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Original Research Article

INNOVATIVE, MODULAR BUILDING FACADES - AS A TOOL TO COUNTERACT THE EFFECTS OF AND TO PREVENT CLIMATE CHANGE

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Abstract

The paper presents original research, encompassing the results of analyses of modular building façade solutions, as well as innovative design concepts based on these results by students of the Faculty of Architecture at the Poznań University of Technology. Adapting architecture to climate change is the main objective behind research and innovative designs. Reduction of carbon dioxide emissions, thermal comfort of buildings, better thermal environment ergonomics for users of buildings' interiors, increased energy efficiency together with the use of renewable energy sources are major challenges for today's designers. Dealing with rainwater, wind and pressure changes are already absolute necessities. Contemporary trends in modern construction in urban areas were identified on the basis of results of analyses of selected existing buildings, presented using tables, graphs and statistical tools. Conclusions from the demonstrated correlations of quantitative data with social, economic and environmental factors became the basis for the students' conceptual assumptions. The selected innovative façade designs presented in the article demonstrate a variety of solutions for modern modular systems which protect buildings from excessive sun exposure, help insulation resist external factors, generate energy, ventilate buildings, use pressure differences, collect water, purify air, protect fauna, etc. As a result, the developed concepts may be indicative of a contemporary

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approach to sustainable building design, based not only on reducing any negative environmental impact and conserving natural resources, but also on designing aesthetic buildings based on classic notions of beauty.

Keywords: module, prefabrication, ecology, environment, architecture, construction, façade, innovation, aesthetics, technology, concept

1. INTRODUCTION

Implementation of innovative solutions in contemporary architectural design is stimulated by climate change, the need for efficient renewable energy sources, global water scarcity and flooding, as well as the degradation of flora and fauna as a result of human activity [12]. Social, economic and ecological considerations play a decisive role when drawing up a building concept [16]. Modern material technologies based on the ability of plastics to respond to changes in the environment; use of dynamic, multifunctional façades that integrate the building's external and internal environments and use of smart tools make it possible to develop façade systems for future buildings, often mimicking biological processes using heuristic methods and parametric design [21, 5]. Searching for modern materials and design techniques, subjecting existing engineering solutions to analyses, conceptualising, looking for new ideas, prototyping and implementing optimal methods are integral to the creation of new inventions that are an answer to the problems of the modern world [1, 14].

The authors' objective, in addition to the above aspects, was to seek out the beauty of architecture. This aspect has been the subject of much previous discussion [25] and current research. After all, spatial harmony [26, 27] and timeless beauty, sometimes neglected in designs focused on best technical or technological solutions, constitute the greatness of a work of architecture.

2. RESEARCH AND ANALYSIS

Analyses of collected data presented as a table (Table 1) pertaining to 140 architectural structures from different parts of the world were carried out. The analyses' results are shown in diagrams with descriptions. Examples of modular building façades, featuring a variety of functions, made it possible to present correlation coefficients, as well as trends in architectural design that correspond to current environmental concerns, including climate change, droughts and floods, degradation of flora and fauna, air pollution and limited stocks of non-renewable energy sources [30].

2.1. Research presented as a table

Table 1 shows basic information on selected buildings with modular façades. The buildings shown therein, identified by students of the Faculty of Architecture at the Poznań University of Technology as the most interesting and modern, conducive to counteracting the effects of and preventing climate change, were discussed in the form of a multimedia presentation in classes as analytical material within the scope of a Master's programme. No site selection criteria other than a modular façade system and an aesthetic appeal of the architectural forms which the façades are a part of were imposed on the students. The vast majority buildings selected by students featuring modular façades, whether actually completed or just designed, date back from the last decade. The attractiveness of these buildings stems not only from their form and modern design solutions, but also the materials used in their construction. The ageing process of façade materials (except for a few such as copper or weathering steel) is often detrimental to the appearance of buildings, thereby affecting their aesthetics.

The structures selected by the students constitute buildings of different sizes, serving a variety of functions, exhibiting a variety of forms and design concepts. The data collected was combined with detailed information pertaining to technology, material science, the environment and ecology. Students used a table based case study to discover current trends depicted in the form of composite charts. Then they drew conclusions, and finally came up with concepts for modern architectural façade solutions by experimenting towards the new [11].

Many of the 140 buildings in Table 1 featuring innovative façades from around the world are located in large cities. Information on buildings located in Warsaw, Poland's largest city is also shown in the table. It includes some of the most important projects of recent years, icons of Polish architecture, designed by well-known and appreciated design studios. The buildings' modern façade designs, interesting forms and dominant features make them stand out from the rest. Their modular façade elements perform a number of significant functions. Apart from ensuring those who experience the highly aesthetic façade and interiors are impressed, these elements also provide improved thermal comfort for the building, better spatial ergonomics and reduce operating costs. Urbanised areas, with narrow streets and a lot of shade reduce the comfort of using interior spaces and impair air quality and thus have a negative impact on human health. The introduction of innovative modular building façade systems, especially in large cities, should contribute to better thermal, visual and acoustic comfort. The systems should also take into account ventilation, natural light and energy management in buildings [13].

Fig. 1. Façades and details. From the left: Złota 44, designed by: Daniel Libeskind (No. 139, Table 1); Warsaw Unit, designed by: Projekt PBPA (No.132, Table 1); Apartments next to Warzelnia, designed by: JEMS Architekci (No.11, Table 1). Phot: H. Michalak

Buildings in the table are arranged alphabetically. The name of the architect or the name of the design office, the year and the city and country in which the construction was carried out are given for each item in the table. Each item is also described by PD, the population density of the town where the façade is located and CT, the climate zone and climate type, in which the following zones have been defined: 1a - circumpolar zone polar climate, 1b - circumpolar zone subpolar climate, 2c - temperate cool zone continental climate, 2d - temperate cool zone transitional climate, 2e - temperate cool zone marine climate, 2c2 - temperate warm zone continental climate, 2d2 - temperate warm zone transitional climate, 2e2 - temperate warm zone maritime climate, 3f - subtropical zone dry and extremely dry climate, 3g - subtropical zone humid climate, 4f - tropical zone dry and extremely dry climate, 4g - tropical zone humid climate, 5h - equatorial zone dry sub-equatorial climate, 5i - equatorial zone humid sub-equatorial climate, 5k - equatorial zone extremely humid climate; degree of air pollution in the range of 0-6, where 0 - WHO target, 1 - good, 2 - moderate, 3 - unhealthy for sensitive groups, 4 - unhealthy, 5 - very unhealthy, 6 - hazardous [37]; AB - area of the building, FF - functions of the façade, where A - maximisation of daylight, B - protection from excessive sun exposure, C - insulation, D - ventilation, E - heat reception, F - heat rejection, H - generation of electricity, I - generation of pressure differences, J - other; ML - type of material from which the coating was made.

Table 1. A study of modular façades across the world

No.	Name	Architect	Year	City, Country	PD	CT	P	AB	FF	ML
1	727 West Madison	FitzGerald	2018	Chicago, USA	4 559	2d2	0	24000	D	Glass
2	Advanced Building	Kirk, Hassell	2013	Brisbane, Australia	408	4g	0	18000	A,B,D	Wood
3	Al Bahar Towers	Aedas Architects	2012	Abu Dhabi, UAE	1 526	4f	3	70000	A, B	Fibreglass
4	Alavi House	BMDesign Studios	2017	Isfahan, Iran	3 559	4f	2	550	B, C, H, D, I	Tesla PV panels
5	Allianz Area	Herzog & de Meuron	2005	Munich, Germany	4 686	2d2	0	171000	A, C	Membrane
6	Amore Pacific World HQ	David Chipperfield	2017	Seoul, South Korea	16,000	2e2	3	216000	A, B, F	Brise-soleil
7	Angdong Hospital	Rural Urban Framework	2014	Beijing, China	160	3g	2	1450	A, D	Ceramics
8	Anibal building	Bernardes Arquitetura	2015	Rio de Janeiro, Brazil	5 105	4g	0	1020	A, B, C	Aluminium
9	Anschutz Health Sciences	ZGF Architects	2019	Aurora, Colorado	60	3f	0	36000	A, B	Glass
10	Apartment Blocks	X -TU	2014	Nanterre, France	7 442	2e2	0	15500	A, D	Glass
11	Apartments next to Warzelnia	JEMS Architekci	2021	Warsaw, Poland	3 467	2d2	2	100000	B	Noble materials
12	Apple Park	Norman Foster	2017	Cupertino	1 997	3f	0	260000	H, D	Glass
13	Arab World Institute	Jean Nouvel	1987	Paris, France	21,274	2e2	2	16894	A, B	Aluminium
14	ArboSkin Pavilion	ITKE	2013	Stuttgart, Germany	3 000	2d2	1	145	B	Bioplastic
15	Aspen Art Museum	Shigeru Ban	2014	Aspen, USA	650	3g	1	3065	B, A, D	Composite wood veneer
16	B House	i.House	2014	Nhà Bè, Vietnam	2 400	2e2	3	82	B, D, J	Photobioreactors
17	Backyard BI(h)OME	Kevin Daly Architects	2016	Los Angeles, USA	3198	3f	2	500	A, B, C	ETFE
18	Bank Nykredit	SHL	2010	Copenhagen, Denmark	4 400	2e2	1	6850	B, C, H	Glass
19	Bent Housing Building	Chris Kabel	2012	Amsterdam, Netherlands	5214	2e2	0	300	B	Concrete
20	Bionic Tower	LAVA	2007	Abu Dhabi, ZEA	1 526	4f	2	108700	B, E	Glass
21	BIQ	Arup	2013	Hamburg, Germany	2 452	2e2	0	839	H, J	Steel
22	BLM House	ATRIA Arquitetos	2014	Brasilia, Brazil	521	5h	2	630	B, J	Aluminium
23	Bornholm Hospital	BJERG	2015	Rønne, Denmark	1 700	2e2	0	25000	H, J	Solar glass
24	Brandenburg Library	Herzog & De Meuron	2005	Cottbus, Germany	603	2d2	1	12667	A	Glass
25	Brise Soleil	Studio Workshop	2017	Papua New Guinea	15	5k	0	173	B, C, F, D	Wood
26	Byggom AB Office Extension	J. Sundberg B. Andréasson	2014	Lund, Sweden	3 472	2e2	0	130	B	Sheet metal
27	Caixa Forum	G. Consuegra	2017	Seville, Spain	4 910	3g	2	10500	J	Alu foam
28	Cartier Building	Jean Nouvel	1994	Paris, France	21,274	2e2	2	11300	J	Aluminium, glass
29	Center for Asian Art Ringling	Machado Silvetti	2016	Sarasota, USA	1 367	4g	2	2369	B	Terracotta

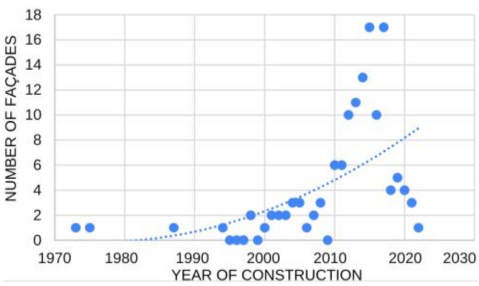
No.	Name	Architect	Year	City, Country	PD	CT	P	AB	FF	ML
30	Central Station	Benthem Crouwel	2016	The Hague, Netherlands	5 345	2e2	0	20000	B, D	Glass, steel
31	CH2 Melbourne	DesignInc	2004	Melbourne, Australia	2 572	3g	1	12500	B, F, D	Wood, sheet metal
32	Children's Museum	Koning Eizenberg	2004	Pittsburgh, USA	2 214	2d2	2	9290	B, C, F, J	Acrylic resin, teflon
33	Circadian Wind	Ned Kahn	2019	Los Angeles, USA	3 198	3f	2	1500	J	Polycarbonate
34	Cloaked in Bricks	Admun Design	2015	Tehran, Iran	18,02 3	3f	2	1100	B, E	Brick
35	CoBLOgó	SUBdV	2014	Centro, Brazil	5 105	5h	2	500	B, C, E	Ceramics
36	D3 House	Pitsou Kedem Architekci	2018	Hertsliya, Israel	3 933	3g	2	670	B	Aluminium
37	Daiwa Ubiquitous	Kengo Kuma & Associates	2014	Tokyo, Japan	6 410	3f	0	2710	B, D	Wood
38	Dom Doświetlający	77 STUDIO Architektury	2022	Magdalenka Poland	200	2d2	2	300	J	Glass
39	Elbphilharmonie	Herzog & de Meuron	2003	Hamburg, Germany	2 396	2e2	0	125512	B, C	Glass
40	Eli & Edythe	Hadid & Schumacher	2012	East Lansing, USA	1 664	2c	2	4274	B, F	Stainless steel
41	EWE & Bursagaz Headquarters	Tago Architects	2016	Bursa, Turkey	1 509	3g	2	9500	B, H	Glass, PV
42	Faculty of Economics and Business	Duque Motta & AA	2013	Santiago, Chile	8 407	3g	1	9290	B, D, J	Concrete
43	FBI Headquarters	Krueck + Sexton	2015	Miramar, USA	1 524,8	4g	1	34838	A, B, J	Aluminium
44	Festival Theatre	Delugan Meissl	2012	Mühlgraben, Austria	74	2d2	2	10000	D, J	Fibre cement
45	Firefly	Ned Kahn	2020	San Francisco, USA	6 633	3f	0	21600	H, J	Polycarbonate
46	French Dream Towers	X -TU	2022	Hangzhou, China	5 374	4g	2	34100	C, D, H, J	Microalgae
47	French School	Jacques Ferrier	2016	Beijing, China	1 313	2c2	3	19000	A, B	Wood
48	Futurium Berlin	Richter Musikowski	2017	Berlin, Germany	4 206	2d2	1	14007	A	Textured glass, metal
49	Glacial Facade	Ned Kahn	2006	Issaquah, USA	1 018	2e2	1	5000	J	Polycarbonate, glass
50	Golf's Tower	Hackenbrioch	2008	San Isidro, Peru	12,50 0	4f	2	7000	B	Glass
51	Green Building	Höweler + Yoon Architecture	2011	Cambridge, USA	10,63 5,794	2e2	0	185806	H	Plastic
52	Hanwha	UNStudio	2013	Seoul, South Korea	16,56 6	2d2	2	57696	C	PV, insulating glass
53	Harpa	Hennig Larsen	2011	Reykjavik, Iceland	480	2e	0	28000	A	Glass
54	Hazza Bin	Pattern Design	2014	AL AIN, UAE	51	4f	3	45000	A, B, E, F, D	PVC / PES
55	House in Travessa Do Patrocinio	L., T. Rebelo de Andrade + Manuel Cachão Tojal	2012	Lisbon, Portugal	6 458	3g	1	248	B, C, F, J	Mediterranean plants

No.	Name	Architect	Year	City, Country	PD	CT	P	AB	FF	ML
56	HUB-1 office tower	Merge Studio	2015	Bangalore, India	11,437	4g	4	13700	A, B, D	Aluminium panels
57	I liv	Nikken Sekkei	2019	Tokyo, Japan	6 410	3g	0	3601	A, B	Glass
58	Intecs Spa	Modostudio, Studio Cattinari	2014	Rome, Italy	2 195	3g	2	3500	B, C	Glass, steel
59	Italian Pavillion EXPO'15	Nemesi	2015	Milan, Italy	7 311	3f	2	27000	J	Concrete
60	Jean-Marie Tjibaou	Renzo Piano	1998	Numea, New Caledonia	2 063	4f	0	8550	B, D	Solid and non-solid wood
61	Jérôme Seydoux Pathé Fondation	Renzo Piano	2014	Paris, France	21274	2e2	2	2200	A	Aluminium, glass
62	Jissen Gakuen Kyogakukan	NASCA	2011	Nanako, Tokyo	22,135	3g	0	1023	A, B	Aluminium
63	John E. Jaqua Center	ZGF Architects	2010	Eugene, Oregon	1 217	3f	2	3716	A, B	Glass
64	Käpylän Posteljooni	Anttinen Oiva	2017	Helsinki, Finland	3 082	2d	0	7737	B, C	Ceramic shutters
65	Kiefer Technic Showroom	Ernst Giselbrecht +Partner	2007	Bad Gleichenber, Austria	53	2d2	0	545	B, C	Perforated aluminium
66	King Fahd National Library	Gerber Architekten	2013	Riyadh, Saudi Arabia	4 853	4f	1	3000	B, D, F	Teflon
67	Kraemer Centre	Yazdani Studio, CannonDesign	2015	Anaheim, USA	2 555	3f	2	1486	A, B	Glass
68	L'Umbracle	Santiago Calatrava	2001	Valencia, Spain	5 853	3g	1	1920	A	Concrete, ceramic tiles
69	L’Hemisfèric	Santiago Calatrava	1998	Valencia, Spain	5 853	3g	1	143000	A, B, J	Concrete, ceramics
70	L’Oceanogràfic	Felix Streibich	2003	Valencia, Spain	5 853	3g	1	110000	B	Concrete, ceramics
71	La Marseillaise	Jean Nouvel	2018	Marseille, France	3 555	2d2	1	46767	J	Aluminium, steel
72	Leawood	El Dorado	2013	Leawood, USA	810	3g	0	1695	F, B	Steel
73	Massport Central	Arrowstreet	2017	Boston, USA	5 400	2e2	0	241547	B, D	Aluminium
74	Media-TIC	Enric Ruiz Geli	2010	Barcelona, Spain	15,992	3g	2	23104	A, B	ETFE
75	Modular	Bureau Fraai	2020	Amsterdam, Netherlands	5 214	2e2	0	510	B, F	Concrete
76	Municipal Library	Archea Associati	2002	Nembro, Italy	763	2d2	2	1500	B	Ceramics
77	Music Conservatory	Architect	2013	Paris, France	21,274	2e2	2	5200	B	Steel
78	Naman Retreat Pure Spa	MIA	2015	Da Nang, Vietnam	4 087	5i	2	1600	B, C, J	Steel
79	Nawa Installation	Zieta Prozessdesign	2017	Wrocław, Poland	2 192	2d2	2	100	B	Steel
80	New Town Hall	Ingenhoven Architects	2017	Freiburg, Germany	1 509	2d2	0	26115	H, D	Crystalline glass
81	New-Blauhaus	Kadawittfeldarchitektur	2015	Mönchengladbach, Germany	1 514	2e2	0	5800	H	Glass, PV
82	Nowogrodzka Prestige	PBPA Project	2008	Warsaw, Poland	3 467	2d2	2	12335	A	Glass, concrete
83	Oasia Hotel Downtown	WOHA	2016	Tanjong Pagar, Singapore	6 067	5k	1	19416	B, D, J	Aluminium

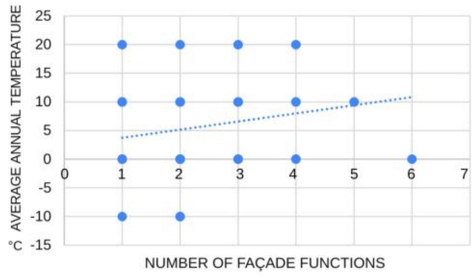
No.	Name	Architect	Year	City, Country	PD	CT	P	AB	FF	ML
84	Office Building for D3	Wwa, Wanders Werner Falasi	2015	Dubai, UAE	762	4f	2	18000	A, B	Glass, PV
85	Office Hispasat Technology Center	Herreros	-	Arganda del Rey, Spain	646	3f	2	3300	B	Aluminium
86	On the wave	APP Polska	2013	Sopot, Poland	2 028	2d2	2	1500	D, J	Glass
87	One Ocean Pavillion	SOMA Lima	2012	Yeosu, South Korea	650	3g	2	5657	J	GFRP
88	Palace of Justice	Ignacio Prego	2019	Pointe-à-Pitre,Gwadelupa	5 700	5i	0	5911	B	Wire mesh
89	Palau de les Arts	Santiago Calatrava	2005	Valencia, Spain	5 853	3g	1	44150	B	Concrete, ceramics
90	Palazzo del Cinema	AZPML	2017	Locarno, Switzerland	818	2e2	1	6500	A, B	Gold-plated panels
91	Parking garage	IwamotoScott, Leong	2015	Miami, USA	3 223	4g	0	23300	B, D, I	Aluminium
92	Pawilon Quadracci	Santiago Calatrava	2001	Milwaukee, USA	2 370	2c2	0	13197	A, B, F	Steel purlins
93	Ports 1961	UUfie	2015	Shanghai, China	3 900	3g	2	1145	B	Glass hollow bricks
94	Prince Philip Museum	Santiago Calatrava	2000	Valencia, Spain	5 853	3g	1	40000	A	Concrete, ceramics
95	Public Parking Structure #6	Behnisch Architekten	2013	Santa Monica, USA	4 117	3g	1	2250	A, D	Metal
96	Punjab Kesari	Studio Symbioza	2017	Delhi, Indie	382	4g	4	18000	A, E, D	Concrete with fibreglass
97	Rainbow chapel	Coordination Asia	2015	Shanghai	3 823	4g	4	1200	A, E	Glass panels
98	Re-Tale Store	Metropolitan	2019	Rawalpindi, Pakistan	8 101	4g	3	900	B	Sheet metal
99	Red River College Innovation Center	Diamond Schmitt architects and Number TEN	2021	Winnipeg, Canada	1 429	2c2	0	9290	H	Glass, satin
100	Residential and Utility Building	Chartier-Corbasson	2017	Paris, France	21,274	2e2	2	932	A, B	Metal
101	Revolving Bricks	A.P.Pars Architects	2015	Arak, Iran	8 100	3f	2	686	B	Brick grid
102	Rhike Park	Studio Fuksas	2010	Tbilisi, Georgia	1 506	4f	2	2900	B, C	Glass
103	RMIT Design	Sean Godsell	2012	Melbourne, Australia	508	3g	0	13000	B, E	Solar panels
104	S2OSB	BINAA	2016	Hendek, Turkey	321	3g	2	3000	B	Aluminium
105	School Nordhavn	C.F. Møller	2017	Copenhagen, Denmark	4 400	2e2	0	25000	E, H	Solar panels
106	SDU Campus	Hennig Larsen	2014	Kolding, Denmark	210	2e2	0	13700	A, B	Perforated steel
107	Sedull Stoll Center	Ludloff	2010	Dogern, Germany	303	2e 2	2	3200	B, C, D, J	Fibreglass fabric
108	Serenada Gallery	WIZJA, Atelier.com	2017	Kraków, Poland	2 384	2d2	2	106600	B	Concrete with fibreglass
109	SGH Innovation Centre	Stelmach i Partnerzy	2021	Warsaw, Poland	3 469	2d2	3	6100	J	Geenery, wood
110	Sidney & Lois Hospital	Rob Ley Studios	2014	Indianapolis, USA	8 054	3g	0	110000	B	Aluminium
111	Snapping facade	Jin Young Song	2022	USA	-	3g	2	0	B	-

No.	Name	Architect	Year	City, Country	PD	CT	P	AB	FF	ML
112	Student Minervahaven	VURB Architects	2021	Amsterdam, Netherlands	5 214	2e2	0	25051	D, H	SolarLAB solar panel
113	Sun Rock	MVRDV	2021	Taiwan, China	620	4g	2	12900	H	PV
114	SUTD	UNStudio	2015	Singapore, Singapore	6 067	5k	2	106000	B, C, F, D	-
115	Swiss Center Technorama	Dürig & Rämi Architects	2002	Winterthur, Switzerland	1 490	2e2	0	11000	I, D	Aluminium
116	Tainan Public Library	MAYU, Mecanoo	2021	Tainan, Taiwan	855	4g	2	37000	B	Aluminium
117	Tainan Church	MAYU architects	2015	Tainan, Taiwan	855	4g	2	1240	B	Aluminium
118	Techno-Prisme Storage Depot	Brisac Gonzalez	2013	Aurillac, France	1 070	2e2	0	500	J	Aluminium
119	The Building Titanic museum	Eric Kuhne and Associates	2012	Belfast, Ireland	2 608	2e2	1	12000	A	Aluminium
120	The Bund Finance Center	Foster, Heatherwick's	2017	Shanghai, China	3 823	3g	2	4000	J	Steel
121	The North Dock Expansion at the Campus	Crawford Architects	-	Kansas City, USA	13	2c2	1	11000	B,D	Aluminium
122	The solar tree	Nudes	2020	India	407	4g	2	1000	H	Wood, PV
123	The Torre de Especialidades	Elegant Embellishments	2011	Mexico, Mexico	6 030	5i	2	23000	J	ProSolve370e
124	The Willis Building	Foster + Partners	1975	Ipswich, England	3 385	2e 2	0	21255	B	Coloured glass
125	The Wyckoff Exchange	Andre Kikoski	2011	Brooklyn, New York	10,636	2e2	0	1000	B, J	Steel
126	Torre Agbar	Jean Nouvel	2004	Barcelona, Spain	15,813	3g	2	41561	J	Aluminium, glass
127	Turbulent Line	UAP + Ned Kahn	2012	Brisbane, Australia	162	4g	0	70000	B, D	Aluminium
128	University	ZGF Architects	2015	Phoenix, USA	1 198	3f	0	20000	B	Composite
129	Urban Green Light	I-Ting Chuang & Jeanne Lee	2016	Taiwan	634	4g	2	0	B, C, D	Recycled materials
130	V on Shenton	UNStudio	2016	Singapore, Singapore	7 797	5k	1	85507	B	Glass
131	Van Marcke Distribution Center	AAVO ARCHITECTS	2018	Kortrijk, Belgium	950	2e2	1	60000	B, C	Aluminium, DucoSun
132	Warsaw Unit	Projekt Polsko-Belgijska Pracownia Architektury	2021	Warsaw, Poland	3 467	2d2	2	59000	J	Aluminium
133	Water Tower	Mathias Klotz	2012	CHILE	985	3g	2	153	J	Aluminium
134	Wave Office Building	Medusa Group	2020	Gdańsk, Poland	1 786	2d2	2	43300	J	Steel
135	Westarkade	Sauerbruch Hutton	2010	Frankfurt am Main, Germany	3 100	2e2	0	39000	B	Aluminium + glass
136	Willis Tower	Skidmore, Owings &Merrill	1973	Chicago, USA	4 559	2d2	1	424000	A, E, H	Glass
137	Xicui Complex	Simone Giostra & Partners	2008	Beijing, China	1 313	2d2	3	2200	H	PV
138	Xinjin Zhi Museum	Kengo Kuma & Associates	2011	Xinjin, China	144	4f	4	787	A, B, C, F	Clay
139	Złota 44	Daniel Libeskind	2017	Warsaw, Poland	3 467	2d2	2	72500	B, J	Glass
140	Zuringhof	GreenCore	2016	Tilburg, Netherlands	1 763	2e2	1	400	C	Mineral brick

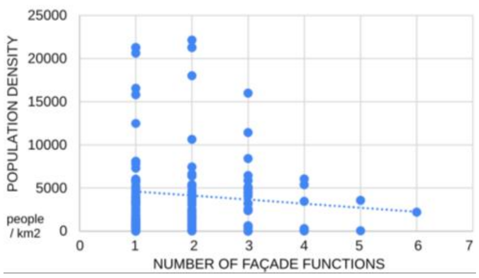
2.2. Analysis of the research presented in the table



(a)



(b)



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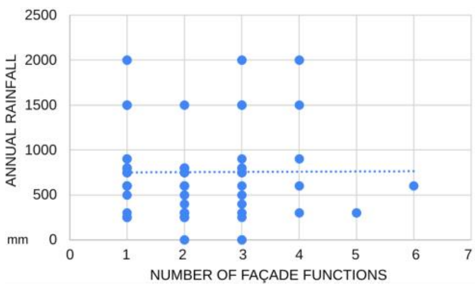

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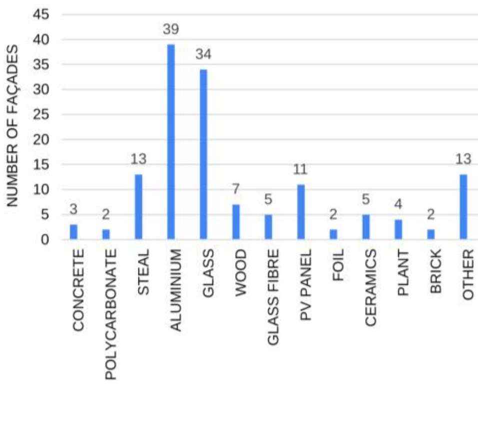

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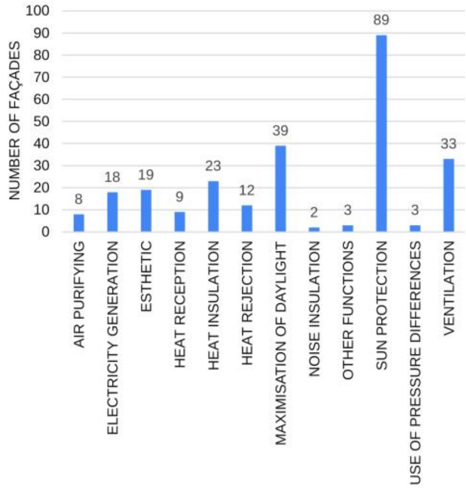

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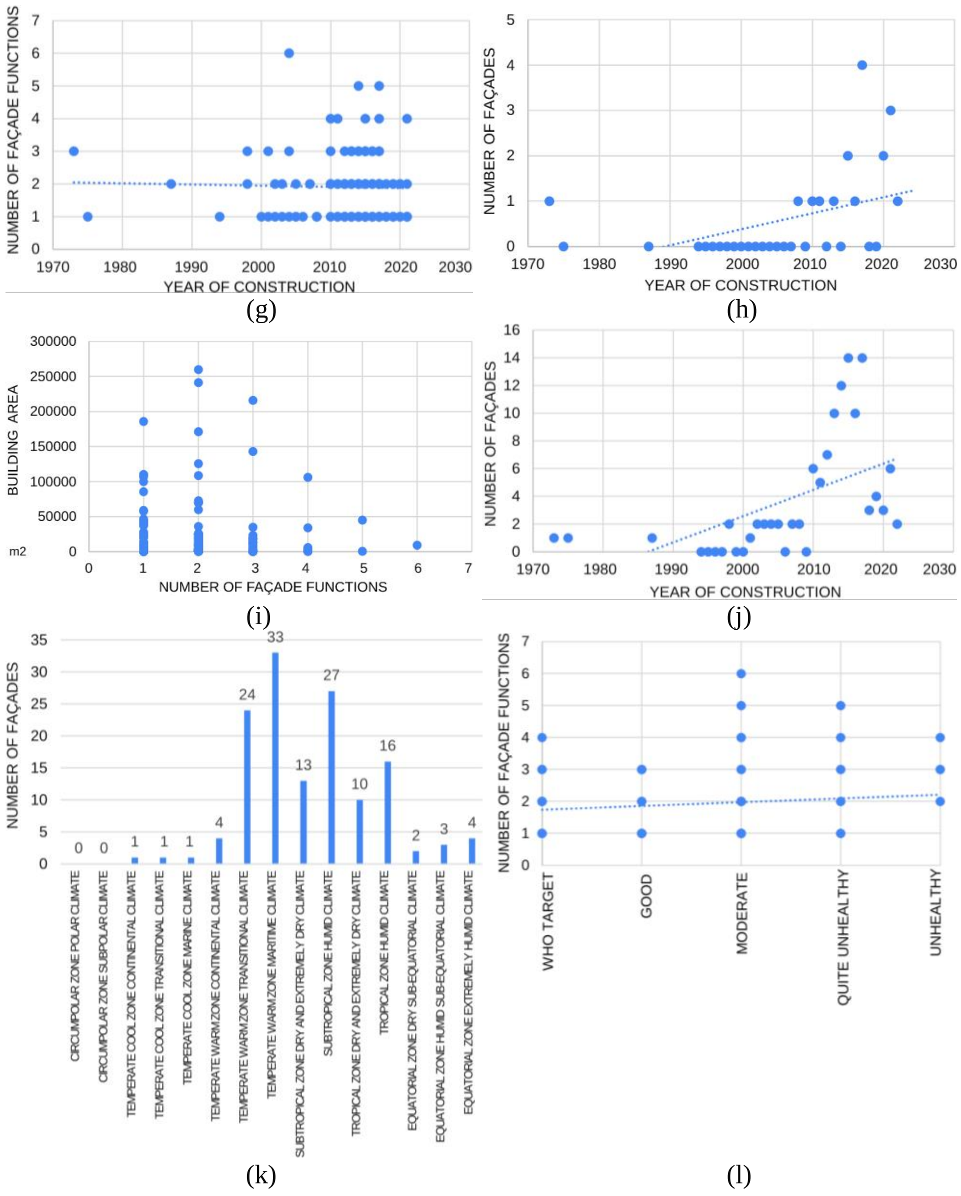

Fig. 2. Analyses: a) Number of modular façades over time b) Number of façade functions vs. annual temperature, c) Number of façade functions vs. population density, d) Number of façade functions vs. annual precipitation, e) Façade materials, f) Façade functions, g) Number of façade functions over time, h) Number of façades using renewable energy sources, i) Number of façade functions vs. building area, j) Number of façades increasing the thermal comfort of the building k) Number of façades vs. climate, l) Number of façade functions vs. air pollution

The research carried out reveals current trends in modern façade design. The graph plotting the number of modular façades in architecture over the years shows a dynamic increase in the number of buildings clad with a cladding made up of regular elements. This trend accelerated between 2010 and 2020 (Fig. 2a). The graph with the number of functions performed by the second skin of a building as a function of the annual average air temperature shows an that the number of functions tends to increase with temperature increases (Fig. 2b). As population density increases – the number of functions the façade performs decreases. One reason for the trend may be difficulties with access to modern technology in areas with low living standards, lack of economic opportunities for the development of design industries and investment in construction innovation (Fig. 2c). A comparative analysis of the number of façade functions and the annual precipitation according to the location of the building in a specific climatic zone shows that the collated values are independent of one another (Fig. 2d). An assessment was carried of the type of material used to form the module shell. Aluminium and glass are most frequently used by engineers. Materials such as photovoltaic cladding, steel or ceramics are also used (Fig. 2e). A further analysis reveals a significant number of instances of façades that maximise the flow of daylight into the interiors and improve the building's ventilation. A large number of buildings also use façades for thermal insulation against external weather conditions and to generate energy (Fig. 2f). The façades of the largest buildings usually had two different functions (Fig. 2g). The number of buildings with modular façades using renewable energy opportunities is increasing from year to year. The graph shows a positive correlation (Fig. 2h). Building area was another parameter that was taken into account. The research did not show that the number of functions the façade performs increases with increasing building floorspace (Fig. 2i). A strong upward trend has also been shown for designers deliberately increasing the thermal comfort for new designs over the last three decades (Fig. 2j). The graph of the number of buildings from the sample plotted against the climate confirms that buildings located in temperate warm maritime and subtropical humid climates are most often covered with modular façades with a variety of functions, most notably protecting the building from excessive solar exposure (Fig. 2k). The number of façade function in relation to the degree of air pollution for the given location was also interpreted. Modular façades were designed for clean, moderately polluted and intensively polluted areas. Most façades which perform a large number of functions, are located in moderately polluted areas. The graph gently deviates towards the number of functions the façade performs increasing in areas where air pollution is worse. In areas with the worst air quality, façades had a minimum of two functions (Fig. 2l). The data collected provides a broad overview of current trends in the construction industry.

3. STUDENTS' CONCEPTS FOR INNOVATIVE SOLUTIONS

Innovative façade solutions using future technologies are intended to address contemporary environmental concerns, seek to conserve the Earth's natural resources and reduce carbon emissions [4]. At the same time, they should ensure comfort for the building's users as a result of correct temperature, ventilation, light levels in rooms [9, 34] and protection against street noise [6]. They also contribute to the quality of construction works by meeting ergonomic thermal environment standards, aimed at improving the use conditions of buildings, workplaces and spaces used by people with disabilities [15]. Finally, they are to become a beautiful model of the art of creating using natural (sun, moon) and artificial light, perversely complementing the deceptively real and the same time illusionistic urban planning and architectural space [24].

The design concepts presented below, by students of the Faculty of Architecture at the Poznań University of Technology demonstrate the possibilities and solutions for creating façades of the buildings of the future. In their works, the students drew inspiration from innovative architectural façades shown in Table 1. Whereas Table 2 presents a summary of the students' design concepts with reference to the features of the structures in Table 1. The following designations are used in the compilation of student concepts and design inspirations (Table 2): No. – number in Table 1 of an architectural façade which provided inspiration for the design; FF – function of the façade which provided the inspiration (A - maximisation of daylight, B - protection from excessive sun exposure, C - insulation, D - ventilation, E - heat reception, F - heat rejection, H - generation of electricity, I - generation of pressure differences, J - other).

Table 2. Compilation of student concepts and design inspirations

Fractal façade		Module with 3 applications		Hexagonal façade		ROMB - Multifunctional façade project		Moving diamonds		Vertical rainfall container		Intelligent automated façade		WA-VE Façade		Solar scales	
Fig. 3		Fig. 4		Fig. 5		Fig. 6		Fig. 7		Fig. 8		Fig. 9		Fig. 10		Fig. 11	
No.	FF	No.	FF	No.	FF	No.	FF	No.	FF	No.	FF	No.	FF	No.	FF	No.	FF
46 50 51 74 129	C,D,H,J B H A,B B,C,D	39 102	B,C B,C	2 54 104	A,B,D A,B,D B	57 88 93 112 113 131	B, F B B H H B, C	105 122 123	H H J	40	B,F	3 13	A,B A,B	4 21 65 72 110	B,C,D,H H, J B,C B,F B	53 120	A J

The designed systems fulfil the following functions:

- increasing the building's thermal comfort by protecting it from excessive solar exposure, ventilation, maximising daylight,
- generating electricity and then making it available for cooling and heating equipment, and preventing the use of non-renewable energy sources that are not environmentally friendly

- collecting water from rainwater and extracting H_2O from air and then recirculating it as utility water,
- air purification using cladding made of nanomaterials and elements covered with natural vegetation,
- protection of fauna, including the protection of birds, creation of shelters, watering holes for animals,
- enhancing the aesthetics of a building by creating an interesting structure on the façade (material, structure, light and shadow contrasts, etc.), using nature's patterns and incorporating lighting elements to improve the lighting performance of the night-time image of urban space [31].

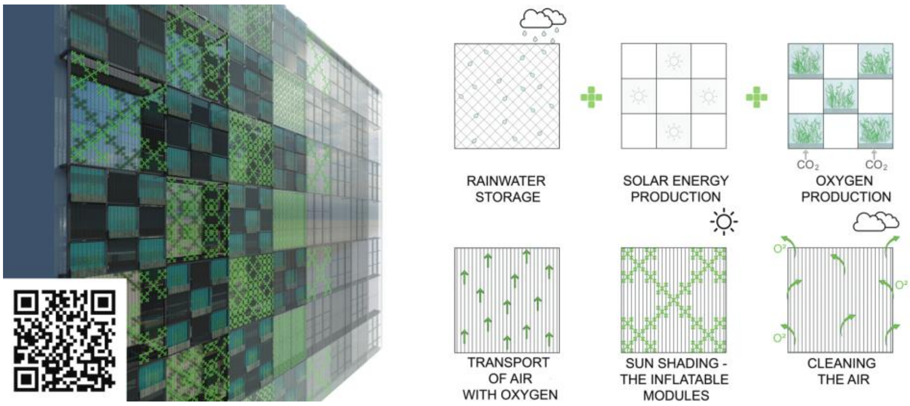

Fig. 3. 'Fractal façade', designed by: Marta Krawczyńska, Maria Kecman, Oliwia Kasprzyk, supervised by: Hanna Michalak. QR Code - more information on the designed façade modules

'Fractal façade' (Fig. 3.) is a façade based on a fractal pattern, which starts with a square with rounded corners, and the module consists of a repetition of five elements of similar cells. The assembled components are placed on metal tubes with a hole. The cladding can be pushed out with air and sucked inside the duct depending on the prevailing weather conditions. The created system is based on a pattern that expands as more components are inflated. Duplication of elements takes place in four stages as the façade is exposed to more sunlight to protect the building against overheating and the need to shade the interiors. The designed components combine with other components in the shape of tubes and with Canadian waterweed and transparent photovoltaic panels through the action of the fractal mechanism. The developed system allows the layout of the modules to be adapted to all buildings and in an infinite number of ways. The technology enables water collection and storage, energy generation, oxygen generation, air purification, interior shading and oxygenated air transport. An inflatable ETFE membrane has been proposed as the material for the fractal elements, the tubes are to be made from polycarbonate and the water collection mesh from recyclable polyester.

Designing a modular system and the opportunity to partially prefabricate the façade elements, makes it possible to complete a building in less time. It also allows for safe working conditions and greater accuracy, resulting in less material consumption, while promoting the idea of recycling [33].

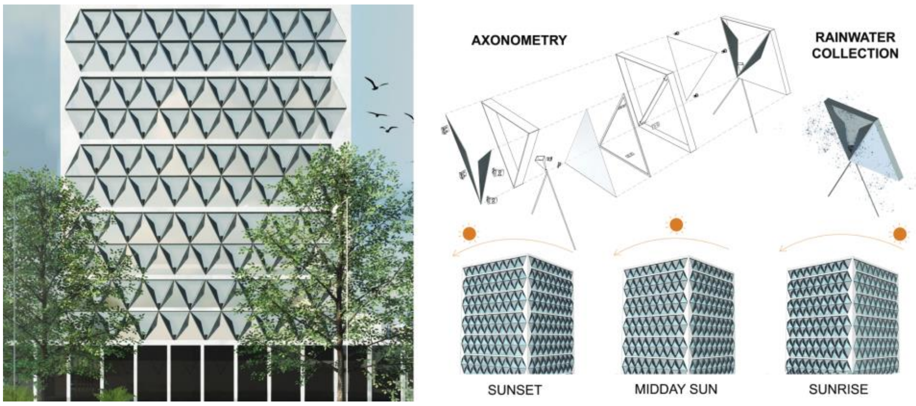

Fig. 4. 'Module with 3 applications', designed by: Natalia Guzicka, Antonina Plota, supervised by: Patrycja Kamińska

'Module with 3 applications' (Fig. 4.) refers to the shape and action of the lotus flower, which adapts spontaneously to climate and weather conditions. The designed repetitive façade element also protects living organisms. The building reduces bird collisions, a problem for tall, glazed buildings; it collects water and, partly in the form of installed drinking troughs, gives birds access to fluids on hot days. The façade is designed to protect the building from overheating and to produce energy through photovoltaic cladding. The repetitive elements are made of aluminium, glass with photovoltaic sections, downpipes and gutters. The façade is dynamic, with individual façade components closing and opening centrifugally according to the needs detected by automatic sensors. To counteract the effects of moisture and dirt, the fixed panel has been coated with a hydrophobic coating. Element dimensions have been adapted to the average distance between the two floors of the building, allowing two modules to be fitted within the height of a single floor. LED elements have been incorporated into the frame and nodal points have been installed to hold the structure in place. This also functions as a warning for animals.

Using patterns inspired by nature enables designers to transform technological solutions into an organism that responds to the variability of the aura [36]. In addition, concepts created by nature are functional and economical in their use of materials [17].

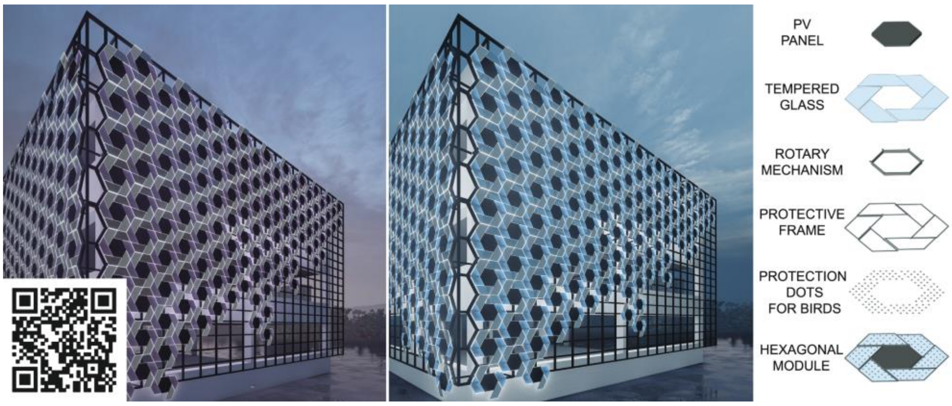

Fig. 5. ‘Hexagonal façade’, designed by: Roksana Kubaszewska, Weronika Jańczak, supervised by: Hanna Michalak

‘Hexagonal façade’ (Fig.5.) is an aesthetic, functional and environmentally friendly façade module design. The coating acts as ventilation, provides shade and also increases the thermal comfort of a building. The component consists of a photovoltaic panel in the centre and tempered glass with rhomboidal shapes covered with dots to protect birds from colliding with the transparent elements held in a protective frame. Movement is enabled by built-in bearings and a rotating mechanism. The hexagonal shape is reminiscent of a honeycomb, where all the sides of the polygon are of the same length. This made it possible to develop a model suitable for prefabrication. Concepts based on a hexagonal form can help with optimising quantities of materials used subject to high surface strength class. This also lowers the carbon footprint of profile production. Hexagonal forms are repeatedly found in biological models of living organisms, and the architect, when designing, can take the concept of nature as a valid model [3], repeatedly used and proven in architectural and industrial design [23].

The dynamics of the components allows to open or close the ventilation of the space between the two skins of the building. The façade is a complex structure in which luminaries and a lighting system are incorporated to illuminate the building. The development of a building envelope system that helps reduce cooling energy requirements makes it possible to make changes to the appearance of an existing building and to ensure new developments inspire architectural expressions [7].

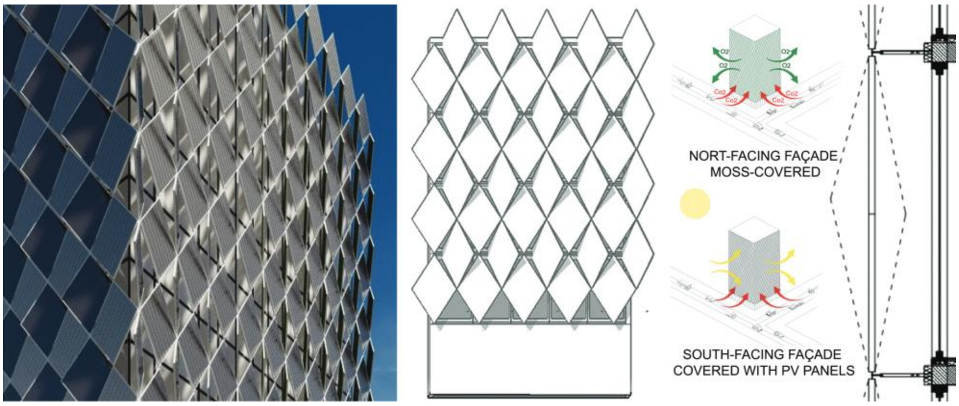

Fig. 6. ‘ROMB - Multifunctional façade project', designed by: Adrianna Nawrot, Marta Skrzypczak, supervised by: Patrycja Kamińska

‘ROMB - Multifunctional façade project’ (Fig. 6.) also cleans air and creates an innovative texture for highly aesthetic interiors and unique façades. A single element comprises a trapezoid covered on one side with weed moss and on the other with a photovoltaic panel. The cladding design entailed the latest material solutions based on smart technology that allows a structure to be automatically controlled, adjusting the position and angle of the modules to the prevailing outdoor conditions. The system makes it possible to shade rooms when sun exposure is at its peak, providing thermal comfort by inhibiting excessive heat build-up. The cladding directs photovoltaic elements towards the sun, shading the interior. In the absence of intense sunlight, the panels position themselves perpendicular to the glazing. At the same time, the other side of the façade, covered with vegetation, eliminates city pollution. The building’s second skin is designed to allow the module to be adapted to a new or an existing façade. It is mounted to the intermediate floors with steel mounting anchors.

The greenery will help to reduce the temperature of the building on hot days and prevent urban heat islands. The introduction of greenery into urbanised space improves air quality, the perception of the urban landscape, and enhances the quality of life [19, 8]. The exteriors of buildings exposed to the destructive influence of weather can be protected from destruction using living walls that are resistant to the sun and acid rain [18].

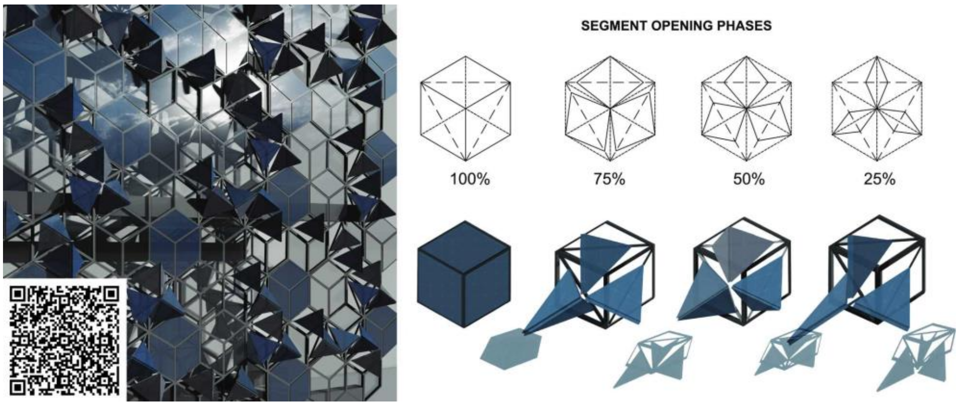

Fig. 7. 'Moving diamonds', designed by: Paulina Kukułka, Monika Milkiewicz, supervised by: Hanna Michalak

'Moving diamonds', (Fig. 7.) is a module designed to generate energy which is then consumed by a building during the course of use. Bionic shapes of pinecone shells inspired the design. The form comprises movable segments which, by changing the angle of inclination, adapt the position of solar panels to the weather conditions in the manner of a living organism. The cone itself also responds to humidity levels in the air [35]. The frame is coated with titanium dioxide nanomaterial, which purifies air. A chemical reaction resulting from the effect of ultraviolet rays on the coated surface breaks smog down into water. TiO_2 also makes it possible to keep components coated with this mixture clean [20]. The entire form comprises eight hexagonal modules divided into three rhombuses with different functions. The components are clad with photovoltaic panels and glass. Segments with installed actuators and rails, covered with a material used to generate energy, open in three increments: 25%, 50% and 75%. The developed technology makes it possible to regulate the light entering a building and to create a changing façade appearance. The idea behind the design was to develop a module that meets the required technical requirements, while acting as a link between the environment and the human being.

The best solution for integrating the interior and exterior of a building is considered to entail the use of a dynamic building façade structure, which makes it possible to adapt sunlight, ventilation, and thermal comfort of a building to changing conditions [5]. Contemporary design requires one to conceptualise kinetic façade solutions, to model prototypes of double façades, to make calculations of energy demand gains and losses during when buildings are in use [28].

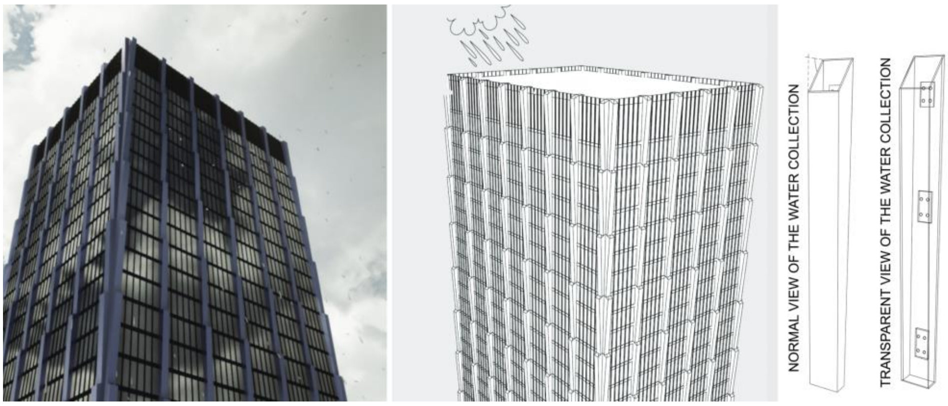

Fig. 8. ‘Vertical rainfall container’, designed by: Martyna Obszyńska, supervised by: Patrycja Kamińska

‘Vertical rainfall container’ (Fig. 8.) is a façade element for collecting rainwater. Its shape is formed by an intuitive funnel-like shape. The design was preceded by research within the scope of the angle of rainfall, ways of storing rainwater and the possibility of using wastewater as utility water, material options and modern design solutions. The concept uses modern technology featuring the latest monitoring systems and sensors. It is also expected to help protect the environment by collecting rainwater for potable and utility purposes, which is considered a form of recycling [22]. The module was based on the idea for designing vertical forms from which water would be discharged into retention basins. The profiles were designed as a minimalist form in keeping with the characteristics of high-rise buildings, made of stainless steel, and fixed to reinforced concrete structure with anchors. The resulting form is simple to prefabricate and can be used on various façades. Standardised component dimensions contribute to lower construction costs [10]. The concept makes it possible to turn an ordinary building element into a component of an environmentally friendly system. The architectural form of the model resembles load-bearing elements of a building and becomes unobtrusive. The suggestion presented here can inspire designers to adapt all structural elements to structures that allow water harvesting on large-area surfaces. The module is made of metal alloy components as the metals used on roofs are considered easy to clean, resulting in water quality of a higher quality that can be used more widely.

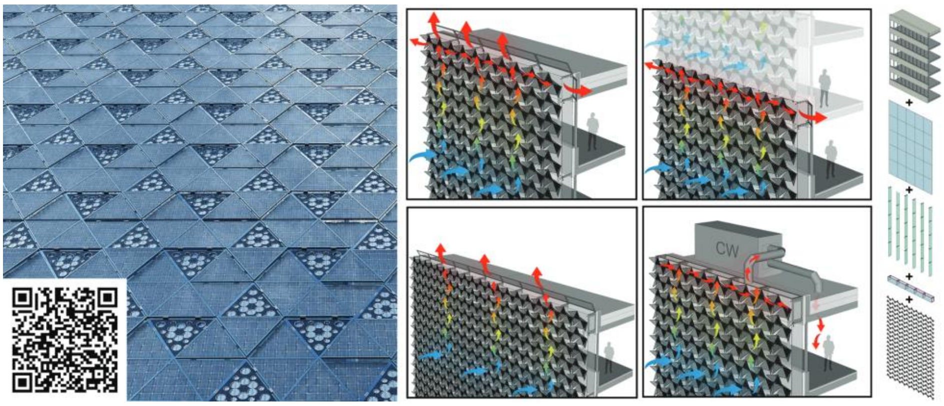

Fig. 9. 'Intelligent automated façade system', designed by: Michał Kacprzyk, supervised by: Hanna Michalak

The intelligent automated façade system (Fig. 9.) is a façade that generates energy, consisting of synchronised modules that function like a living organism, reacting to changing weather conditions by changing the appearance of the façade. The dynamic external façade of a building consists of a double building skin made of glass, vertical glass internal divisions, mechanically opening flaps with top and side outlets as well as modules. The shape of the individual segments is based on a triangular form in which straight and then geometric divisions were drawn as the starting pattern. The structure is built from stainless steel, the central panel is filled with carbon fibre and the side panels are 50% transparent photovoltaic cells. Polycarbonate wind turbines have a vertical axis of rotation. Point brackets are used to mount it to the façade. Stainless steel hinges are responsible for the opening and closing. The concept is to make it possible to heat a building using the greenhouse effect and the heating generated by photovoltaic panels; to cool the building through interior shading and mechanical or gravity fed airflow, generate energy through the use of moving photovoltaic cells and rotating wind turbines. Selection of lightweight and durable construction materials that are resistant to the elements, use of a minimum number of damage-prone elements in the module, prefabrication suitability, easy and fast assembly and installation of the lighting elements create an excellent and unique system with high aesthetic qualities.

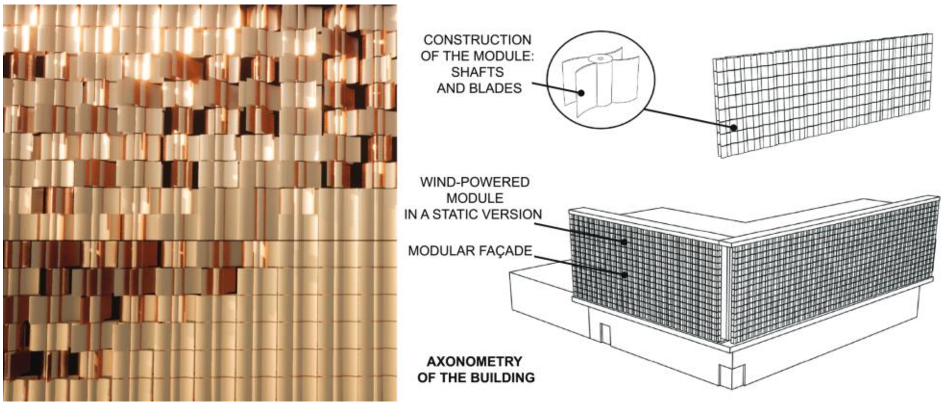

Fig. 10. 'WA-VE Façade ', designed by: Ida Pacer, supervised by: Patrycja Kamińska

‘WA-VE Façade’ (Fig. 10.) is a dedicated façade system designed to generate electricity from wind while maintaining the aesthetic qualities of architecture. The developed variant brings together elements in an additive way to create a complex, dynamic structure, which, as in the previous design – changes in appearance under the influence of the weather. The structure is made of galvanised metal, creating an elegant pattern that reflects the sun's rays and enhances the appearance of a building. Curved blades allow the entire element to be set in motion around its own axis with the shaft located in a central position. According to the design, the necessary generator and engine room are to be located in close proximity to the building. A repetitive section comprising four blades and a shaft should be easy to prefabricate. In order to design the best module, twelve possible solutions were created, and a comparative analysis was carried out, which helped to select the concept that was best in the designer's opinion. The project was preceded by extensive research into wind action, wind turbine design, material options as well as the latest technologies for generating energy using renewable sources. The suggestion for installing segments on a building façade was put forward in accordance with the conclusions of analyses pertaining to the selection of the most effective façade wind exposure. Similar concepts for a second skin of a building may also cater for a reduction in the building’s energy demand or act analogous to blinds, allowing air to flow and change the pressure distribution acting on the internal façade [29].

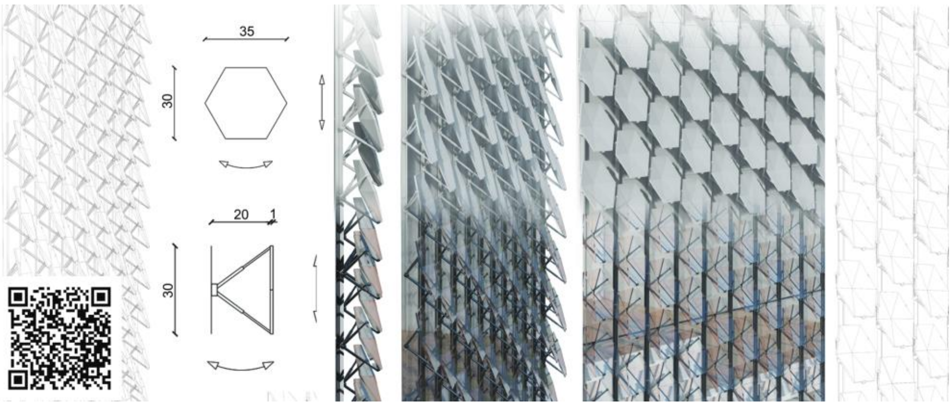

Fig. 11. 'Solar scales', designed by: Weronika Anioł, Marta Frankiewicz, Adrianna Krańska supervised by: Hanna Michalak

‘Solar scales’ (Fig. 11.) is a design for a second skin of a building with modules that react to the movement of the sun. Their position is adjusted using pneumatic devices. The glass panels are covered with a perovskite film, made of transparent photovoltaic cells that will ensure that the required amount of light is delivered to the building's interior. The kinetics of the façade increase the efficiency of the coating responding to the sun's rays and improve energy production. The light supply and the thermal comfort of the building are controlled by moving the panels. For the cladding, abundantly available glass was used which is suitable for forming any desired shape. Transparent materials can be tinted and made with the addition of an opaque element to adapt a façade to the purpose of a building. The simple design and assembly of the modules are intended to ensure economic efficiency during the construction process and transport of components from a factory, helping to reduce the environmental impact of the complex processes of sourcing materials and logistics.

4. SUMMARY AND CONCLUSIONS

The performed tabular research provides an overview of recent architectural developments entailing modern, multifunctional façades used to counteract the effects of and to prevent climate change. The analyses revealed current trends in design, as well as the relationship between technology as well as social, economic and environmental factors. Student concepts for façade modules, developed under the guidance of the article's authors, present proposals for architectural solutions that protect the environment and use state-of-the-art materials and technologies.

The research carried out contributed to the following conclusions:

- The number of buildings with modular façades designed to protect the environment is increasing, with most designs seen in temperate and subtropical climate zones. These concepts primarily serve to increase the thermal comfort of a building and, at present, mainly use standard materials that have been known in the construction industry for centuries.
- In order to further develop façade forms comprising repetitive elements and the way these modules function, the use of modern materials and technologies should be designed and proposed to investors, based on the latest scientific research in the development of nanomaterials, mechanics, protection of fauna in the urbanised city [2], optimisation of structures and shells use of available tools and methods [32], as well as on how living organisms work. The suggestions described in this article, developed by students of the Faculty of Architecture at the Poznan University of Technology, under the guidance of the authors, are, in the authors' opinion, a response to the challenges associated with Sustainable Development Goals (SDGs): 7, 9, 11 and 13 of the 2030 Agenda for Sustainable Development [38] faced by contemporary designers.
- The design and manufacture of modern modular solutions should necessarily go hand in hand not only with the development of the idea of reusing previously produced, used materials, but also with well thought-out material solutions and technological processes that allow the majority of building components, including the described façades, to be recycled. The authors of this article wish to develop this idea in further research within the scope of modular design.

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