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A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review

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**Abstract**

Visual and thermal comfort for occupants significantly depend on exterior environmental climatic conditions, which are continuously changing. In particular, optimizing visual and thermal comfort simultaneously is a difficult topic due to mutual conflicts between them. This literature review article studies the façade, as a complex interface between inside of buildings and the outside that has a capability to function as a protective or regulatory element against severe fluctuations of external climate. Six interrelated subjects are studied including kinetic façade, biomimicry, building form as a microclimate modifier, energy efficiency, comfort condition, and parametric design thinking. The literature review process answers following research questions: (1) what are the interdisciplinary subjects corresponding to kinetic façade design process for creating an innovative architectural process? (2) What is the most important factor in kinetic façade design with the aim to improve occupants’ visual and thermal comfort simultaneously based on multidisciplinary investigation?

Many research has been carried out about kinetic façade concepts, strategies, principles, and criteria. However, interdisciplinary studies for proposing kinetic façade form is relatively rare. Also, adaptive daylight façade with daily solar geometry variation has been highly required. Therefore, generative-parametric and quick form finding method for responding to different climates would be a solution for providing more adaptability to dynamic daylight. This study aims to propose a kinetic façade design process which have capability to improve occupant visual & thermal comfort simultaneously by controlling on-site renewable energy resources consist of solar radiation and wind. Façade as an only interface between inside and outside of building, far from the literal and historical perceptions, is recognized by intrinsic functional attributes including complexity, heterogeneity and multidisciplinary. Moreover, the interrelated subjects impact façade form individually and aggregately regarding to functional scenario that is changed the perception of kinetic façade from elegant and fashionable state to a functional and practical element.

**1. Introduction**

Occupants comfort and energy consumption are important issues in the field of architectural design and building technology. The demand for thermal and visual comfort from occupants has been increased considerably. The energy consumption and CO2 emission as well as the capital cost of building’s operational energy have been augmented [1]. The use of passive design strategies in the early stages of the design is a priority for architects and engineers to optimize the benefits from on-site renewable energy resources such as daylight [2]. However, optimizing occupant comfort by using daylight is challenging because there are two distinct spaces including interior (inside) and the environment (outside), which are interacting together. Furthermore, optimizing visual and thermal comfort is difficult due to conflicts between them. In particular, sun diurnal movements giving rise to different hourly daylight circumstances that influence the indoor comfort conditions. However, interdisciplinary study through architectural design, light and human well-being could lead to the detection of optimal solutions regarding all aforementioned criteria (Fig. 1).

The façade is a complex interface between inside of buildings and the outside environment that has the capability to function as a protective or regulatory element against severe fluctuations of external...
climate [5] p18) "Originally Façade is a French word for the principle front of a building that faces on to a street or open spaces while morphology is a particular form, shape, or structure" [4]. And from "a metonymy for architecture as a whole, the façade is the elements most invested with political and cultural meaning" [5] p3. For example, the Great Pyramid of Giza, Egypt (2560 BC) mentioned to political effects in architecture and court life of Han golden age (206 BC, 220 AD) in Chinese art referred to cultural meaning [5 pp.10,21](Fig. 2a and b). Overall, "architectural history perception of façade role is a conservative element for conveying a sense of stability and permanence" [5 p180]. However, the complexity of façade increased from 1930s with the introduction of fully automatic Girasole villa by Angelo Invernizzi. "The entire building which is inspired by sunflower, rotates on a mechanical track with inner glazed courtyard following the path of the sun" [5 p.184] (Fig. 2d). Indeed, for environmental adaptation, that means "the ability to maintain stable internal conditions while tolerating changing environmental condition" [6], needs to move toward policies of controls by changing from static to dynamic façade [5 p.180].

The sliding shoji doors, as an earliest example of kinetic façade elements, have been required manpower to move and do interested functions (Fig. 2c). Their physical structures have been constituted by translucent paper and a wooden lattice frame. The kinetic characteristic of shoji doors have provided high flexibility in building functions which enhance sense of spaciousness and daylight performance in any rooms. The evolution of the façades originates from historical perception with movable elements such as a sliding Shoji door in traditional Japanese architecture, to responsive and programmable medium, such as Aedas's Al-bahar Towers in Abu Dhabi with operable petals for controlling daylight, considerably emphasized on regulatory functions of façade [5 pp.180-187, 3 p.18] (Fig. 3). Façade's regulatory functions consist of changing, controlling and responding. These are implemented by dynamic responses to environmental stimuli, according to certain parameters for meeting desired goals.

Kinetic façade concepts have been identified by nature, technology and architecture to create multifunctional elements for solving design problems by multidisciplinary strategy [7 p.14]. Moreover, there are multidisciplinary factors that influence the kinetic concept. Multidisciplinary investigation provides an opportunity to explore a wide domain of parameters across different fields to detect multi-objective solution for multi-domain problems [8]. Overall, a kinetic concept can be a significant strategy for optimizing regulatory function of façade which needs to respond to different stimuli for meeting occupant comfort. These goals will be investigated by identifying and changing important façade factors which affect comfort condition with the aim to control climatic fluctuations.

An investigation of the existing literature revealed an expanding interest in the kinetic architecture study. There are varied publication and research studies, which consider and identify diverse terms, strategies and approaches of kinetic façade [7 p.27, 8,10-22]. The capability for producing everything by movements refers to kinetic term that applied translation, rotation and scale [10,11,13,15,22]. Indeed, "kinetic architecture identified as a form should react to the set of
pressures establishing an equilibrium" [7,13].

This study recognizes relevant disciplines to kinetic architecture, occupants' visual and thermal comfort, biomimicry, microclimate and their approaches with the aim to conceptualize an adaptive façade form. And also, enable architects and building physics experts to think about multifunctional aspects of kinetic façade and its potential for dynamical response to daylight variations. To this end, the study has been led by the following research questions: (1) what are the interdisciplinary subjects corresponding to kinetic façade concept for creating an innovative architectural form? (2) What is the most effective factor in kinetic façade with the aim to improve occupants' visual and thermal comfort simultaneously based on multidisciplinary investigation? A kinetic façade is a multifunctional and complex zone; thereby investigating different fields by parametric design thinking leads to achieving an adaptive façade. Developing an adaptive and responsive façade requires moving beyond the historical perception of façade. Moreover, façade as the only interface between building interior and ambient environment is influenced by several subjects which makes complexity and heterogeneity for façade. Multidisciplinary investigation of the relevant subjects to façade enables detecting an appropriate dynamic geometry for kinetic façade function (Fig. 4). This research article investigates interrelated fields of literature including: Kinetic façade, Biomimicry, Building form as a microclimate modifier, Energy efficiency, indoor comfort, Parametric design thinking.

2. Method

The literature review process, as a tool for conducting potentially relevant literature to research topic, was applied. Google Scholar and Scopus were the databases used to find relevant articles. The search was performed using the keywords "Kinetic façade, responsive and adaptive envelope, optimization algorithm, net zero energy building, Daylight, daily solar geometry, multidisciplinary function, parametric and generative design, form finding, biomimicry, bionic, morphology, modifying microclimate, morphological approach, Thermostatic form finding, energy efficiency, architectural design façade form, movement, simulation, nature and performance evaluation." The search criteria were based on characteristics of the several groups in this study. A total of 43 keywords were used and categorized into six groups: kinetic façade, biomimicry, modifying microclimate, Energy efficiency, Comfort condition and parametric design thinking (such as Asaf, Badarnah, Göran & Werner, Ghaffarianhoseini et al., Grobman, & Elimelech, Reinhart, Wortmann & Tunçer).

Combinations of keywords were used in the Google Scholar and Scopus research databases for further and more precise searches. The following combinations of keywords were selected: "biomimicry morphological approach", "performance of modifying microclimate", "parametric design for form finding", "climatic based daylight metrics", "adaptive and responsive daylight systems" "complex and convertible form" and "geometric transformation".

3. Building form as a microclimate modifier

Regulatory function of façade benefits from modifying microclimate in ambient environment by controlling airflow, solar radiation across the façade body resulting in adjusting surfaces temperature of the building nearby the interior spaces. Although Herzog et al., [3 p.18–21] refer to vegetation and bodies of water as measures influencing the microclimate, exploring traditional courtyard building characteristics, as a microclimate modifier, reveals several courtyard elements which significantly affect microclimate (Table 5).

Courtyard building, as an old form of dwelling, pervasively applied in all times, climates and locations such as Iran, China and Middle East. Despite the socio-cultural aspects, courtyard building demonstrated extraordinary response to climate specifically in harsh condition [23,24]. Meir et al. [25] monitored air temperature and weather data in semi enclosed courtyard located at hot-dry region, as a microclimate modifier. In addition, they concluded that a microclimate modifier can affect air movement, daylight, ventilation and living style resulting in improving thermal comfort in enclosed public area and surrounding spaces.

Modifying microclimate is studied based on method, software, climate, microclimate modifier type, function, effective parameters and microclimate forces which are explained in the following Table 1:

- Method & software: as shown in Table 1, most of the studies applied a case study field survey and simulation analysis, while parametric simulation has been used rarely. Moreover, the most common simulation programs were ENVI-met, TRANSYS and IES-VE.
- Climate: hot-dry climate has been mostly investigated regard to other climates specifically the cold one.
- Type: traditional courtyard buildings, which have square shape, have been applied for the case study researches frequently, while internal semi open and U shape courtyards have been explored scarcely.
- Effective parameters: geometry and orientation have been designated as the effective parameters which influenced the microclimate modifier functions.
- Function: most of the researches addressed thermal regulation,
Table 1 Modifying microclimate literature scope, terms, parameters, trends, functions and forces.

| Author                  | Ref | Year | Method-Software | Climate | Microclimate Modifier type | Function | Effective Parameters | Microclimate Forces |
|-------------------------|-----|------|-----------------|---------|----------------------------|----------|----------------------|---------------------|
| Mei et al.              | [25] | 1995 | LS/CSFS         | HD      | SEC                        | MM/TC/NV/DP/EE | G/O/SD               | S/W                 |
| AL-Masri & Abu-Hijleh   | [24] | 2012 | QS/SA-IV        | HA      | TCB                        | EE/DP     | NF/GT                | S                   |
| Heidary                 | [28] | 2010 | LB/CSFS         | D       | TCB                        | TR/MM/NV/SD/EE | G                   | S/W                 |
| Sadafei et al.          | [20] | 2011 | CSFS/QS-SA- E   | Y       | ISOC                       | MM/TC/NV/SD/DP | Ow                   | S/W                 |
| Sofiabi et al.          | [21] | 2016 | LS/CSFS         | CD      | TCB                        | TC/SEC/EE | O/G/HAW              | S/W                 |
| Almahdy et al.          | [31] | 2013 | CSFS/QS-SA-IV  | T       | USC                        | MM/TR/SD/EE | O/HAW                | S                   |
| Cho & Mohammadzadeh     | [32] | 2013 | LS/QS-SA- EP    | HD      | TCB                        | TC/TR/MM  | Ow/NV                | S/W                 |
| Ghaffarianhosseini et al.| [33] | 2015 | LS/QS-PS- Em    | HH      | TCB                        | TC/TR/SD/NV/MM/EE | O/HAW        | S/W                 |
| Al Dauoud               | [26] | 2008 | LS/QS/PS- D     | HD/HBL/T/C | TCB         | EE/DP/TR/MM            | GT                   | S                   |
| Malekzadeh and Loveday  | [27] | 2008 | LS/QS-SA-T/Em   | HD      | TCB                        | MM/EE/TC/TR/EE | M/HAW/O/AV/P/T    | S/W                 |
| Berkovic et al.         | [30] | 2012 | LS/QS-SA/T/Em   | HA      | TCB                        | TC/SD/MM/EE | V/Ow/T/G/O            | S/W                 |
| Narrollahi et al.       | [36] | 2017 | CSFS/QS-SA- E   | HD      | TCB                        | TR/NV/MM/DP/EE | G/O                   | S/W                 |
| Chandel et al.          | [35] | 2016 | LS/CSFS/QS      | HH      | TCB                        | EE/TC/TR/DP | G/O/Ow                | S                   |
| Abdulkareem             | [29] | 2016 | LS/CSFS/QS      | HD      | TCB                        | MM/TR/TC/EE/DP | MM/EE/TC/EE/DP   | S/W                 |
| Sofiabi et al.          | [37] | 2017 | CSFS/QS-SA- DB  | HD      | TCB                        | MM/TC/TR/EE | G/O                   | S                   |

Method_LS: Library Study, CSFS: Case Study Field Survey, SA: Simulation Analysis, QS: Quantitative Study, PS: Parametric Simulation; Software_DB: Design Builder, Em: ENVI-met, T: TRANSYS, D: DOE2-IE, EP: EnergyPlus, IV: IES,VE, E: ECOTECT; Climate_HH: Hot-Humid, HD: Hot-Dry, HA: Hot-Arid, T: Tropical, Te: Temperate, CD: Cold Desert, D: Desert, C: Cold; Building Type_SEC: Semi Enclosed Courtyard, TCB: Traditional Courtyard Building, ISOC: Internal Semi Open Courtyard, USC: U Shape Courtyard, Function_TC: Thermal Comfort, TR: Thermal Regulator, VC: Visual Comfort, DP: Daylight Performance, NV: Natural Ventilation, SD: Shading Device, SCC: Socio-Cultural Characteristic, EE: Energy Efficiency, DM: Daily Migration, MM: Microclimate modifier; G: Geometry, O: Orientation, HAW: Height and Albed of Wall, GT: Glazing Type, NP: Number of Floors, Ow: Opening, M: Material, T: Tree, WP: Water Pool, S: Shade, V: Veranda, AO: Architectural Ornament; Microclimate Force: S: Solar; W: Wind.

thematic comfort, daylight performance, natural ventilation, energy efficiency and shading device as the main functions of a microclimate modifier. However, the occupant daily migration for providing thermal and visual comfort, as an interactive characteristic of modifying microclimate, was not adequately explored and investigated (Fig. 5).

- Microclimate forces: solar radiation and wind are the notable forces which affect microclimate condition, while solar radiation has been determined as the most important one.

The traditional courtyards building as a microclimate modifier have the capability to control solar radiation and wind. Consequently, regulatory function of courtyard provides daylight performance, air movement and natural ventilation, energy efficiency, indoor and outdoor thermal & visual comfort. More importantly, planning interior spaces around of the courtyard facilitates occupant daily migration for responding to different climatic conditions specifically dynamic daylight movements during daily time. Exploring several studies about the courtyard building as a microclimate modifier, determines effective parameters and elements, which considerably influence microclimate condition, consist of geometry, orientation, height and albedo of wall, glazing type, number of floors, opening, material, tree, water pool, shade, veranda and architectural ornament (Table 1). Overall, geometry and orientation are recognized as the most important factors which control solar radiation and wind. Furthermore, new researches can be performed by focusing on cold and hot-dry climates in the same time using parametric simulation. Semi-open spaces and three dimensional shape changes in façade, as an advanced shading device, have an adequate potential to be investigated as three dimensional kinetic modular elements in façade for improving daylight performance, visual and thermal comfort. The concept of occupant daily migration has an opportunity to be implemented by means of kinetic movements in the façade Modular elements. Moreover, these elements might be able to transform based on their geometrical characteristics and orientations (Fig. 5).

4. Kinetic façade

4.1. State of the arts

Multi-disciplinarily investigations across different fields of kinetic façades are relatively rare and under-researched. However, there are studies that consider their apparent and general characteristics. These studies can be classified based on research methods into qualitative and quantitative research.

Qualitative research about kinetic façade reviewed and compared existing case study examples and strategies in order to represent a brief outline of movable façade’s features and performance. Ramzy &Fayed [12] applied qualitative method for discussing several types of kinetic façade’s advantages, problems and possible solutions while Bakker et al. [16] surveyed influence of automated façade operation on users’ satisfaction by case study and questionnaire hypothesis testing. Furthermore, Megahed [22] analyzed several kinetic concepts and compared them in order to propose a conceptual framework for kinetic classification and design strategies. Similarly Barozzi et al. [38] reviewed the adaptive envelopes and outlining the state of the art of these façades. Panopoulos & Papadopoulos [39] studied available smart façades and the way of retrofitting them to an existing office building as well.

Quantitative methods have pervasively been applied for analyzing and evaluating kinetic façade’s performance based on multifunctional intrinsicality of them. Dynamic envelope operation aims to reduce energy consumption and total cost (construction and maintenance), improving thermal comfort and daylight performance. One promising approach taken is the researchers have applied digital model simulation and parametric evaluation for assessing kinetic façade’s performance regarding aforementioned goals (Fig. 6). Pesenti et al. [17] explored existing origami patterns by parametric digital modeling in order to reduce energy consumption of actuators, while Mahmoud & Elghazi [18] investigated daytime performance with hexagonal patterns’ movements (translation and rotation). Similarly, Grobman et al. [20] considered the capability of kinetic shading elements for optimizing dynamic daylight by quantitative and parametric simulation method. Likewise, Elzeyadi [21] simulated parametric digital models and compared six main shade typologies for energy saving and visual comfort. Finally, Loonen et al. [8] proposed the application of parametric and generative design tools for evaluating energy performance and architectural form finding with regard to multi-domain parameters.

Multidisciplinary investigation about kinetic façade requires the application of both quantitative and qualitative research together. Hypothesis could be derived from qualitative studies and subsequently analyzed, tested and receive feedback by a quantitative approach. Although, qualitative research gathered by parametric thinking for supplying principles and constraints for dynamic patterns and geometries;
quantitative approach such as parametric modeling explores and detects high performance architectural free form regarding requested functions. Incorporation of qualitative and quantitative approaches in the unified design framework provides an opportunity to create multidisciplinary principles and patterns for kinetic façade function that have the capability to adapt to different conditions (Table 2).

4.2. Kinetic concept

The adaptive kinetic façade investigated through architectural conceptual design, mechanism, evaluation, materialization and maintenance process based on several design frameworks for kinetic architecture that are represented by Asefi [10], Fouad [13], Werner [14], Alkhayyat [15] and Megahed [21].

- The architectural design phase is a fundamental stage of kinetic terms that specifies direction and procedure of next levels by proposing concept, module and morphology [10,13,15,22]. Design concept provides idea for changing from static into dynamic.
- Mechanism pertains to movements and technology with the aim to create motions [15,22]. These movements are derived from intrinsic control (geometry and material's properties) and extrinsic control...
Kinetic façade researches trends in both quantitative and qualitative approach.

| Author            | Year  | Function, Method and Tools                                                                 | Limitation & Gap                                                                 |
|-------------------|-------|-------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Megahed [22]      | 2017  | Conceptual framework for kinetic façade, literature review, comparing existing examples, case study | Requiring integration of different fields for multidisciplinary investigation       |
| Grobman et al. [20]| 2017  | Apply quantitative method and tool for dynamic daylighting, Parametric Simulation method and tools, Case Study analyzing, Comparing results, Using values as indicators for evaluation, Tools: Rhinoceros, Grasshopper, Diva, Radiance/DAYSIM, Python. | The lack of a method or tool for rapid analysis and simulation, Less research on movable Shading device. Require to Study daylight performance in real time operation (hourly analyze), Need to investigate on dynamic movement of external shading façade. |
| Elzeyadi [21]     | 2017  | Comparing the performance of different dynamic shading topologies, Case Study, parametric simulation model, Construct and test experimental prototypes of six main shade typologies, Comparing results. Tools: parametric simulation engine IES VETM | Understanding cost of construction and maintenance. It assumes shading device just closed or opened. Analyzing during different season and daily solar geometry variation will be needed. Utilizing existing shading typology. Information and academic research about different scopes of adaptive façade is scarce. Multi domain interaction. Uncertainty analysis (weather condition, diverse orientations), Dynamic geometry during the daily time (hourly change). Need to parametric and generative design tools for analyzing performance & architectural form finding. Need to contribution of new material, technology and expertise. |
| Loonen et al. [8]  | 2017  | Identify five widely used BPS tools, Comparing between different overview, Literature review. |                                                                        |
| Panopoulos & Papadopoulos [39] | 2017  | Investigates the available smart façade and the way to contribute and retrofit smart façade to an existing office building. Literature review, Comparing different smart façades |                                                                        |
| Mahmoud & Elghazi [18] | 2016  | Using parametric simulation for evaluating daylight performance, Parametric simulation method and case studies Tools: Rhinoceros, Grasshopper & Diva | Kinetic transformation derived from combination of translation, rotation and scale should be investigated. Energy performance and life-cost should be studied. No inspiration source for creating dynamic geometry. Scientifically papers dealing with façade shading are rare. Importance of climatic context. Need Multi domain interaction |
| Barozzi et al. [38] | 2016  | Overview of adaptable envelopes and shading systems. Literature review several papers and examples Comparing different idea and examples. |                                                                        |
| Pesenti et al. [17] | 2015  | Explore existing origami patterns, Digital Model, comparing result, Case study Tools: Rhinoceros, Grasshopper & Diva | Utilize existing origami pattern and no inspiration for creating geometry. Need Multi domain interaction |
| Bakker et al. [16] | 2014  | Explores and quantifies the influence of automated façade operation on user Satisfaction Case Study environment, experimental survey, Questionnaire survey and Hypothesis testing. | Utilize existing shade typologies |
| Asefi [11]        | 2012  | Considers incorporation of art, engineering and technology in architecture and capability of transformation in responding to occupant requirement. Survey several architectural examples of kinetic façade, Explaining features and compare. | Need to more investigate on dynamic façade. |
| Ramzy & Fayed [12] | 2011  | Discuss about different types of kinetic building and façade, problems and possible solutions. Qualitative methodology depends on practical and experimental case studies | Need to more investigation for biomechanical inspiration of dynamic façade. Construction and life cost. |

(sensors and actuators). Therefore, innovative mechanism for kinetic façade is realized by a combination of morphology and politics of control.

- Evaluation process is performed by verification and validation of reliable factors based on initial conceptual design [10,15,22]. Moreover, there are particular indicators for diverse functions of kinetic façade that show their performance such as assessing daylight performance for visual comfort and evaluating indoor operation temperature and relative humidity for thermal comfort in two phases: static and dynamic.
- Materialization points out to construction and operation process that could be apportioned into stable configuration, appropriate material, reliability and safety, manufacture and shipment [10,13,15,22].
- Maintenance addressed life expectancy, maintenance and management strategy, capital cost, running and maintenance cost [10,14,22].

The architectural design concept addresses inspirational ideas and morphological approach as important subjects for changing from static into the dynamic state. However, the mechanism mentions to technology and intelligent system which apply geometry, and materials to create kinetic element. Integrating architectural design concept and mechanism by means of morphological approach leads to create responsive and adaptive form for kinetic façade to meet occupant requirements. Evaluation level has an important role in the kinetic conception that influences the façade form configuration. There are several functions that should be assessed based on indicators. Therefore, choosing appropriate metrics for evaluating occupants comfort considerably affect façade form transformations. In summary incorporation of the architectural design concept, mechanism and evaluation have potential to lead the creation of a reliable cycle for exploring and detecting movable patterns for kinetic façade (Fig. 6).

4.3. Indoor comfort using kinetic façades

Since comfort concept has been evolved in the course of time, notion of changing façade configuration over time is an approach to improve thermal & visual comfort. Three dimensional shape changes in façade elements, have a potential to control the microclimate forces...
Table 3
Analyzing kinetic façade regarding interactivity and indoor comfort condition by movement types and characteristic element [11,15, 40].

| Project Name                  | Year | Climate | Characteristic element | Detail                                                                 | Movement type | Scale of kinetic element | Function Indoor environment quality |
|-------------------------------|------|---------|------------------------|----------------------------------------------------------------------|---------------|--------------------------|------------------------------------|
| Manitoba Hydro               | 2009 | Dfb     |                        |                                                                       | F             | LEF                      | IDD, IW, DP, CSH, AMNV              |
| Thyssen Krupp Cube, Q1        | 2010 | Cfb     |                        |                                                                       | F, P          | LEF                      | IDD, RG, DP                         |
| Kiefer Technic Showroom       | 2007 | Cfb     |                        |                                                                       | Fo            | LEF                      | IDD, IFS, DP, CSH                   |
| EWE Arena                     | 2005 | Cfb     |                        |                                                                       | S             | PF                       | GEF, DP                            |
| House at the Milbertur        | 2008 | Dfb     |                        |                                                                       | Fo, S         | LEF                      | IDD, DP                            |
| St. Ingbert Town Hall         | 2009 | Cfb     |                        |                                                                       | Fo, S         | LEF                      | IDD, DP, CSH                        |
| Al Bahar Towers               | 2012 | BWh     |                        |                                                                       | Fo, EC        | LEF                      | IDD, DP, RG, CSH                    |

(continued on next page)
For instance, Kiefer Technic Showroom is interactive due to functional scenario resulting in reduction of glare and thermal performance. "Michael Fox, the head of the MIT Kinetic Design Group, has proposed a taxonomy of kinetic controls which may be translated into three types of behavior in kinetic facades: the manual, the autonomous and the responsive. In this progression, the responsive envelope responds to natural forces, having been programmed to produce a desired visual effect or move according to certain parameters" [5] pp.185–187. The responsive kinetic façade, by applying sensors and actuators, interacts morphologically with the ambient environment to improve interested functions, such as thermal and visual comfort, according to certain parameters. To illustrate, kinetic façade of Al Bahar Towers and Helio Trace Centre of Architecture decrease solar heat gains by 50% and 81% respectively compare with fixed facades [15]. Similarly, Media ICT Building, which using contractions and inflation according sunlight resulting in filtering heat and UV Rays by 85% [40]. Moreover, “dynamic shade provided substantial increase in indoor comfort for both cooling and heating seasons ranging from 13.3% to 26.9% [20].”

Table 3 shows several existing kinetic facades which have been considered based on climate, movement types, scale of kinetic element, function and indoor environment quality.

| Project Name        | Year | Climate | Characteristic element | Detail | Movement type | Scale of kinetic element | Function | Indoor environment quality |
|---------------------|------|---------|------------------------|--------|---------------|--------------------------|----------|---------------------------|
| Institut du Monde Arabe | 1987 | Cfb     | R, LEF, IDD, DP        |        | R             | LEF                      | IDD      | DP                        |
| SDU Campus           | 2014 | Cfb     | F, LEF, IDD, IFS, DP, CSH |        | F             | LEF                      | IDD, IFS | DP, CSH                   |
| Sharifi-Ha House     | 2013 | Csa     | R, PF, ISC, IFS, DP, CSH |        | R             | PF                       | ISC, IFS | DP, CSH                   |

Climate, Dfb: Humid continental, Cfb: Temperate, BWh: Warm desert, Csa: mild, semi-humid; Movement type, F: Flap, Fo: Fold, R: Rotate, P: Pivot, S: Slide, EC: Expand & Contract, PH: Pneumatic or Hydraulic; Scale of kinetic element, WF: The whole façade as one piece, PF: Parts or volumes in the façade, LEF: Larger element in façade, SEF: Small elements in façade; Functions, IDD: Interactive to dynamic daylight, IHM: Interactive to human movement, IW: Interactive to wind, GEF: Generating energy in façade, ISC: Interactive to seasons change, IFS: Interactive functional scenarios; Indoor environment quality. RG: Reducing Glare, DP: Daylight Performance, CSH: Control Solar Heating, AMNV: Air Movement & Natural Ventilation.

(solar and wind). For instance Kiefer Technic Showroom is interactive due to functional scenario resulting in reduction of glare and thermal performance. "Michael Fox, the head of the MIT Kinetic Design Group, has proposed a taxonomy of kinetic controls which may be translated into three types of behavior in kinetic facades: the manual, the autonomous and the responsive. In this progression, the responsive envelope responds to natural forces, having been programmed to produce a desired visual effect or move according to certain parameters" [5] pp.185–187. The responsive kinetic façade, by applying sensors and actuators, interacts morphologically with the ambient environment to improve interested functions, such as thermal and visual comfort, according to certain parameters. To illustrate, kinetic façade of Al Bahar Towers and Helio Trace Centre of Architecture decrease solar heat gains by 50% and 81% respectively compare with fixed facades [15]. Similarly, Media ICT Building, which using contractions and inflation according sunlight resulting in filtering heat and UV Rays by 85% [40]. Moreover, “dynamic shade provided substantial increase in indoor comfort for both cooling and heating seasons ranging from 13.3% to 26.9% [20].”

Table 3 shows several existing kinetic facades which have been considered based on climate, movement types, scale of kinetic element, function and indoor environment quality.

- Most of the case studies have been constructed in the mild temperate-fully humid region with warm summer.
- The kinetic facades are the second façade layers which interact individually regard to environmental stimuli.
- Folding, rotating and sliding are frequently used, while, extracting-contracting is rarely applied.
- Though in the most of the case studies, kinetic elements are recognized as a large element in the façade, Sharifi Ha House and EWE Arena are taken into account as parts or volumes in the façade.

- Being interactive to dynamic daylight is identified as the most important function for kinetic façade. However, being interactive due to functional scenario is an under developing target in the recent years.
- Daylight performance and controlling solar heating, derived from the kinetic façade function, are the remarkable factors which improve indoor environment quality specifically thermal and visual comfort. For instance, Al Bahar Towers and Thyssen Krupp Cube improve visual comfort by ameliorating daylight performance and reducing glare.

Being interactive to functional scenario has a capability to reduce glare and provide visual comfort for occupants. Indeed, three dimensional shape changes of kinetic façade is a prominent attribute for being interactive and responsive to functional scenario. The thermal comfort and daylight have been considerably met by the kinetic façade operation in different cases. Regarding Mahmoud & Elghazi [18], dynamic shading improved daylight by approximately 50% in summer & spring and about 30% in autumn & winter compare to a base case. Also, they claimed rotational movements enhanced illumination levels more than translation motion. Elzeyadi, 2017 [21] simulated several types of dynamic screens in a parametric software and stated an egg-crates system has a potential to reduce solar thermal load between 50.64%.

Driver parameters for evaluating visual & thermal comfort, which used in parametric and algorithmic design, need to be investigated. Therefore, exploring comfort condition literature assists to find appropriate measurable metrics for evaluating the comfort conditions of occupants. Indeed, using measurable metrics for the comfort evaluation
accelerates process of regeneration of the parametric façade configuration.

Natural light has positive impacts on health conditions and energy efficiency [41,42]. However there are some issues such as heat gains and visual discomfort (daylight glare) that should be considered for obtaining visual comfort. “Balancing visual comfort and daylight is always challenging” [41] which needs to study relationship between human needs and environment light based on specific factors such as: “the amount of light, the uniformity of light, the quality of light in rendering color, the prediction of the risk of glare for occupants” [[42–45] pp.261–266]. Consequently, parametric simulation by using these factors have potential to prepare data for evaluation process with the aim to consider daylight performance precisely and quickly [ [45] p.261, 46].

In the same way, Thermal comfort is a complex topic due to human and physical aspects. Human factors addressed physiological and psychological parameters such as clothing insulation, metabolic rate, age and gender that need face-to-face survey. However physical factors point to indoor operation temperature, relative humidity and air velocity [47–49]. Optimizing thermal comfort with passive techniques implies to natural ventilation and solar control systems [47]. Regarding to wind force, façade form and its surfaces influence wind speed and air flow pattern which improve thermoregulation of the building [50]. Solar shading device and window’s properties play important roles for reducing energy consumption and preventing overheating [49,51]. Utilizing complex fenestration systems facilitated by kinetic solar shading device have potential to achieve trade-off solutions for conflicts between visual and thermal comfort [41,44,52]. To end, balancing between geometry, orientations, window to wall ratio, glazing material, color, reflectivity and emissivity lead to improve visual and thermal comfort [41,44,53].

4.4. Energy efficiency

4.4.1. Net zero energy building

The operation of buildings contribute to about a third of the global energy use and a similar share of the greenhouse gas emissions [1]. Building indoor environment is now generally conditioned by conventional HVAC1 systems, consequently increasing the energy consumption. In a net zero-energy building (NZEB), the amount of energy is reduced by proper envelope design, insulation and heat recovery (wintertime), shading (summertime) and applying natural ventilation. With respect to NZEB definition, the required energy to operate the building is generated by renewable energy sources on or near the building [54,55]. Furthermore, European Parliament [56] and Massachusetts NZEB [57] specified the definition of NZEB as following principles: A) applying on-site renewable energy sources B) the annually energy consumption is equal or less than energy production from on-site sources C) the capital cost of annual function is equal or less than energy grid D) reduce carbon emission and dependence on fossil fuels. However, Wang et al. [2] indicated passive strategy in the early stage of the conceptual design as a sustainable approach for balancing energy consumption by means of smart function and renewable sources. Preparing occupants comfort in the interior space with optimal energy consumption is a prominent issue for architects and engineers. Utilizing technology such as HVAC system for providing comfort condition, consumed a large amount of energy for operation. Consequently, greenhouse gas emission and capital cost of energy consumption will have been increased. Therefore there is a need to apply optimal strategy in the early stage of design for using technology in the proper way. Passive sustainable design leads to combining passive strategy and active technology in order to balance energy consumption and provide occupants comfort. Particularly, generating energy from on-site renewable source (solar radiance) is a smart function that could be applied in diverse locations and climates. Accordingly, designing architectural elements, such as movable shading device or kinetic façade, leads to optimization of occupant comfort and energy proficiency of building as well as decrease the amount of greenhouse emission. For example, Manitoba Hydro has a biodynamic double façade which improves energy efficiency up to 70% [40]. Furthermore, dynamic shades have a great potential to save 20–30% in energy use for commercial buildings [20], while kinetic photocells by tracking sun produce 30–40% more energy than a similar fixed system [12].

4.4.2. Passive strategies & active technology

Integration of passive design strategies & active technology in the shape of kinetic façade leads to balance energy requirement and logical respond to several conditions (Fig. 5 & Table 2). Passive strategies refer to precise and accurate solar design with the aim to reduce heat gains, need of artificial cooling, heating and visual glare [59,61]. Moreover, there are passive design parameters which affect thermal & visual comfort consist of orientation, plan dimensions, window-to-wall ratio of several face, material, color and shading type [62,68]. Active technology is applied in order to use smart and responsive functions, such as smart electrochromic glass, for progressing building’s energy proficiency, occupant’s thermal & visual comfort [69,70]. This can be illustrated by dynamic movement that altered building configuration regarding to solar real-time position [71].

With respect to passive strategies, applying responsive surfaces, which have a capability to change orientations, forms, colors and materials, is an innovative idea for achieving more efficiency in buildings [72,74]. Furthermore, optical characteristics of material including solar reflectance and emissivity considerably affect façade thermal balance and visual comfort [75,76]. Consequently changing form, orientation and material properties need to be investigated for improving energy proficiency of building.

In terms of active technology, building benefits from reconfigurable geometry, multifunctional mechanism, dynamic and responsive skin in order to meet users demands [17,77,78] (Fig. 7). Therefore, using sensors, actuators and self-folding surface in the façade form provides an opportunity for sensing and real time responding to ambient environment changes [[79] p.109].

5. Biomimicry

Bios is a Greek word that refers to “life” and mimics means “to imitate” [80]. Moreover, biomimicry, can be translated as “learning the best opinions of nature by imitating them” [81]. More specifically, “Both biomimicry and biomimetic are the sciences that observe the form, function, ecosystem in nature and then aim to produce sustainable solutions for humans by imitating these designs or by taking inspiration from them” [82]. Furthermore, nature have survived due to evolutionary character which provides high performance and intelligent system. Therefore, their form and function are changing continuously and maintaining to develop based on new climatic conditions [83].

Levels of interest in nature consist of organism, behavior and ecosystem [81,84], while form, shape and manufacture process are suggested by Hyde [85]. Numerous varied movable components in the nature, including that of plants, animals and humans provide adaptability for several motions and transformation. There are simple principles of leverage derived from animals such as shark jaw that could produce quick and strong forces [7 p.16]. With respect to plants, movements called tropisms [7 p.14] which classified under different categories as follows: “A) phototropism (response to light stimulus)
The study of overlapping fields of biology and architecture that show innovative potential for architectural problems is defined as Biomimicry by Radwana & Osama [91]. Subsequently, inspired by nature for building's architectural design leads to use on-site resources (temporary sunlight) for generating renewable energy with the aim to reduce greenhouse gas emission and be energy efficient in real time operation. To illustrate, mimicking the form of soup bubble in the Water Cube of Beijing provides energy saving by 30% as well as reduction of artificial lighting by 55%. Moreover, The Council House 2 in Melbourne is inspired by Tree organism and behavior for making a kinetic shading façade which enables saving energy of 82% and reduction of artificial light and mechanical ventilation by 65% [91]. Since material and movement are the two most applied topics in the transmitting solutions from nature to technology, movement topics including of kinetic movements, release mechanism, structural configuration lead building have to be more responsive to continuous environment changes [92]. Specifically, biomechanical systems in the kinetic buildings, such as revolving building, have enough potential for adapting to different climatic conditions [12]. For example, Drag-spelhuset is an expandable building located on the shore of the lake Övre Gla in Sweden. The extendable building has capability to be adapted with the number of occupants and different weather conditions by seasonally alteration which has been inspired from cocoon to butterfly transformation. Moreover, double skin of the building has provided more energy efficiency and extra shelters against the cold and rainy weather respectively (Fig. 8). Plant like building has no ability for moving, while different parts of its body move individually, use functional system and respond to environmental conditions. Integration of geometry, material & technology in the shape of flexible façade needs to study motion aspects of plant organs such as leaves and petals with regard to several stimulus [93]. To illustrate, plant movement inspirations are applied for transforming rigid body to soft & flexible one such as Flectofin hingless louver system [93].

Thematic pavilion, which has been exhibited at Expo 2012 in Yeosu Korea, was a kinematic façade that designed by Soma architects. Individual kinematic fines have been applied in the façade for controlling daylight conditions and demonstrating the aesthetic aspects of lighting effects. The concept of the dynamic fines have been extracted from elastic deformation of the kinetic system in the Strelitzia reginae flower. Therefore, basic principles of Flectofin have been applied to project Flectofin louvers (Fig. 9). Furthermore, Shanghai Qizhang Forest Sports City Centre with dynamic retractable roof located in Minhang District of Shanghai in China. Mitsuru Senda & Environment Design institute designed its dynamic roof based on Magnolia petals capability in response to several weather conditions. The roof, which can be opened and closed automatically, controls indoor environment and also hosts indoor and outdoor sport events. Kinetic movements of magnolia flower have been used in the design process by means of mathematical relations containing rotation and translation (Fig. 9).

5.1. Biomimicry approaches

Biomimicry approaches are categorized into two primary ways: the first one referred to define human desires or designing problem and looking for solutions in nature, named Top-Down approach [84, 92, 103] or called problem-driven, biologically inspired design [84] (Fig. 10a). The second one identified a particular characteristic, behavior or function in an organism or ecosystem and translating into human designs that termed Bottom Up approach or biology influencing design [81,84,85,91,97,103] (Fig. 10b).

5.2. Top-down approach

Despite the fact that solution driven approach (Bottom-up) is suggested by many resources, problem driven approach (Top-down) is more practiced by many researchers and has more popularity in implementation [102]. Although, bottom-up approach applied by Sokhandan & Monadjemi [97] represents high capability of visual tracking model inspired from brain & eye mechanism for generating solar energy. However, sometimes lack of technology for implementing is important issue about ineffectiveness of this approach. Moreover, processing this approach needs experts and specialist about appropriate phenomena such as biologists and physiologists. Conversely, top-down approach is started by definition of design problem based on individual experts impressions which will be vary regard to different perspectives. Furthermore, filtering biological investigation by design problem definition with the aim to make sufficient exploration space for detecting efficient and meaningful pulps. Hierarchical exploration for finding appropriate natural phenomena leads to application of functional convergence approach for developing subcategories in a predefined framework. Consequently, appropriate biological solutions will be identified. As an example, considering water management functions leads to discover a suitable case for movement patterns [6,94,96] or analyzing mathematical relations of spiral seashell's body acquires principles for deployable structures (Fig. 11) [98].

Top-down approach's processes are defined by many researches [84,92,96,98,99,102] almost follow specific processes which are mentioned in Fig. 8a. Nevertheless, there are some differences among procedure of them. Defining challenge precisely, prevents searching irrelevant pinnacles in the early stages as well as improves the final
pinnacle selection. To illustrate, heat regulation strategy by Lidia Badarnah [94] refers to systematic exploration option, consisting of challenge, analogy, process & factors, scenario and pinnacle. Applying Top-down approach extremely needs for filtering the aforementioned levels with the aim to make sufficient exploration space for detecting efficient and meaningful pinnacles, where degree of freedom is significantly influencing the process of choosing appropriate factors. Degree of freedom obviously implies to amount of personal experience and knowledge of researchers that makes purposeful framework for discovering possible solutions. Spanning biology to engineering practices multidisciplinary cooperation between biology, mechanic, physic, architecture, for creating intelligence and sustainable geometry such as designing deployable structure inspired by earthworm [83]. Therefore, Top-down approach facilitates using bio inspired idea for detecting

![Fig. 8. Dragspelhuset building in Sweden inspired from cocoon to butterfly transformation. Left side is the normal form and right side is after extension [13].](image)

![Fig. 9. Left side Thematic pavilion with kinematic facade at Expo 2012 in Yeosu Korea [22,93] and right side Shanghai Qizhang Forest Sports City Centre with dynamic retractable roof in Minhang District of Shanghai in China [13].](image)

![Fig. 10. a Top-down [84] b Bottom-up [84].](image)
design solutions based on individual expertise, points of view and functional scenarios. Consequently, multifunctional biological analogies could be investigated and considered as well as different organs’ solutions for common problem with the aim to discover multifunction solutions for a design problem [102].

5.3. Biomimicry morphological approach

Exploring natural phenomena, for finding appropriate principles, implement in different scales and levels. Indeed, scale addresses microscopic and macroscopic investigations, while level refers to physiology, morphology and behavior aspects. There are numerous samples in every scale and level. However, discovering suitable pinnacles, regarding environmental adaptability for façade, significantly depends on exploring an appropriate level in biomimicry. Following literature reviewed several bioinspired researches to demonstrate different methods, functions, levels and effective parameters correspond to final product (Table 4).

A comprehensive review of precedent literature in biomimicry reveals a constant trend for applying morphological characteristics of natural phenomena to provide more adaptability with environment by means of complex and flexible forms [6,81,82,94,96,104,118], convertible [104,106,116] and hierarchical structures [118] (Table 4). Also, using bio inspired solutions, which exploited by morphological approach, have developed material properties, smart material and energy efficient shape change [81,82,105,109,117]. Integrating bio-complex form and smart material has capability to create an innovative system for building which is intelligent [111,112,115], responsive [108,115,117] and adaptive [6,91,94,96,107,113,116,118] regarding environmental conditions. Climatic design, which influenced by the innovative systems, is apportioned to thermoregulation [6,91,94,96,106,108,113,115] and daylight performance [6,91,94,96,107,108,113,114,118]. Though thermoregulation implies heat gain, retention, dissipation and prevention, natural ventilations and air flow, daylight performance notices controlling solar radiation features comprising intensity, direction and color in order to provide visual comfort for occupants. The bio-inspired systems affect energy performance of buildings as well by improving energy efficiency [6,82,91,94,96,112,115], production [6,94,95,106] and conservation [6,81]. Furthermore, the main focus of most of the biomimicry researches is energy efficiency. The biomimicry studies indicate geometrical transformation [6,81,91,94,96,104,106,108,112,114,116] and dynamic mechanism [81,106,107,109,111,114,116], which have been extracted from natural phenomena, are the innovative solutions for developing movement types in kinetic forms and smart materials. Building façade form has been taken into account as one of the most important functions that benefits from bio inspired geometries and complex forms with the aim to be more adapted with the environmental condition [6,81,91,94,96,105,108,112,114,118].

Interdisciplinary relation of the aforementioned parameters proves complexity and heterogeneity of façade that show façade form has been influenced by several interconnected factors in different levels. Therefore, the bio responsive façade and being interactive due to environment stimuli are the innovative topics which have a great potential to provide energy efficiency and improve visual and thermal comfort.

In summary, physiological, morphological and behavioral levels of natural phenomena have been investigated from microscopic and macroscopic scales. Bio inspired products have capability to perform interdisciplinary functions including energy conservation/production, climatic control and thermal regulation, controlling daylight and allowing airflow, convertible and flexible structure with high performance strategies consist of intelligent and responsive system, smart material, energy efficient shape change, hierarchical structure and dynamic configuration. Exploring effective parameters in several biomimicry research and comparing different features together reveals that morphological approach is the most effective classification among the biomimicry levels (Table 5). More importantly, utilizing dynamic configuration (complex geometry) in response to severe climatic condition is an effective way to preserve and optimize internal comfort condition. Façade as a regulator element has the potential to interact morphologically with intermediate environment for controlling solar radiation and wind forces. For example, based on Badarnah [6] conclusion that “form follow environment”, mimicking extensibility of plant cell walls

Fig. 10. (continued)

Fig. 11. Mathematical relations of spiral seashell body [98].
pological schema. Similarly, decomposition technique impacts levels of freedom in an explorative algorithm by typological and topological schema, referring to the explorative design of sub-types by changing of parametric variables, versus a topological-schema, referring to a topological explorative type of design of versioning types by changing the values of their associative relationships [119].

These second most important factor is exploitative process, recognized as a switching time from exploration to extraction [120,121]. Inadequate exploration area might lead to missing some optimal solutions [121]. Then exploration space is taken into account as the first most important factors in the early stage of design. Parametric design thinking applies non-linearly approaches in order to increase cumulativity and divergent thinking as well as decomposition process. Consequently, many design variants and diverse methods will be combined together to create multidisciplinary platform for exploring wide domain of design varieties. These second most important factor is exploitative process, recognized as a switching time from exploration to extraction [120,121], considerably depends on degree of freedom. Principles, rules and constraints, which derived from several subjects regarding the main topic, make different levels of freedom in an exploitation algorithm by typological and topological schema. Similarly, decomposition technique impacts levels of freedom remarkably. This technique is an effective method for establishing parametric design thinking due to flexibility and easier change in the design alternatives [122].

Visual & thermal comforts for occupants are directly depending on ambient environmental conditions, which are changing continuously. Therefore, an adaptable multi-disciplinary platform for redesigning and regenerating could be found by parametric design thinking. It promotes nonlinear connections across different fields and facilitates the decomposition process which provides wider exploration area. More specifically, decomposing generative algorithm, in different levels, makes exceptional opportunities for changing degree of freedom based on several points of view. Accordingly, multidisciplinary design platform will be established more flexible, generative, evaluative and performance based (Figs. 4 and 5).

6. Parametric design thinking

Parametric design thinking facilitates quantitative and qualitative evaluations in design process by integrating parametric modeling and energy analysis tools [119,120] (Fig. 13). Detecting optimal architectural form for regulating daylight needs to apply sufficient explorative space and ideal switch time between explorative and exploitative process [120,121]. Inadequate exploration area might lead to missing some optimal solutions [121]. Then exploration space is taken into account as the first most important factors in the early stage of design. Parametric design thinking applies non-linearly approaches in order to increase cumulativity and divergent thinking as well as decomposition process. Consequently, many design variants and diverse methods will be combined together to create multidisciplinary platform for exploring wide domain of design varieties.

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6. Parametric simulation modeling

Digital modeling and simulation tools are applied in the recent research as one of the important part of the investigation (Fig. 14) [46,51,128]. Preparing databases for evaluation process significantly depends on the elaborate digital modeling which created by different parameters. Moreover, programmed software, such as Rhino3D & Grasshopper, implement natural evolutionary functions in the current architectural research for analyzing and optimizing complex models by diverse parameters [51]. Therefore, Using computational design tools and rapid generative evolutionary algorithm are effective ways for creating concept in the early steps of design [123 p. xii [124,125]]. In particular, algorithmic design methods bring the state of the art in the non-linear design system and have a capability for realizing the complex geometric design across multiple objectives [125].

A multidisciplinary approach creates complex adaptive systems which are characterized by their ability to dynamically respond environmental changes ([124,127] pp.202–217 [128]). Adaptive and inter-disciplinary functions apply meta-heuristic optimization methods such as a multi objective algorithm due to its flexibility and rebuild process. Last but not least, parametric design method has been made on algorithmic based. "Algorithm is a defined series of instructions that seek to achieve a specific defined objective in a restricted number of phases. It takes one value or a set of values as input, performs a set of computational calculations that convert the input, and lastly produces one value or a series of values as output" [15] p.23).

Parametric simulation model has ability to provide a rapid generative algorithm for creating movable patterns regarding diverse parameters. With respect to multifunctional process, parametric approach is a necessity for modeling and evaluating kinetic façade, in the
Table 5
Applying morphological characteristics of natural phenomena to provide more adaptability with environment.

| Author           | Ref   | Year | Biological analogy                                                                 | Extracted Pattern/form                                                                 | Innovative System                                                                                     |
|------------------|-------|------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| Göran & Werner   | [107] | 2015 | Abstraction, geometric transformation from Rib structures of Actinoptychus          | ![Image](image1.png)                                                                     | Shading façade geometry is abstracted from leaves surface stomata function (opening and closing)     |
| Nour ElDin et al.| [108] | 2016 | Creating breathing wall which is adapted to daylight and natural air ventilation    | ![Image](image2.png)                                                                     | Creating breathing wall which is adapted to daylight and natural air ventilation inspired by termite mound |
| Körner et al.    | [116] | 2017 | Snap-trap of the biological role-model Aldrovanda vesiculosa and abstracted kinematic principle curved-line folding. | ![Image](image3.png)                                                                     | Snap-trap of the biological role-model Aldrovanda vesiculosa and abstracted kinematic principle curved-line folding. |
| Schieber et al.  | [119] | 2018 | Hindwings of insects as concept generator for hingeless foldable shading systems    | ![Image](image4.png)                                                                     | Hindwings of insects as concept generator for hingeless foldable shading systems                      |
| Knippers & Speck | [105] | 2012 | Flectofin louvers and lamella façade inspired by Strelitizia reginae flower         | ![Image](image5.png)                                                                     | Flectofin louvers and lamella façade inspired by Strelitizia reginae flower                           |

(continued on next page)
real time operation. Individual subjects such as daylight, occupants comfort and façade architectural form have special principle, rules and restriction which significantly impact the final design concept. Consequently, there are conflicts among multidisciplinary integration. In summary, parametric investigation provides a unique opportunity to explore digital model across multiple options and variables with the aim to achieve the most optimal trade off solutions regarding all criteria.

7. Discussion and conclusion

Many researches have been carried out about kinetic concepts strategies, principles, and criteria. However, interdisciplinary studies for proposing high performance kinetic concept are relatively rare. Therefore, generative-parametric and quick form finding method for responding to climate fluctuation would be a solution for providing more adaptability to dynamic environmental stimuli. This literature review study investigates interrelated fields, terms and keywords which lead to determine significant subjects consist of building form as a microclimate modifier, kinetic facade, biomimicry, indoor comfort, energy efficiency and parametric thinking with the aim to
conceptualize an adaptive façade form to improve visual and thermal comfort by interdisciplinary strategy. And also, enable architects and building physics experts to think about multifunctional aspects of kinetic façade and its potential for dynamical response to the microclimate forces fluctuations.

Façade regulatory function modifies microclimate across the building ambient environment by controlling solar radiation and wind (air flow). Building form, as a microclimate modifier, benefits from geometry and orientation which considerably control the microclimate forces. Furthermore, these factors provide daylight performance, natural ventilation, energy efficiency, indoor and outdoor thermal comfort. Overall, façade design has ability to progress its regulatory function significantly, and benefits from altering orientation and geometry by using “complex form” [19]. Also, Semi-open spaces and three dimensional shape changes in façade, as an advanced shading device, have an adequate potential to be investigated as three dimensional modular elements in façade for improving daylight performance, visual and thermal comfort.

The combination of biomimicry, technologies and architecture empowers kinetic concept development [[7] p.14] where architectural design concept addresses concept, module and morphological approach while mechanism refers to technology and movements. Indeed, integrating mechanism and architectural design concept by means of morphological approach leads to investigate geometry and politics of control. Exploring morphologies, which considerably affect kinetic façade performance, have significant potential for innovation. Bioinspired façades have potential to be climatic responsive and energy efficient by regulating daylight, airflow, natural ventilation and thermal behavior. Investigating several biomimicry studies approves dominant position of the morphological level in nature for environmentally adaptation. With respect to Badarnah [6] “form follows environment”, façade, as a regulator element, has an opportunity to benefit from biomimicry morphological approach with the aim to control solar radiation and wind resulting in modifying microclimate in ambient environment. Therefore, façade “maintains stable internal conditions while tolerating changing environmental condition.”

Parametric design facilitates interdisciplinary study to encourage cumulativity and divergent thinking. Indeed, exploring kinetic concept, biomimicry, microclimate, energy efficiency and comfort condition, by parametric thinking provides more visibility to detect main principles which affect all of aforementioned subjects simultaneously. Therefore, kinetic façade design principles to be investigated by a kinetic façade design morphological approach (Fig. 15).

The historical conservative characteristic of façade role is turned into the regulatory element which has capability to improve quality of indoor comfort while tolerating climate fluctuation in ambient environment. Façade as an only interface between inside and outside of building, far from the literal and conventional perceptions, is recognized by intrinsic functional attributes including complexity, heterogeneity and multidisciplinary. Indeed, façade regulatory function, according on layer of façade, is evolved based on different stimuli in course of the time. Interactivity to functional scenario stimulates heterogeneity beside of the façade complexity. For instance, Al Bahar Towers and Sharifi Ha House are operated under complex façade systems, while functional scenario gives rise to heterogeneity in the façade form where Al Bahar benefits from large elements in the façade and Sharifi Ha House uses parts of the façade (Table 3). Multidisciplinary investigation facilitates moving toward interactivity to functional scenario in building. Indeed, exploring the building form, as a microclimate modifier, lead to apply concept of occupants’ daily migration to façade

| Kinetic | Biomimicry | Modifying Microclimate | Comfort Conditions | Parametric Design Thinking | Energy Efficiency |
|---------|------------|------------------------|--------------------|--------------------------|------------------|
| Architectural design concept | Form | Microclimate notable forces: Solar & wind | Physical aspect | Sufficient explorative space | Applying on-site renewable energy sources |
| Mechanism | Innovative system | Microclimate modifier Functions: thermoregulation, daylight performance, facilitating occupant daily migration | Human factor | The amount of light | Integrating passive design strategies & active technology |
| Evaluation | Climatic design | Functions: thermoregulation, daylight performance, facilitating occupant daily migration | Thermal comfort metrics (PMV & PET) | The uniformity of light | Using optical characteristics of material (Solar reflectance & emissivity) |
| | Façade function | Effective Parameters: geometry & orientation | The quality of light in rendering color | The prediction of the risk of glare for occupants | |
form by designing a kinetic façade which is interactive due to occupant position. Consequently, these subjects impact façade form individually and aggregately regard to functional scenario that is changed the perception of kinetic façade from elegant and fashionable state to a functional and practical element (Fig. 5). Indeed, “simple relationships between parts give rise to complex interactive behavior and relationships with environment” which have a capability to be applied into responsive façade form regarding ever-changing ambient environment ([129], p.176).

Fig. 4 represents an algorithmic kinetic façade design process on multidisciplinary investigation that is supported by the concept of building form as a microclimate modifier. The morphological approach is identified by an innovative façade design processes which provides idea for changing from static to dynamic. Kinetic façade, which applied bio inspired geometry, patterns & principles, is topologically transformed to control the microclimate forces in ambient environment. Indoor comfort is evaluated thermally & visually to consider performance of the transformable form. If the comfort criteria are met by the kinetic façade, an optimal form is achieved. Otherwise, biomimicry morphological approach will be applied for developing a new typology with the aim to detect an optimal form regarding the interested functions. The iteration loop has a potential to be performed infinite times for discovering unforeseen alternative forms based on customizable parameters and goals.

The interdisciplinary framework demonstrates potential of kinetic façade concept which is interconnected to biomimicry and modifying microclimate for changing orientation and geometry to control solar radiation and wind as the notable forces in the microclimate. Consequently, modifying microclimate improves thermal and visual comfort simultaneously. Geometry and complex form, which derived from biomimicry by means of morphological approach, lead to detect high performance forms and configuration for responsive façade in the real time operation (Fig. 15).

Further research is investigating performance of applying occupants daily migration and building form on indoor comfort based on geometry and orientation. And also comparing these results with the performance of an adaptive kinetic façade from which used three dimensional shape changes by parametric simulation (Fig. 5). In particular, approaches of translating and applying biomimicry principles to parametric instructions need to be studied for optimizing the adaptive façade form performance regarding comfort conditions. More specifically, exploring the parametric and generative form finding loop is a great opportunity to find significant parameters which affect kinetic façade regarding multifunctional scenario (Fig. 6).

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