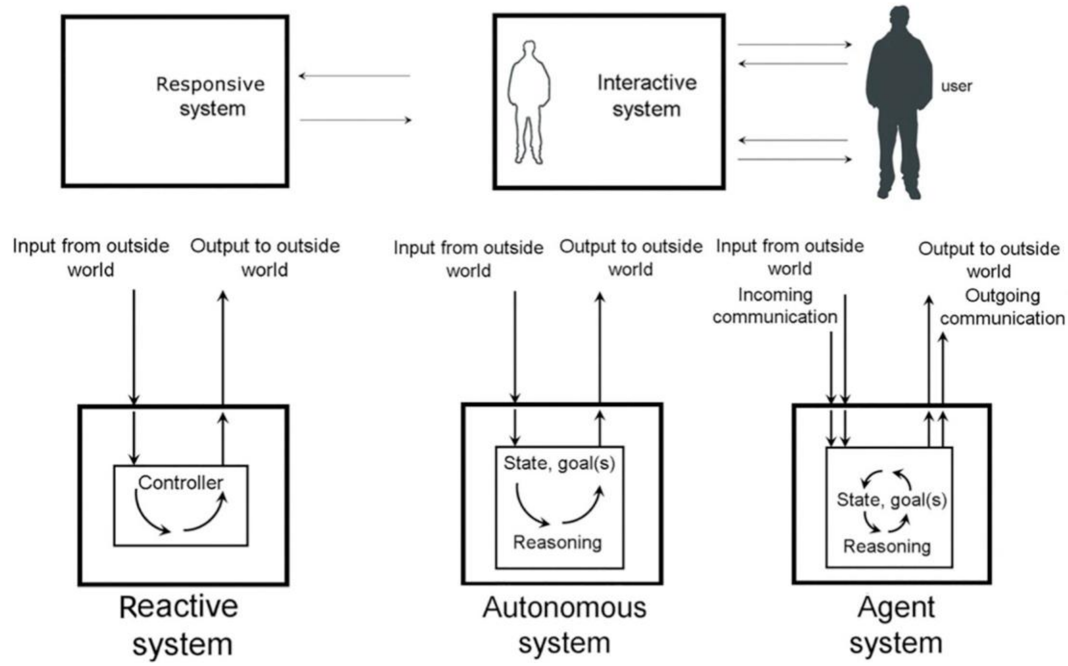


Fig. 14. Responsive architectural systems based on types of technology [73].

categorised the operation of kinetic screens or cladding into three types: (1) central control, which employs sensors, central controller and actuators, driving the same order for all actuator devices; (2) sensor–-actuator control units, which are self-processing and self-actuating, with an advantage of sharing information with other neighbouring units through an 'information hub', allowing for a coincident reaction between elements; and (3) independent sensor–actuator devices, which directly react to their environment without obtaining any input from other adjacent units. On the other hand, decentralised control is an intricate method with a small and low-cost controller for each kinetic element, which can communicate with its peers, and it can be implemented with parametric design tools [84].

4.2.3. Potential scenarios and issues to control a dynamic shading system

Considering motorised Venetian blinds and lighting control as case studies, this section describes the potential scenarios to control a dynamic shading system as an individual protocol or incorporated with other intelligent systems (mixed control systems).

A- Single-protocol scheme

Two protocols can be established to control a dynamic shading device, namely, open-loop and closed-loop scheme, as shown in Fig. 15. In the closed-loop system, the control signal adjusts the slat angle based on two inputs: daylight setpoint (desired illuminance value) and measured workplane illuminance (feedback) [33,69,85]. However, this type has substantial issues, such as inaccuracy due to the disruption of artificial lights and room geometry on sensors allocation [85]. In the open-loop control, indoor daylight levels do not affect the system performance, where the controller is directly provided by outdoor climatic information through exterior sensors for comparison with the setpoint [69,85]. However, this control might lead to additional complexity and disturbances due to unconsidered variables, such as the optical properties of the shading device and interior space characteristics [69]. This control can also involve a local network of several sensors to share information [85]. Thus, a multivariable control scheme that considers the intersection amongst different variables might achieve satisfactory performance [50]. Despite the complex variables brought by open-loop

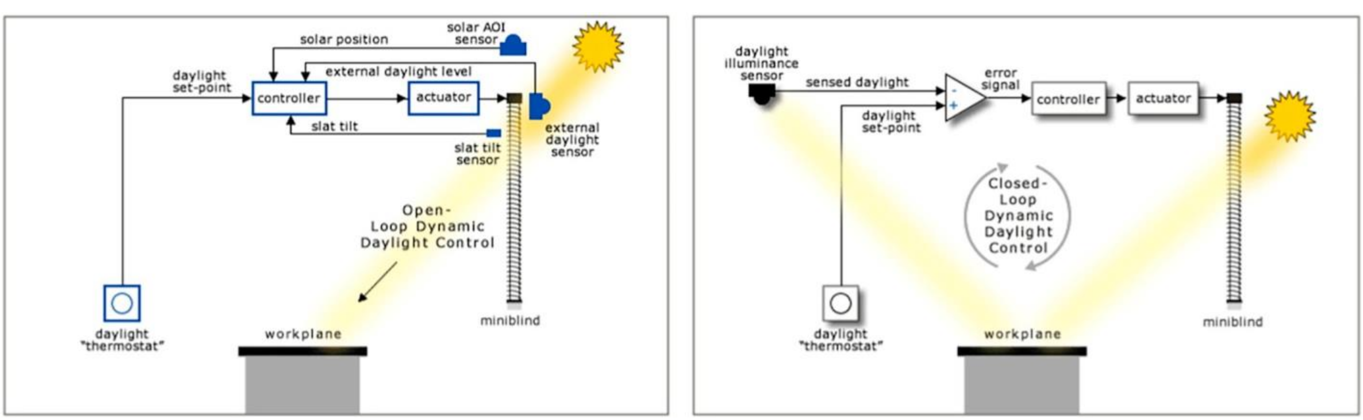


Fig. 15. Dynamic shading system with open-loop and closed-loop protocols [85].

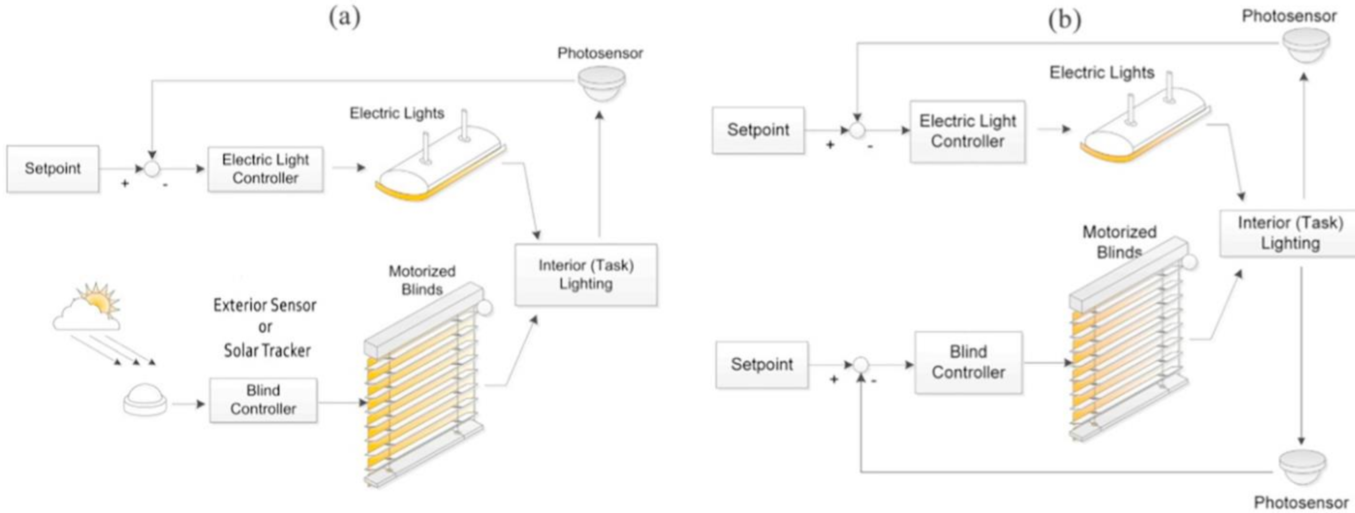


Fig. 16. (a) Independent control of closed-loop lighting system and open-loop blinds system. (b) Independent control of two closed-loop systems; blinds and electric lighting [69].

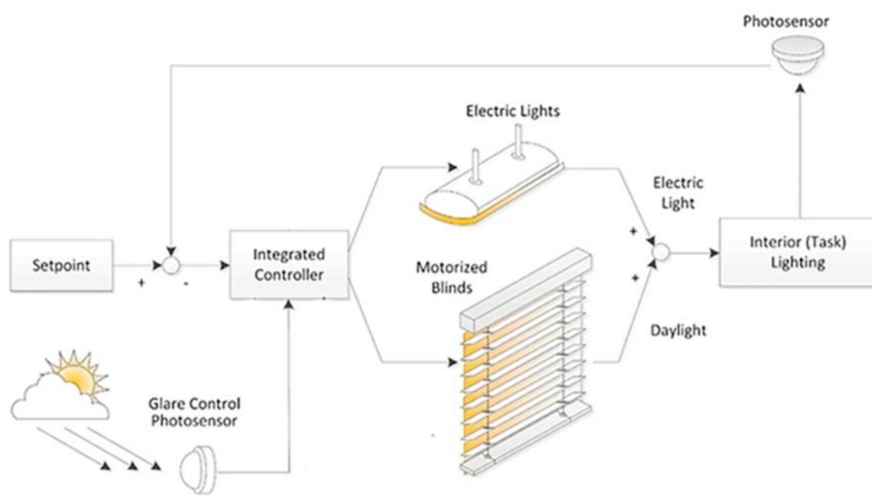


Fig. 17. (a) Integrated lighting and shading control systems [69].

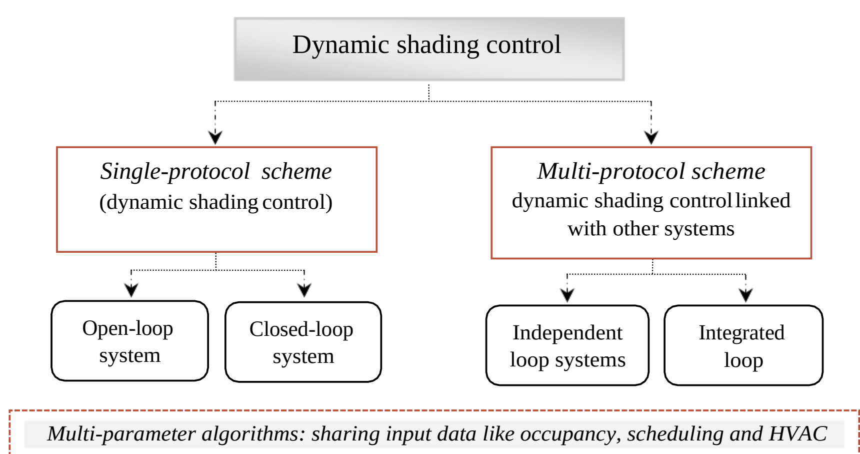


Fig. 18. Potential scenarios to control a dynamic shading system.

protocol, it is still an autonomous and cost-effective method because it can employ one sensor to control a set of devices, such as a roof-mounted sensor [33], which is preferable in multiple control zones such as open-plan office spaces [46].

B- Multi-protocol scheme (independent and integrated systems)

Several scenarios, such as the installation of hybrid approaches that combine open- and closed-loop systems [85] or multiple feedback-loop, which is widely employed in the real practices [50], can be established to avoid the issues of each type of individual control. Hybridisation of control systems is a promising strategy in the automation field [46] but requires careful analysis to avoid some probable issues. For example, a multi-protocol scheme of two systems, such as shading and electric lighting, is an important strategy to maintain the optimum situation of daylight and energy inside the building [69].

Fig. 16 illustrates two different scenarios of independently controlled multi-loop schemes [69]. However, each of these scenarios has potential drawbacks [29,69]. Mukherjee et al. [69] claimed that employing two or more feedback systems that address the same variable requires a careful design strategy. For instance, when installing two closed-loop systems, blinds and electric lighting that work separately and address indoor illuminance level from two different sensors without any shared information will lead to a non-optimal operation or serious performance devolution [86], as indicated in Fig. 16(b). How- ever, a fully integrated closed-loop system can realise optimal results because it employs shared input data within the control scheme [29] using a single photosensor device, as shown in Fig. 17(a) [69]. This strategy aims to attain the setpoint whilst maximising daylight utilisation [66,69].

Mukherjee et al. [69] used MATLAB simulation to test three scenarios of a hybrid scheme, that is, combined shading and electric lighting control. The study obtained the following results: (1) Multi-feedback loops that work independently cause the blinds to remain closed, whilst the desired workplane illuminance is always sustained by electric lighting, which resulted in low comfort and high energy consumption. (2) The use of the lighting closed-loop scheme along with the shading open-loop scheme, which adjusts slats based on solar angles as shown in Fig. 16(a), drives fully deployable blinds day and night. (3) An integrated closed-loop scheme to control blinds and electric lighting within one platform outperformed the other strategies by improving illuminance level, preventing glare and decreasing lighting demand, as shown in Fig. 17.

Employing mixed control systems, such as shading and lighting, provides an effective strategy to conserve energy and bridge any gap in shading performance. Parise and Martirano [87,88] stressed that daylight and artificial lights must be considered in coordination to maximise daylight usage and maintain visual comfort. ul Haq et al. [46] urged to consider shading and lighting control as a whole idea at the early design stage to achieve ultimate energy savings. Different forms of daylight-linked systems can be utilised with dynamic shading to maximise daylight availability. Al-Obaidi et al. [36] utilised a fibre optic daylight system (FODS), which uses fibre optic cables to deliver natural light into a space, along with roof light and dynamic shading in one integrated platform. Therefore, dynamic shading control can be applied as an individual system using single-protocol scheme or linked with other systems in the space, such as DCS or FODS, through a multi-protocol scheme working within independent or integrated platforms capable of sharing other data, such as occupancy, scheduling and HVAC [46]. All these scenarios are illustrated in Fig. 18.

4.3. Platforms and methods of dynamic shading systems

The performance of dynamic shading systems can be investigated by using simulation or experimental platforms or a combination of both [40]. The theoretical approaches usually employ a simulation software based on mathematical models to propose optimal configurations based on the daily, seasonal or yearly performance against a specific metric [40,89–91], or a control strategy (algorithm) developed by the software [53,92–94]. The experimental technique depends on the application of a mechanism to test the system behaviour [63,95,96]. The tools and workflow of activities of different methodologies will be discussed in the following sections.

4.3.1. Theoretical methods (simulation-based methodologies)

Computer simulation that utilises mathematical models has shown its effectiveness through high computing power in addition to its ability to simulate and predict the real-life performance of buildings [27]. It further offers a well-controlled environment that facilitates dynamic optimisation [40], as shown in Fig. 19. Although simulation programs can generate optimum designs under a specific climate, they have limitations in relation to daylight analysis [91]. Current simulation techniques generally lack a reliable and automatic projection of motion due to the absence of proper means. The survey shows that dynamic tools for real-time assessments under variable climatic data are not provided, whilst the evaluation of dynamic systems must consider variable conditions [25,90]. Therefore, some literature tested the dynamic geometries at several positions to obtain optimum configurations based on specific design criteria [7,40], while other studies employed parametric tools along with genetic algorithms, such as Galapagos in Grasshopper, to generate optimal solutions using climate-based analysis at different times of the year [97]. Several tools such as Ladybug and Honeybee are utilised to link CAD and visual scripting interfaces (Grasshopper and Dynamo) to a host of simulation engines, especially, Radiance and EnergyPlus to generate weather acquisitions and analyse
daylight performance [13], or conduct a field study using static configurations predefined in the simulation [15,98]. Lim and Heng [15] proposed optimum light shelves design using radiance-based simulation and tested it under real climate using a 1:20 scale model. Similarly, Hashemi [98] proposed effective louvre configurations through IES simulation, and measured the indoor illuminance under real climate using a 1:1 scale mock-up. However, these studies did not develop any operation mechanism but considered static shading elements for field measurements. Fig. 20 illustrates the workflow of such methodologies.

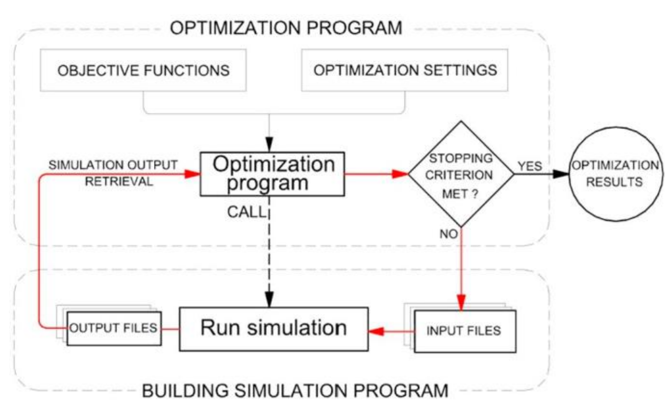


Fig. 19. Algorithm of the optimisation process in simulation-based methodologies [103].

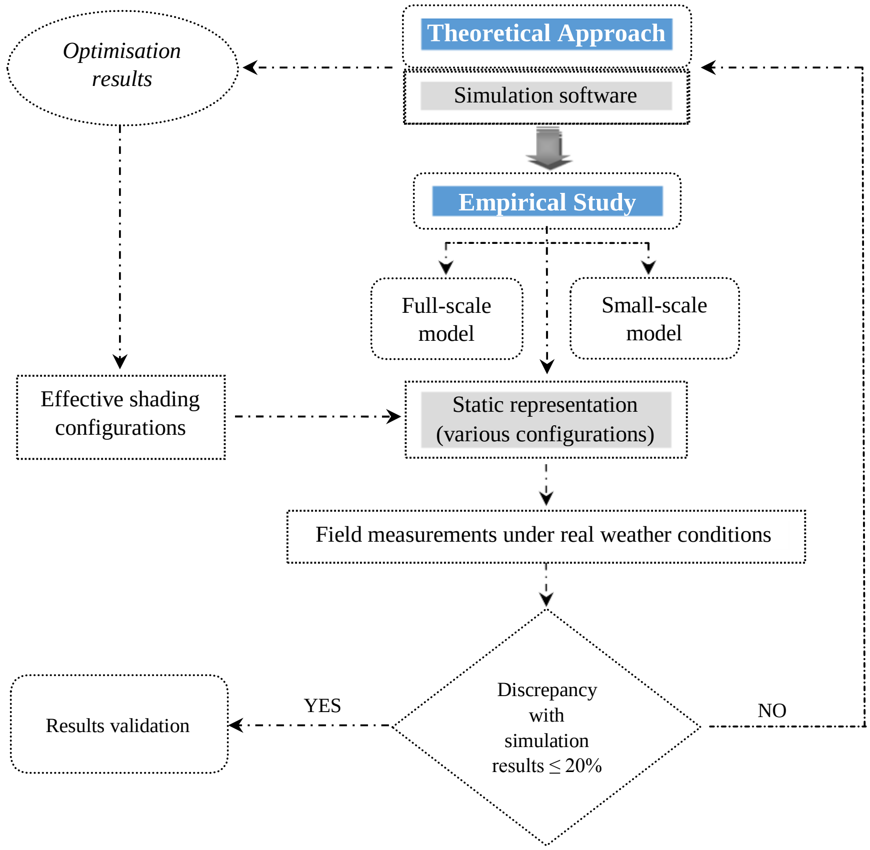


Fig. 20. Methodology to evaluate dynamic shading performance without using active mechanism.

4.3.2. Experimental methods (mechanism/responsive behaviour)

This approach presents methods that implement an operating mechanism to test the system behaviour. These methods use a controlling algorithm based on logic units or digital control (software program) [25], which can be applied to actual-scale models [95], or small-scale prototypes that frequently use parametric software tools, such as Grasshopper plug-in and Arduino hardware with low-cost micro- controllers [84], Fig. 21. Other studies have developed real controlling algorithm with actual-scale models [36,63]. Thus, the following three experimental methods can be employed: (i) real control with actual- scale models, (ii) digital control with actual-scale models and (iii) di- gital control with physical scale models (operational prototypes), as illustrated in Fig. 22. These methodologies generally rely on empirical observations to assess the capability of the system to respond in real time and accordingly evaluate its impact on the built environment [95]. Therefore, several aspects, such as kinetic response, environmental performance, automation tools and control systems, can be highlighted. Digital control represents the most striking advancement that is frequently applied in this approach. This method assesses the responsive capability of the system towards a specific stimulus [95] by using a set of rules determined by the designer within a digital environment. A group of tools is engaged in this process, such as Arduino, which is described by Sharaidin [25] as “an open-source electronic platform based on easy-to-use software”. It interacts with the environment by receiving inputs and sending outputs using sensors and actuators. Arduino can be programmed by writing codes in programming languages, such as C++ and Python, in Arduino programming, processing and Grasshopper [25,96]. The other component in this process

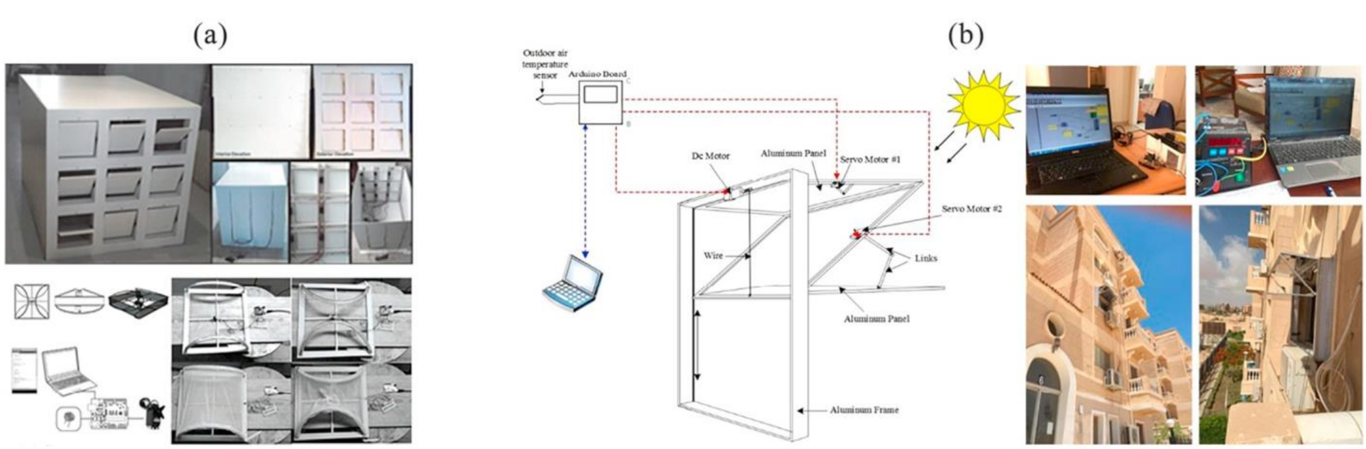


Fig. 21. Methodologies using digital control: (a) with small prototypes [84] and (b) with full-scale models on actual building [95].

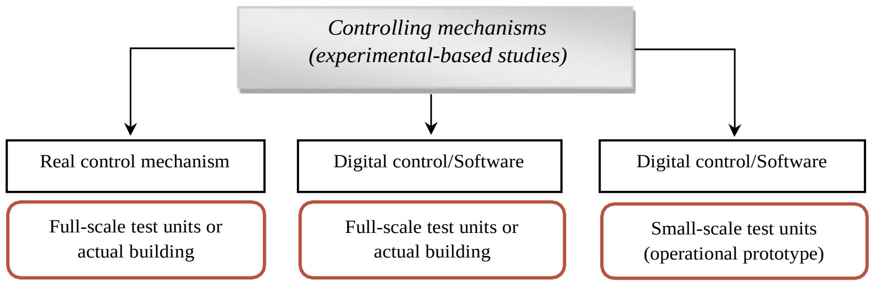


Fig. 22. Application of controlling mechanisms over testing units in the experiment-based methodologies.

is the software tools that allow for an interactive link between the digital and analogue devices. For example, Firefly software directly connects the Arduino microcontroller to an algorithmic software, such as Grasshopper, which introduces a visual programming language operated within Rhinoceros. Some physical devices, such as DC voltage regulator and input devices, which include light, luminosity or temperature sensors and actuators such as rotary actuator (servomotor) which is used to adjust angular position, velocity and acceleration, are also engaged [25].

5. Analytical evaluation of dynamic shading systems

Studies on dynamic shading systems were reviewed based on the metrics presented in the methodology section, and two forms of classification were conducted: (1) geometric-based analysis, which investigates the identity and depth of shading model design, and (2) performance-based analysis, which examines the environmental or energy performance of the system through theoretical and experimental approaches.

5.1. Geometric-based analysis (design and motion layout)

This section comprehensively investigates the depth of a moveable system which describes the sum and complexity of the individual interacting movements required to produce a large movement [56]. Fiorito et al. [55] related the complexity of design to system identity. Schaeffer and Vogt [56] identified three aspects that can increase the geometric complexity of a dynamic movement. First, mobile elements change over time, generating two- or three-dimensional movement, which considerably increases geometric intricacy. Second, the combination of individual movements that follow a hierarchical pattern within the kinematic chain in addition to the number of performed movements, such as a combination of translation and rotation movements that produces complex patterns, such as contracting or folding. In addition, the degree of freedom of coordinate axes can generate complex typologies, such as revolving [55]. Third, the collective combination of linear chains creates transforming structures, such as three-dimensional lattices.

From this, the design of motion layout addresses the movement types and typologies, along with the architectural formulation of shading units and elements. These parameters are crucial to assess the geometric intricacy of a shading device. Generally, the architectural composition of shading elements is affected by the façade style, where the following two main forms can be distinguished based on the aperture type:

(1) Single-unit devices, in which the model is composed of one shading unit located over the window; this unit might include one or more moveable elements, such as a roller shade (one unit/one element) [43] or kinetic assembly (one unit/set of moveable elements) [95].
(2) Multi-unit devices, in which the model consists of numerous units, and each unit can include single or multiple moveable elements where two synthesis methods can be followed by (i) horizontal or vertical replication of elements, such as Venetian blinds, louvres and fins [40,63,94], (ii) grid-based replication, which might be composed of arrays of single-element units, such as kinetic cladding [84], and (iii) arrays of multiple-element units, such as origami screens [92,99].

On the basis of this description, the reviewed studies can be divided into two groups: simple and complex shading models. The complexity of the model is determined based on two metrics: (a) multiplicity of elements and movements per shading unit or grid (x,y surface) or within one kinetic device, and (b) complex typologies, which result from a combination of two or more types of movements within the shading device or unit. Consequently, all grid-based shading models are labelled as complex devices even if they consist of single-element units, because they can create two or three-dimensional transforming structures [56]. Table 1 illustrates twenty reviewed studies, where the shading systems are categorised as simple and complex models. Table 2 presents a complete analysis of the geometric and motion design parameters of the presented shading devices. All the criteria of shading model complexity are highlighted accordingly.

5.2. Performance-based analysis (design criteria, control strategies and performance)

The study found that some methodologies generally presented less interpretation in relation to automation and control issues. Therefore, the performance of dynamic systems is classified and reviewed based on two approaches: (a) simulation-based studies conducted solely or along with empirical validation without applying an operation mechanism and (b) experimental-based studies that test the responsive behaviour of the system through a controlling algorithm. The geometric complexity will be distinguished accordingly.

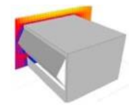
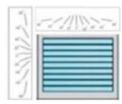
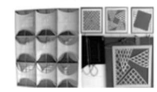
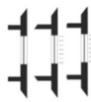
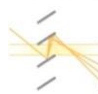
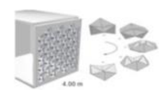
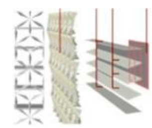
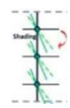
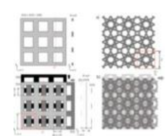
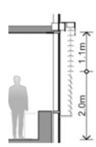
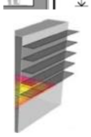
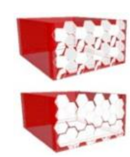
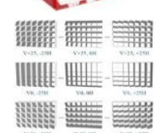
5.2.1. Performance of dynamic shading systems through simulation-based studies

1) Simple geometries

Tzempelikos and Athienitis [38] tested a dynamic roller shade on an office space in Canada against lighting and cooling energy using simulation. The device is driven by incident solar radiation, where it opens at < 20 W/m^2. This strategy, along with dimming light control, can reduce 50% of annual cooling energy compared with a non-shaded window whilst increasing lighting demand. Hammad and Abu-Hijleh [40] tested the impact of dynamic louvres on lighting and HVAC energy of an office space in Abu Dhabi. The control aims to ensure minimum energy consumption incorporated with a light dimming strategy that considers the occupancy parameter. Several slat angles were modelled and tested in IES simulation program. Although a slight preference over static louvres was observed in most cases, the effective model achieved the maximum energy reduction of around 28%–34% amongst other scenarios.

Konstantoglou et al. [93] presented seven strategies to control a

Table 1
Dynamic shading systems based on model design complexity.

Dynamic shading systems									
Simple shading models					Complex shading models				
No.	Study	System	Motion type	Graphical models	No	Study	System	Motion type/ pattern	Graphical models
1	Tzempelikos and Athienitis [38]	Roller shade	Translation		11	Kensek and Hansanuwat [7]	Folding panels	Rotation+ translation/folding	
2	Hammad and Abu-Hijleh [40]	Louvres	Rotation		12	Grobman and Yekutiel [100]	Kinetic cladding	Rotation translation	
3	Nielsen et al. [94]	Venetian blinds	Rotation translation		13	Yekutiel and Grobman [84]	Kinetic cladding	Rotation/ revolving	
4	Konstantoglou et al. [93]	Louvres	Rotation		14	Elghazi et al. [92]	Origami	Rotation+ translation/folding	
5	Yun et al. [101]	Venetian blinds	Rotation		15	Sabry et al. [99]	Louvres Origami	Rotation+ translation/folding	
6	Sjarifudin and Justina [96]	Louvres	Rotation		16	Kim et al. [53]	Origami	Rotation+ translation/folding	
7	Priatman et al. [63]	Vertical fins	Rotation		17	Giovannini et al. [52]	Kinetic Mashrabiya (SVM)	Translation	
8	Bunning and Crawford [79]	Venetian blinds	Rotation		18	Ahmed et al. [95]	Kinetic device	Rotation+ translation/folding, sliding	
9	Grobman et al. [89]	Louvres	Rotation		19	Mahmoud and Elghazi [90]	Hexagon-based grid	Rotation translation	
10	Skarning et al. [43]	Roller shade	Translation		20	Wagdy et al. [91]	Solar screens	Rotation	

dynamic louvre in an office building in Greece. EnergyPlus software allows the tilt angles to be set every hour on a yearly basis. The system was evaluated based on total energy for lighting, cooling and heating. A threefold plan to ensure adequate illuminance, prevent glare and provide a view to the outside achieved the best results with a reduction of 25% in lighting energy in comparison with static louvres. Yun et al. [101] examined automated Venetian blinds against energy and visual comfort of offices in South Korea. A total of 10 strategies of lighting and shading control were tested in EnergyPlus and Diva-for-Rhino and activated by illuminance threshold using an interior–exterior sensor. When illuminance level exceeds the value of (3 k lx indoors, 10 k, 20 k and 40 k lx outdoors), the slats are adjusted to 0°, 15° and 30°, respectively, and vice versa. The results were validated with a 1:1 scale mock-up, providing evidence for adequate daylight level and a reduction in glare and energy loads for lighting and cooling, respectively.

Bunning and Crawford [79] investigated the energy performance of directionally selective Venetian blinds in an office building in Melbourne and Brisbane, Australia. A control strategy based on hourly sky condition and relative solar angle was developed in DesignBuilder and EnergyPlus software to adjust the slats into upper and lower groups. The results showed that dynamic control delivered remarkable energy savings of approximately 24.9% compared with that of fixed overhang and static internal blinds. Grobman et al. [89] investigated the capability of dynamic louvres to ensure proper internal illuminance in an office space in the Mediterranean climate. The benchmark is the optimum values of average useful daylight illuminance (AUDI). Rhino3D modelling software, Grasshopper and DIVA plug-in simulation tool were employed to define the optimum configurations, which improved

Table 2
Criteria of defining simple and complex shading models based on geometric and motion design parameters.

Parameters of geometric and kinetic complexity of dynamic shading devices

Study	Model	Units	Moveable elements per unit	Motion type	Movement number per unit	Motion characteristic	Formulation strategy	Motion typology	Degree of freedom (rotation)
Simple shading models									
Tzempelikos and Athienitis [38] and Skarning et al. [43]	Roller shade	Single unit	Single element	Translation	Single movement	2D	One piece	–	–
Nielsen et al. [94], Yun et al. [101] and Bunning and Crawford [79]	Venetian blinds	Multiple units	Single element/ unit	Rotation	Single movement/ unit	3D	Horizontal replication	Swivel	(0°–90°), (0°–30°), (0°–25°)
Hammad and Abu-Hijleh [40], Konstantoglou et al. [93], Sjarifudin and Justina [96] and Grobman et al. [89]	Louvres	Multiple units	Single element/ unit	Rotation	Single movement/ unit	3D	Horizontal replication	Swivel	(−80°–80°), (0°–90°), (0°–75°), (−45°–45°).
Priatman et al. [63]	Vertical Fins	Multiple units	Single element/ unit	Rotation	Single movement/ unit	3D	Vertical replication	Swivel	−90°–90°
Complex shading models									
Kensek and Hansanuwat [7]	Folding panels	Single unit	Multiple element/ unit	Translation rotation	Multiple movements/unit	3D	One piece	Folding	–
Grobman and Yekutiel [100]	Kinetic cladding	Multiple units	Multiple element/ unit	Rotation Translation	Multiple movements/unit	2D 3D	Grid-based	Swivel Expanding	–
Yekutiel and Grobman [84]	Kinetic cladding	Multiple units	Single element/ unit	Rotation	Single movement/ unit	3D	Grid-based	Revolving	360°
Elghazi et al. [92], Sabry et al. [99] and Kim et al. [53]	Origami screens	Multiple units	Multiple element/ unit	Translation rotation	Multiple movements/unit	3D	Grid-based	Folding	–
Giovannini et al. [52]	Kinetic Mashrabiya	Single unit	Multiple element/ unit	Translation	Multiple movements/unit	3D	One piece	Complex typology	–
Ahmed et al. [95]	Kinetic device	Single unit	Multiple element/ unit	Translation rotation	Multiple movements/unit	3D	One piece	Complex typology	–
Mahmoud and Elghazi [90]	Kinetic panels	Multiple units	Single element/ unit	Translation Rotation	Single movement/ unit	2D 3D	Grid-based	Sliding Flap	– 30°–165°
Wagdy et al. [91]	Solar screens	Multiple units	Single element/ unit	Rotation	Single movement/ unit	3D	Grid-based	Swivel	−25°–25°

Table 3

Dynamic shading systems (design criteria and control strategies).

Performance of dynamic shading systems								
No.	Study	Location	Climate	System	Design criteria	Lighting control	Control strategies: Control schemes	Control strategies: Algorithm/Set point
	Simulation-based studies (theoretical approaches)							Controlling algorithm
1	Tzempelikos and Athienitis (2007)	Canada/ Montreal	Humid continental	Roller shade	Energy (lighting /cooling)	•	Feed-forward	The shade opens when solar radiation is < 20 w/m²
2	Nielsen et al. (2011)	Denmark	Temperate	Blinds	Daylight Energy (lighting, cooling and heating)	•	Feedback	The blinds are lowered when indoor air temperature is over 24° or the risk of glare exceeds
3	Yun et al. (2014)	South Korea/ Seoul	Humid subtropical	Blinds	Daylight/Glare Energy (lighting/cooling)	•	Feedback	The slats are adjusted at 0°, 15° and 30° when illuminance level is (3klx indoors: 10, 20 and 40 k lx outdoor), respectively
4	Bunning and Crawford (2016)	Australia/ Melbourne-Brisbane	Maritime/ Humid subtropical	Blinds	Energy (lighting, cooling, heating and ventilation)	•	Feed-forward	The blinds are adjusted based on hourly sky condition and annual solar angles
5	Skarning et al. (2017)	Italy /Rome-Copenhagen	Warm/cold temperate	Roller shade	Daylight Thermal Energy (heating loads)		Feed-forward	The shade closes when a certain value of 18° C outdoor air temperature and 300 w/m² solar irradiation exceeds.
6	Konstantoglou et al., (2013)	Greece	Mediterranean	Louvre	Energy (lighting, cooling and heating) View		Feedback	The slats are adjusted at angles (0°-90°) with a step of 10° to ensure WPI of 500 lx, glare index DGI<22 and visual connection to the exterior.
7	Kim et al (2015)	UAE/Abu Dhabi	Arid	Origami	Energy (cooling loads)		Feed-forward	Incidence sun angle 0°–90° of a given surface drives three states: closed, partially and fully open
8	Giovannini et al. (2015)	UAE/ Abu Dhabi	Arid	SVM	Daylight Energy (lighting /cooling)		Feed-forward	The SVM switches from open to closed configuration when solar angle is < 60° and the cosine of incidence angle (cp) is < 60°
	Simulation-based studies (theoretical approaches)							Design criteria
9	Hammad and Abu-Hijleh (2010)	UAE/ Abu Dhabi	Arid	Louvre	Energy (lighting /cooling)	•	NA	Minimum energy use
10	Grobman et al. (2017)	Mediterranean region	Mediterranean	Louvre	Daylight		NA	Optimal AUDI values
11	Kensek and Hansanuwat (2011)	USA/Dallas	Humid subtropical	Folding panels	Daylight Ventilation Thermal loads Energy generation		NA	Optimum situation of thermal loads, daylighting, ventilation, and energy generation.
12	Elghazi et al. (2014)	Egypt/Cairo	Arid	Origami	Daylight/Glare		NA	Maximising daylit area and minimising overlit and ASE areas.
13	Sabry et al (2015)	Egypt/Cairo	Arid	Kinetic skin	Daylight		NA	Best indoor illuminance levels
14	Mahmoud and Elghazi (2016)	Egypt/Cairo	Arid	Hexagons grid	Daylight		NA	Target illuminance of 300 lx
15	Wagdy et al. (2016)	USA/Boston	Humid continental	Solar screens	Daylight/Glare		NA	ASE = 0 and maximising sDA
	Experimental-based methodologies							Set point (reference)
16	Grobman and Yekutiel (2013)	Indoors	-	Kinetic screens	Daylight		Feedback	Internal illuminance 200 lx
17	Yekutiel and Grobman (2014)	Indoors	-	Kinetic cladding	Daylight		Feedback	Internal light distribution 200 lx
18	Ahmed et al. (2016)	Egypt/Cairo	Arid	Folding panels	Thermal Energy (cooling)		Feedback	Indoor air temperature 28 °C
19	Sjarifundi and Justina (2014)	Indonesia	Tropical	Louvre	Daylight/Glare		Feedback	Workplane illuminance 350–750 lx
20	Priatman et al. (2015)	Indonesia	Tropical	Vertical fins	Daylight Thermal		Feedback	Indoor illuminance of 300 lx

the yearly AUDI up to 33.68% over unshaded windows and between 5.68%–22.01% over seasonally adjusted louvres.

2) Complex geometries

Kensek and Hansanuwat [7] tested the performance of kinetic overhang, louvres and folding panels which are integrated PV modules based on integrated criteria, including daylight, thermal, ventilation and energy generation in US office buildings. A set of simulation software was employed to assess different models and to define the optimum configurations that achieved around 28%–33% reduction in cooling and heating demand for all models, maintained a work plane illuminance of 200–500 lx and dramatically increased energy generation; meanwhile, the ventilation improvement was low over static cases. Elghazi et al. [92] examined the daylight performance of origami screens in a residential space in Egypt using two metrics; spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). Grasshopper and DIVA-for-Rhino helped define the optimum opening rates in centralised behaviour based on a control strategy that maximises the daylit area and minimises the overlit and ASE areas. The daylight performance of origami screens outperformed LEED standards with Kaleido- cycle size of 30 cm and 64° rotation angles.

Sabry et al. [99] evaluated the daylight performance of an office space in Egypt with a kinetic double-skin system of louvres and folding triangular screens, each of which includes six centrally based moveable elements. The study employs Grasshopper and DIVA-for-Rhino software. A control strategy that seeks the best indoor illuminance levels generated an optimal configuration with a radius of 60 cm and rotation angle of 70° for folding units and 105 cm depth for louvres. Kim et al. [53] compared the cooling energy performance of complex kinetic shading (origami) with simple fixed shading in office buildings in UAE. Rhino/Grasshopper was utilised for modelling, and eQUEST tool was used for energy simulation. Motion was triggered by the incidence angle (θ) between the sun's direction vector and the normal vector of a surface. The kinetic system consumed the same energy as fixed shading with 60% opening, less energy with over 60% opening and 9% lower energy than that of non-shaded surfaces. Giovannini et al. [52] evaluated three-shield kinetic Mashrabiya in offices in UAE based on daylight and energy performance. The motion of the perforated shields was triggered by sun angles. Several case studies were tested using DIVA-for-Rhino and EnergyPlus to determine the effective positions. The system decreased the total energy up to 27% and lighting loads up to 65.7% over reflective glazed non-shaded façade; meanwhile, cooling demand was minimised by 17.2% over low-E double-glazed façade with adjustable Venetian blinds.

Mahmoud and Elghazi [90] assessed the daylight performance of a kinetic hexagonal grid on a glazed office in Egypt with translation and rotation motion targeting an indoor illuminance of 300 lx. Grasshopper and DIVA-for-Rhino software helped derive the optimum design. The rotational motion maintained almost 100% daylit areas and improved daylight performance by 50% in hot/warm seasons and 30% in cold seasons compared with those of bare façade with WWR of 20%. Wagdy et al. [91] tested daylight performance on an office unit in Boston, with a dynamic solar screen composed of a modular grid of hollow cells rotating horizontally and vertically within a range of 50°. The targeted criteria seek to maximise spatial daylight autonomy (sDA) with ASE = 0. The system improved daylight availability over Venetian blinds and increased the sDA from 17% to 54% whilst eliminating visual discomfort with ASE of 0%.

5.2.2. Performance of dynamic shading systems through experimental studies (responsive behaviour)

1) Simple geometries

Sjarifudin and Justina [96] tested dynamic louvres against visual comfort in a SOHO building in Jakarta. The study used simulation to obtain the appropriate opening angles and developed a controlling algorithm using Grasshopper software. A parametric camshaft system provided with simulation analysis data was employed to generate a kinetic mechanism. A full-scale prototype was applied to a SOHO unit façade and tested for one day to meet illuminance levels of 350–750 lx at the workplane. The system achieved the optimum visual comfort by varying the louvre angles between 15°–75°. Priatman et al. [63] tested dynamically automated fins (perforated and opaque) against thermal and visual performance of an office unit in Indonesia. A feedback loop was designed to maintain indoor illuminance of 300 lx. The dynamic mechanism enhanced indoor temperature by ± 3 °C, whilst the daylight distribution was fairly improved with perforated blades, leading to energy savings for cooling and lighting.

2) Complex geometries

Yekutiel and Grobman [84] tested the centralised and autonomous control of kinetic cladding using digital control over a scaled prototype, as shown in Fig. 21. The system employs a feedback loop stimulated by outdoor and indoor illuminance, where each shading element is provided with internal and external sensors and a servo motor for actuating, whilst the data are updated through an information hub. The experiment showed that decentralised control outperforms the centralised system in terms of daylight distribution. Ahmed et al. [95] evaluated the thermal and energy performance of a single-unit kinetic system in a residential room in Egypt, as shown in Fig. 21(b). The study utilised digital control using an Arduino microcontroller and a servo motor as actuator. A feedback loop was designed using Grasshopper to maintain an indoor air temperature of 28 °C. Field measurements proved the efficiency of the kinetic mechanism, which improved the thermal condition by 2 °C – 3 °C in the summer and decreased relative humidity by 15%, resulting in 20% savings in cooling loads over non-shaded windows. All the results on control strategies and design criteria are summarised in Table 3.

6. Discussion

This study conducted a critical review of design parameters and evaluation strategies for dynamic shading systems. The review of previous studies showed that dynamic solar shading is an effective bioclimatic strategy because it can achieve notable energy savings and improve the comfort level inside buildings. In addition, the study found that the design of dynamic movements at the level of shading units plays an essential role in increasing the geometric intricacy of shading models. Different typologies (architectural types) can be produced from every type of movement based on the degree of freedom related to geometrical restrictions. Furthermore, the study identified several traditional patterns such as origami and Mashrabiya presented in the de- sign of dynamic shading, which help preserve the urban heritage while involving novel technologies to enhance building performance. On the other hand, this study found that kinetic applications in shading sys- tems are no longer confined to conventional models, where a variety of complex dynamic geometries are involved.

The study clarified the mechanical and electrical elements of dynamic shading systems. Their features were found to be fairly influenced by the model geometric design. Meanwhile, using active energy to operate dynamic systems may be critical for mechanical application. However, this study found that renewable energy could be a viable source of power to operate dynamic systems, but a clear understanding of utilising motion type, the degree of freedom, size and weight of shading elements and façade coverage area, is required to conserve energy. In addition, the review highlighted the essential aspects related to automation and control systems, which include sensors, actuators, controller and software. Two analytical schemes of control can be formulated: open-loop (feed-forward) and closed-loop (feedback), in

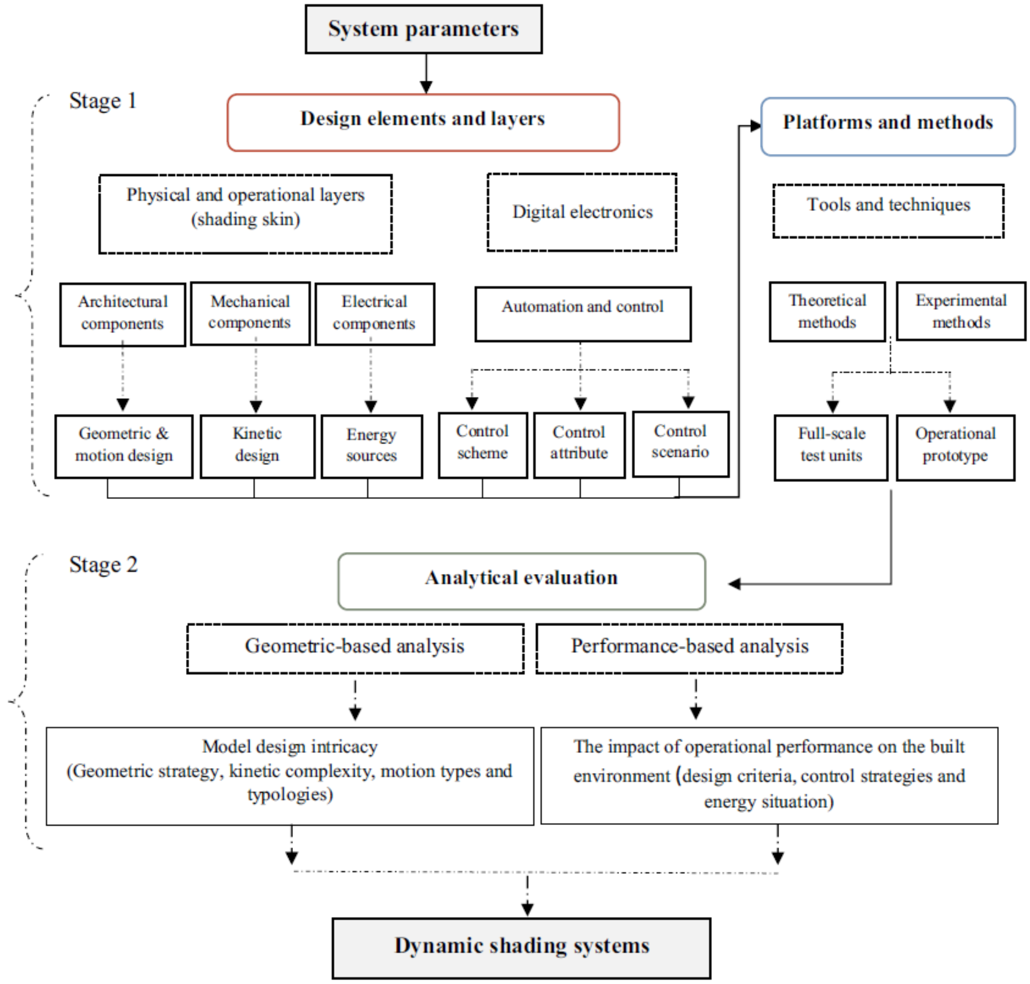


Fig. 23. Systematic framework of dynamic shading systems for architects.

addition to multi-loop schemes that allow the shading control to be linked with other systems in the space within an independent or integrated platform. The study also clarified the controller technologies, identifying two models, namely, responsive/reactive and interactive systems. Accordingly, this study differentiated between automatic and automated control.

Dynamic shading models were investigated through two main methods: theoretical or simulation-based studies and experimental studies, which developed a responsive mechanism. Interestingly, the majority of written works adopted computer simulation as the main tool due to its high optimisation capacity and time-saving practices. By contrast, current simulation software is insufficient for providing a real-time assessment of moveable elements for a long-term. Instead, some software simulations offer several approaches; a few allow for setting a control strategy at a specific threshold, whilst other programs allow for defining effective configurations over the year based on optimal yearly results and a specific benchmark. However, this method is needs further development to examine the autonomous behaviour of multi-unit structures and to cover different evaluation metrics. Generally, simulation software might reflect inaccurate evaluation, especially with regard to daylight performance in specific climatic zones. Therefore, conducting an empirical validation under real climate conditions is recommended.

The review recorded a few experimental methodologies that frequently employ digital control using Arduino microcontroller, which was found to be a promising technology in addition to the parametric software tools addressed in most methodologies. These studies provided a good indication of the responsive and kinetic performance of the system and allowed for testing various controlling techniques; however, these studies have limitations because they were conducted at a specific time. Thus, a long-term assessment is needed to test the efficiency of these systems for an entire year to prove their adaptive behaviour.

The review found that the evaluation criteria of the dynamic system are varied based on several preferences, such as indoor space activity, climatic conditions, local standard recommendations and model design concept. Most shading studies in this review were generally conducted in hot, temperate, arid, warm, tropical and subtropical climates, specifically on office buildings, whilst a few studies involved residential spaces. Notably, the majority of conventional models were assessed against energy demand, whilst the complex models and kinetic applications were frequently evaluated based on daylight performance. However, thermal performance criteria with regard to air temperature were limited and occasionally considered through cooling and/or heating demand, whilst energy generation, ventilation and view were rarely addressed.

Accordingly, a variety of control strategies were proposed either by simulation software or through a controlling algorithm during experiments. Daylighting studies involved several stimuli such as; incident solar radiation, solar angles in the sky, hourly sky condition, incident angles of the sun and exterior and/or interior illuminance considering different thresholds to trigger motion based on the local standards and climatic zone. Studies based on thermal performance adopted stimuli, such as incident solar radiation and indoor or outdoor air temperature according to the control scheme, and were mostly conducted in warm and hot climates. Notably, a few studies employed a multivariable control strategy triggered by two set points through a hybrid control perspective defined by the values of the continuous variables and a discrete mode. For example, a study conducted in a warm climate set two variables: outdoor air temperature and incident solar radiation on the window. Another study, conducted on office buildings in a temperate climate, set indoor air temperature and glare index as interchangeable stimuli. Similarly, studies conducted in tropical and subtropical climates emphasised the illuminance and sky model by including the sky condition as input data along with solar angles or considered indoor–outdoor illuminance variable. However, these strategies were affected by the nature of the tropical climate with regard to its dynamic outdoor illuminance and the cloudy sky condition. Solar angles were primarily addressed as a trigger in an arid climate most likely due to the unbroken sunshine throughout the year.

The performance of dynamic shading systems was analysed through simple and complex model designs in different climates and building activities and through various control strategies and objectives. This study found that all the dynamic systems and the proposed control strategies can achieve notable improvements in daylighting performance and visual comfort in nearly all climates and spaces. In hot and warm climates, all dynamic shading devices achieved positive results with respect to daylight, thermal and energy performance. In cold and temperate climates, daylighting and visual comfort situation were evidently enhanced by applying dynamic solar shading; meanwhile, it resulted in different energy demands especially space heating demand that showed no improvement in residential spaces and a negative influence on office spaces due to the consideration of visual comfort as a primary factor throughout the year. Other factors can serve as influential design parameters, such as orientation, perimeter dimensions, element material properties, glazing type and aperture size, which can be further manipulated by the changeable opening rates of shading units, providing variable WWRs in a day. Furthermore, incorporating additional systems, such as dimming or task lighting control through a multi-loop system, along with sharing data such as HVAC and occupancy, achieved remarkable enhancements in the overall performance of different systems and helped bridge any potential gap in dynamic shading performance.

Finally, dynamic solar shading was found to be an important intelligent strategy to maintain a comfortable indoor environment and improve building energy efficiency, especially in hot regions, where the resolution of visual issues systematically improves indoor thermal conditions throughout the year. However, dynamic shading is not an ideal solution for passive heating in functional spaces, such as offices, in cold and moderate climates, but is considered a useful practice due to its effectiveness in improving the visual condition, reducing overheating in hot seasons and minimising the overall annual energy demand. In the end, the study summarised the main aspects that provide a systematic framework of dynamic shading systems for architects as shown in Fig. 23.

7. Conclusions

This study presented a critical review of dynamic shading systems to identify different models, applications and evaluation strategies. The study identified different parameters engaged in the design of dynamic shading systems by examining the geometries, control strategies and mechanisms of different models. This study further addressed related components that are involved in the making of a dynamic system, which covers the combination of architectural, mechanical, electrical and software components, resulting in multi-scale design process. This study found that dynamic façade systems are commonly perceived as a technological trend rather than an architectural element that has been frequently neglected. Therefore, the study distinguished two levels of architectural design: (i) macro-scale level, which focuses on the composition of units, elements and movements and (ii) micro-scale level, which concerns the geometric shape, dimensions, motion layout and typology at the level of the shading unit. In addition, this study highlighted the essential aspects related to automation and control systems, such as analytical schemes, control attributes and potential scenarios. Finally, this study set a platform for designers and stakeholders on the basis of thorough research and investigation on dynamic shading systems, identifying the following issues and possibilities:

1. The architectural component is an influential aspect in the design of dynamic solar shading not only to improve the aesthetic and cultural values of building façades but to further enhance their performance. Furthermore, it has a direct impact on the design of other components, such as mechanical, electrical and automation, thereby helping to fabricate a cost-effective solution.
2. The current methodologies adopted to evaluate dynamic shading systems have two forms: theoretical methods based on computer simulation and experimental methods. Both methods present potentials and limitations. Computer simulation provides a reliable, effective and time-saving optimisation tool although it does not clearly highlight some influential parameters, such as mechanical, automation and control aspects. Experimental-based studies provide a realistic evaluation that would examine all parameters at several levels, namely, geometric, kinetic, electric and electronic, in addition to the control system, thereby assessing their impact on the built environment accordingly. However, these experiments were frequently conducted on a specific date or indoors; thus, the adaptive behaviour of the system to maintain indoor comfort under real climate throughout the year is unclear. A long-term assessment under real climate is recommended.
3. Current simulation software needs concrete actions from software developers to offer a real-time evaluation of moveable elements under variable climatic data, and to engage potential scenarios in controlling and automation, especially for complex geometries. In addition, daylighting tools need further improvements by considering the dynamic changes of sky condition and illuminance especially in fluctuated climates such as the tropics.
4. The automation and control aspects constitute an essential component of dynamic shading systems, which highly affect its performance. Thus, their parameters should be considered at the early stage of design with regard to (i) control strategies and scenarios, such as single- or multiple-protocol scheme, open-loop or closed- loop system, single- or multi-variable system; (ii) controlling technologies, such as self-sensing and self-actuating technology, centralised and decentralised control, reactive or interactive system; and (iii) controlling algorithm, that is, the desired setpoint and the stimulus, which should be carefully designed through an accurate analysis of the site climatic realities and the benchmark in the local standards.
5. Despite their installation cost and reliance on active energy, dynamic systems are still considered an efficient passive strategy due to their ability to save building energy and utilise passive energy sources. However, the passive design approach has expanded along with intelligent implications by employing passive and active elements in a hybrid form.
6. Selecting a suitable dynamic shading system should be adaptable to different realities, where environmental and energy performance are the most important aspects in some regions in addition to aesthetics, maintenance, safety, cost, privacy and other constructional or economical considerations.
7. The overall annual energy can serve as a key indicator to assess a dynamic system performance, meanwhile a particular attention should be given to daylighting efficiency in functional spaces, such

as classrooms, reading rooms or office buildings.

8. The successful design of dynamic solar shading necessitates a multi-criterion methodology, which considers a hierarchy amongst multiple factors, such as indoor space activity, climatic zone and user requirements.

Finally, all the previous materials should be considered within an integrated platform to realise a successful dynamic shading design, which was found to be an effective bioclimatic strategy, especially in hot regions. However, further studies are needed in the field of theoretical evaluation methods especially in terms of considering variable climatic parameters and controlling technologies.

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