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Original Research Article

MULTI-CRITERIA ANALYSIS AND DESIGN IDEAS OF GREEN FAÇADE SYSTEMS AS ECO-FRIENDLY ARCHITECTURAL SOLUTIONS

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A b s t r a c t

The article discusses current trends in designing green and eco-friendly façades of buildings of different functions in Poland and around the world. Information collected on completed façade projects, associated research and conclusions formulated on the basis thereof, indicate trends and possibilities for the use of contemporary material solutions and technologies in designing various forms of vertical 'greenery' which support sustainable development of urban areas. The main objective of the research was to identify the most important features of green façades as eco-friendly architectural solutions. A case study with descriptions of the features and qualitative elements of 100 of the most architecturally interesting buildings with characteristic external wall structures was constructed for research purposes. The sites selected for the case study represent a review of global trends. The data was then used for a multi-criteria analysis of green façade systems from the perspective of eco-friendly architectural solutions. The conducted research, analyses and discussions on solutions already in place were then implemented as guidelines for innovative architectural design solutions, which were presented at the Faculty of Architecture at Poznań University of Technology in the form of selected diagrams and student visualisations. These comprised highly aesthetic compositions, possible to implement in the near future.

Keywords: green façade, innovation in architecture, urban greenery, concept, aesthetics, eco-friendly solution, modular system

1. INTRODUCTION

One of the main strategies of the 17 Sustainable Development Goals (SDGs) entails combating climate change and acting to protect the environment. The capacity to formulate new, eco-friendly concepts for innovative architectural solutions enables designers to work towards a common plan: to improve the future wellbeing of people and of the planet. The authors' choice of subject and methodology for this article was inspired by new, rapidly developing, interdisciplinary technologies and techniques, and equally rapid, yet unfavourable climate changes. The façades of buildings or certain engineering

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structures can be a key aspect in the design of sustainable structures with a positive environmental impact [36]. Introducing more natural walls for new builds in cities, constructed on previously undeveloped sites makes it possible to combat the effects of climate change [25, 28] resulting from the increase in CO_2 emissions during urban development by taking land out of agricultural production [11, 1]. In addition, the use of green façades provides an opportunity to introduce natural elements into the urban space when revitalising built-up areas. This reduces the environmental impact of sites where people live and work [13, 26]. Greenery-covered façades contribute to the protection of many bird and insect species, which also helps improve biodiversity [35]. On the other hand, the progressive development of technology for the construction of elements in the building industry, including façades, allows prefabricated and modular solutions to be implemented [19]. This reduces labour intensity, lowers construction costs, reduces the amount of excess hazardous gases released into the atmosphere during production and often optimises the weight of the structure [2, 5].

Applying greenery to building façades was already practiced in antiquity. The famous Hanging Gardens of Seramis in Babylon are one example. Today, in an era of climate change, it is becoming an extremely important aspect of urban design. Many researchers are taking up that subject. According to the authors, there is a particular reason for making an effort within this subject area: the increasing lack of horizontal surfaces for the introduction of greenery, in an all-too - dense urban fabric, and the need to design a beautiful and friendly space for human habitation that evokes positive emotions, while at the same time promoting its quality. Garcia's (and team) study, in addition to the already proven, strictly technical advantages of using vertical greenery systems for building façades (building cooling), points to a small body of data on intangible environmental benefits [10]. The positive impact of such solutions on public health is well known, with some even calling green façades " the tools for the humanisation of a modern city" [22]. Wang et al. conducted a comparative study of the number of green wall technologies, analysed their contribution to urban sustainability and offered guidance for sustainable area planning [37]. The researchers presented very detailed case studies, ranging from the impact of vertical greenery systems on the thermal comfort of urban interiors, for example in cramped urban streets [39], to increasing the interior comfort of single-family buildings with only a small section of the façade as a green wall [30], to the possibility of reusing rainwater once it has passed through a green façade [32]. Mostafa describes the crucial importance of façades for energy consumption and comfort in buildings, pointing to the need to design and implement smart façades, ones which are interesting in terms of visual effects [21]. A similar view is shared by Drozd and Kowalik, who presented an up-to-date overview of the materials used for façades [7]. The research presented below is a continuation of the reflections of the authors of this article [16], based on available literature, interviews with users of urban spaces during conferences and popular science meetings at the international "Landscape Arena" which took place in Poznań's International Fairs, exchange of experiences within the scope of the Spring Corner platform, as well as - and primarily - their work with architecture students at the Faculty of Architecture at Poznań University of Technology on innovative, conceptual designs of environmentally friendly façades.

2. RESEARCH AND ANALYSES

2.1. Research objective, scope and methods

The objective of the research is to identify the most important features of green façades as eco-friendly solutions. The conducted research provides answers to the following questions: "What are the most important features of a newly-designed eco-friendly green façade?" Components of a built environment are the subject of research within the scope of architecture. Green façades of buildings are the element selected as the subject of research for this article. A multi-criteria analysis was performed in order to achieve the objective of the research. The aforementioned research method makes it possible to define building preference groups and, as a popular comparative method, it may be used to select appropriate solutions in a design problem associated with the subject of this article.

At the start of the performed research, a review of already constructed green façades all over the world was carried out using literature sources, articles available on the largest global architectural websites (such as ArchDaily and Dezeen) as well as other spatial (such as Google Maps and Geoportal) and statistical (such as City Population and IQAir) data.

The collected data was used to compile a case study table, suitable for use in comparative research. The case study makes it possible to examine a number of quality elements and features simultaneously. A multi-criteria analysis of green façade systems was performed from the perspective of eco-friendly architectural solutions (Tab. 1). The above literature review (as well as those referred to hereinbelow) made it possible to highlight criteria adequate for the title of the article and significant for choosing appropriate design solutions.

Then, using the collected data, diagrams depicting the results of research with respect to the required criteria were plotted in a spreadsheet.

Subsequently, all building features relevant to the research were recoded using the site visit technique, entailing in-situ viewings of selected structures. Photographic records of the buildings were also made during the research. These included the architectural and urban planning contexts as well as the green façades themselves.

In conjunction with the above, the objective of the chosen methodology – to define building preference groups, is appropriate for the objective of this article – to identify the most important features of green façades. The present research may be applied in practice, contributing to the improvement of the design process.

Additionally, design concepts developed on the basis of conclusions derived from analyses and discussions which took place whilst developing concept strategies, which (in the authors' opinion), may contribute to shaping a sustainable tomorrow are presented as an appendix to the present article.

The main objective of the research, research methods and techniques used to carry out scientific research on current trends and the development of new green and environmentally friendly façade solutions presented in this article are reflected in the simplified model for creating innovative green and environmentally friendly façade solutions in architecture (Fig.1).

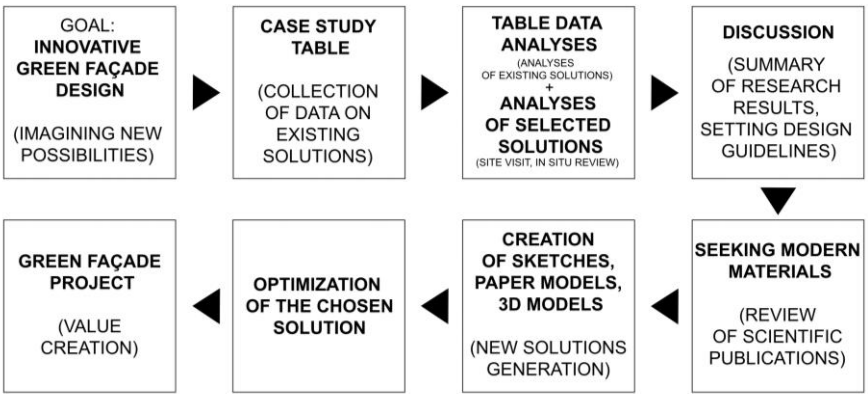


Fig. 1. A simplified model of the process of creating innovative green façade solutions in architecture, Source: authors' own work

Conclusions formulated by analysing data compiled in the table were used as both guidelines and to determine the design boundary conditions. Heuristic methods were used in the search for innovative design solutions. Here the “brainstorming” method, used during creative sessions at the Faculty of Architecture's current curricular activities and the “analogue transfer” method, especially with regard to aspects related to bionics, but also new technologies, were particularly useful.

Application of scientific research and new concepts will contribute to increasing modernity [18, 14] fostering a sustainable future.

2.2. Case study table

As part of the research, a Case Study Table - Modular Green Façades (Table 1) was compiled with data on 100 architectural projects with green façades. The sample collected comprises green façade buildings constructed over the last 30 years and located all over the world. Students were asked to find the most interesting examples associated with modularity (according to the authors, use of repetitive elements reduces production costs), subjectively high aesthetics and beauty of the building shape (which, to us architects, is very important), as well as modern technology or technique (for the most recent ones).

The table presents the following information: investment name; architect; year the façade was built; CC – construction location; BF – building function (where: BM – residential buildings, BB – office buildings, BH – commercial and service buildings, BP – industrial buildings, BSI – hospital and other healthcare buildings, BK – education, science, culture and sports buildings, BT – transport and communication buildings, ZM – silos, tanks and storage buildings, BPU - production, service and farm utility buildings, PB – other non-residential buildings); HG – building height category (where: N – low, SW – medium-tall, W – tall, WW – very tall); other greenery accompanying the building, PD – local population density, C – zone and climate (where: 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 c., 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); AP – local air pollution (where: 0 – meets WHO guidelines, 1 – exceeds the norm by between 1 and 2 times, 2 – exceeds the norm between 2 and 3 times, 3 – exceeds the norm between 3 and 5 times, 4 – exceeds the norm between 5 and 7 times, 5 - exceeds the norm between 7 and 10 times, 6 – exceeds the norm by more than 10 times) [40]; T – type of green wall (where: A1 – module integrated into the wall support structure, A2 – module on independent structure, B1 – module integrated into the wall support structure with a pot, B2 – module on independent structure with a pot, C1 – module integrated into the wall support structure in the form of vegetation pockets, C2 – module on independent structure with a pot in the form of vegetation pockets, D1 – other); FA – surface area of the green wall; exposure of modules; FF – façade functions (A – maximisation of daylight, B – protection against excessive sun exposure, C – insulation, D – ventilation, E – heat reflection, H – electricity generation, I – utilisation of pressure differences, J – other e.g. water harvesting); MA – size of module; PA – number of species on façade; W – façade irrigation method (where: aa – water harvesting from the air, ab – supply of drip line integrated into the greenery irrigation system at the building, ac – water system supplied from the building, ad – pots in between floors, ae – pots on the roof, az – rainwater irrigation, ax – pots, af – other).

Table 1. Case study – modular green façades

CASE STUDY – MODULAR GREEN FAÇADES																	
	BASIC INFORMATION							EXTERNAL FACTORS			DETAILED GREEN FAÇADE INFORMATION						
No.	Building name	Architect	Year	CC	BF	HG	Other greenery	PD [person/km²]	C	AP	T	FA [m²]	Module exposure	FF	MA [mm]	PA	W
1	Posejdon Center	Max Bischoff, Franciszek Kocimski, FBA Szczecin	2019	Szczecin, PL	BB	W	greenery in pots and on the courtyard, green roof	1313	2d2	2	C1	150	western, from the courtyard	J	~600x400	>5	az
2	European Environment Agency Headquarters	Façade Johanna Rossbach with Mangor and Nagel Arkitektirma	2010	Copenhagen, DK	BB	SW	none	4400	2e2	1	C2	~250	southern temporary front elevation	J	~600x400/ 500x500	>5	az
3	Vertical LivingGallery	SDA, Sansiri PCL, Shma	2011	Bangkok, THA	BK	N	none	5279	4g	3	C1	~400	western	B,C,F	~1000x3000	>5	ab
4	Tree House	ADDP Architects LLP	2013	Singapore, SGP	BM	WW	greenery in flower beds	6067	5k	2	A2	2289	western	B	~1200x4000	>5	aa
5	Palacio de Congresos Europa	Urbanarbolismo, Singulargreen, Urbaser, Zikotz	2013	Álava, ES	BK	SW	greenery in flower beds	327	3g	1	A2	1492	eastern	C	~500x500	>5	ac
6	Kö-Bogen II	Ingenhoven Architects	2020	Düsseldorf, DE	BH	W	green roof	2839	2e2	2	B2	~1400	northern, western	C,F,D	~400x1000	1	ab
7	BIQ house	Arup	2013	Hamburg, DE	BM	SW	greenery in flower beds	2452	2d2	1	A1	226	southern, eastern, western	E,H	2500x700	8	ac
8	Striebinger Block	Marika Shiroi-Clark	2014	Cleveland, USA	BM	SW	none	4793	2e2	2	C1	~120	southern	B,C,F	810x610	11	ab
9	Mercure Centrum	AiR Jurkowscy	2021	Katowice, PL	BH	SW	greenery in interiors	3850	2d2	3	C1	237	northern and western	J,B,C	1800x1000	>5	ab
10	Consorcio Santiago	Enrique Browne and Borja Huidobro	2020	Las Condes, CL	BB	WW	none	2524	3f	3	B2	2700	western, northern and southern	B,E,C	-	3	ac
11	Musee du quai Branly	Patric Blanc	2004	Paris, FR	BK	SW	green patio	21274	2e2	2	B2	2415	northern	B,C,J	~500x500	>5	af,az
12	Greenhouse Antwerp	Sempergreen, CONIX RDBM	2016	Antwerp, BE	BH	SW	green wall	2595	2e2	2	A1	~750	southern	C,J	~500x1500	>5	ac
13	Naman Retreat the Babylon	Vo Trong Naghia Architects	2015	Danang, Vietnam	BH	SW	green wall	4087	4g	2	B2	~1400	northern, southern, eastern, western	B,F,J	~400x3000	4	aa acad
14	House in Travessa Do Patrocinio	Manuel Cachão Tojal, T. , L. Rebelo de Andrade	2012	Lisbon, PT	BM	N	none	5053	3g	1	A1	100	southern, eastern, western	C,F	-	25	aa, ab
15	Villa M	Philippe Starck	2021	Paris, FR	BH	W	roof garden, greenery on terraces in pots and on balconies	21888	2e2.	2	B1	~250	eastern	B	~500x1500	>5	ad
16	One Central Park	Ateliers Jean Nouvel	2014	Sydney, AU	BB	WW	roof garden, greenery on terraces in pots and on balconies	7080	3g	1	C2	~30000	northern, southern, eastern, western	B	~500x500	>5	aa, ac
17	KMC Corporate Office	RMA Architects	2012	Hyderabad, IN	BB	SW	greenery in flower beds next to the building	7600	4f	5	B2	~1800	northern, southern, eastern, western	B	~600x3000/ ~1000x3000	>5	af
18	Urban Farming Office	VTN Architects	2022	Ho Chi Minh, VNM	BB	SW	greenery in pots in the building	14424	5i	3	B3	~600	northern, eastern, western	D,J	~1000x400	>5	af, az

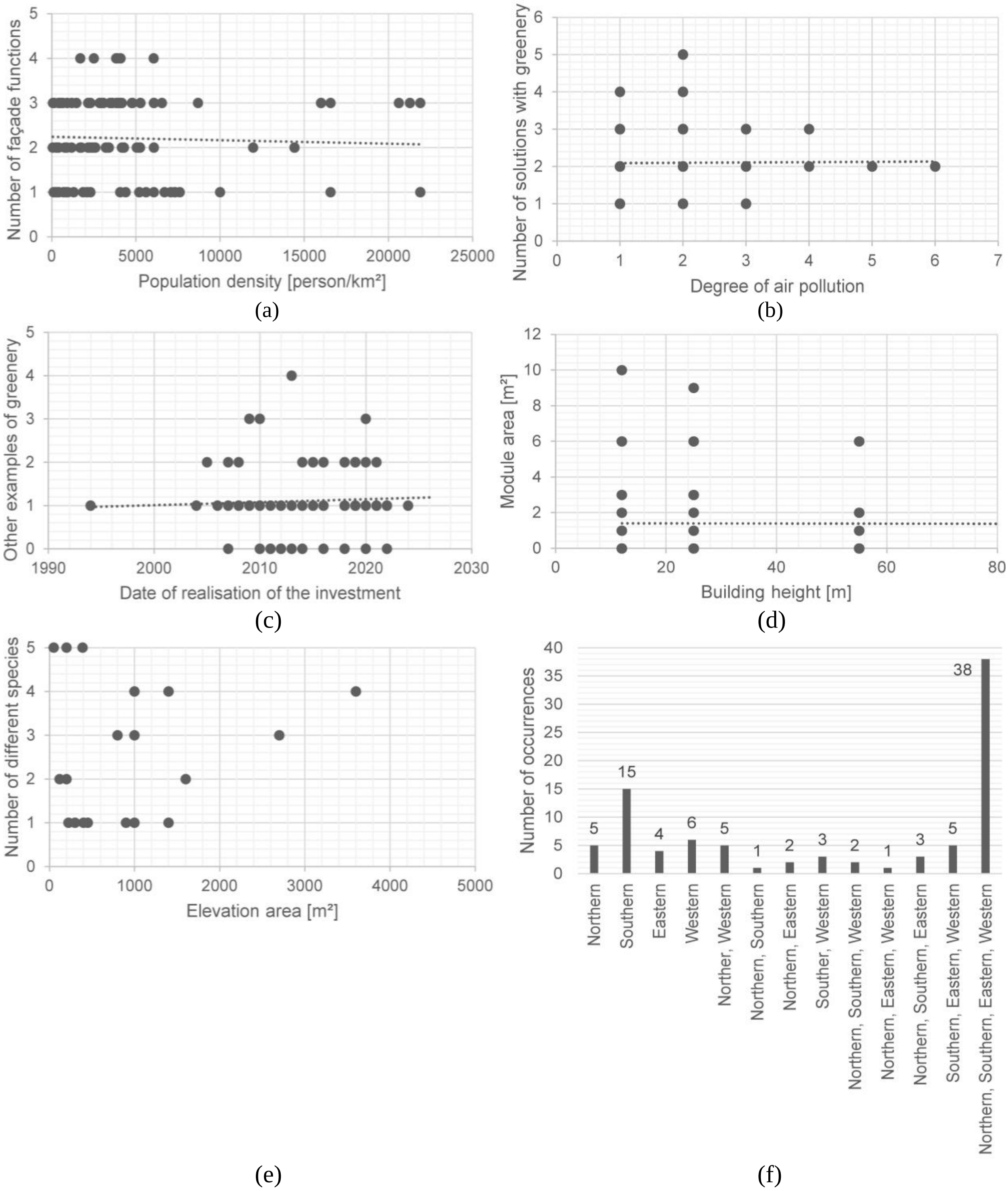
19	Bay Meadows Welcome	BCV Architecture + Interiors	2013	San Mateo, CA	BM	N	greenery in flower beds	658	3g	1	A2	125	northern	B, C, F	~500x500	>5	aa, ab
20	Sky House	MIA Design Studio	2019	An Phu, VNM	BM	N	greenery on balcony in pots, greenery on roof	307	5h	3	A1	~600	northern, southern, eastern, western	D,J	~500x500, ~1000x1000	>5	ad
21	Phong House	VHL. Architecture	2018	Ho Chi Minh, VNM	BM	N	greenery in pots, greenery in interiors	4292	5i	2	B2	~130	northern, southern, eastern, western	B,J	~300x300	>5	aa
22	Breathing House	VTN Architects	2019	Hoa Xuan, VNM	BM	SW	green roof, greenery in interiors	1177	5i	2	C1	~120	northern, southern	B,J	~100x4000	2	ad
23	Stadthaus M1	Barkow Leibinger	2013	Freiburg, DE	BM	SW	none	1465	2d2	1	A2	~1600	southern, eastern, western	B,C,D	-	~2	aa, ab
24	Jakob Factory	G8A Architecture & Urban Planning	2020	Ho Chi Minh City, VNM	BP	W	greenery on façade structural level	3926	5i	3	B2	~3600	northern, southern, eastern, western	B,C,D	~2000x3000	<5	aa, ad
25	Butik Ann Demeulemeester	Mass Studies	2007	Seoul, KOR	BH	N	green stairs inside building	16566	2d2	3	A1	~350	northern, southern, eastern, western	B,C,F	~500x500	<5	ab
26	Caxia Forum	Herzog & de Meuron	2008	Madrid, ES	BK	W	greenery in interiors	5266	3f	2	A2	~450	southern	B,C,F	~2000x3000	<5	ab
27	Semiahmoo Public Library	Green over Gray	2011	Vancouver, CA	BK	N	greenery in flower beds	5249	2c2	1	C1	10150	eastern, western	B,C	~3000 x 2000	>5	ab
28	Library in San Vicente	Jose Maria Chofre	2010	San Vicente, ES	BK	SW	none	105	3g	2	A2	540	western	B	3000 x 2000	>5	ab
29	The Oasis of Aboukir	Patric Blanc	2013	Paris, FR	BM	SW	greenery in flower beds	21888	2e2	2	A2	251	western	J	~3000 x 2000	>5	ac
30	London's Living Wall	Gary Grant	2013	London, UK	BH	W	none	5200	2e2	1	B2	350	-	B,J	~400 x 400	>5	ac
31	Athenaeum Hotel	Patric Blanc	2009	London, UK	BH	W	greenery in pots	5200	2e2	1	A2	329	southern	J	-	>5	ac
32	Commerciale Fiordaliso	Francesco Bollani	2010	Rozzano, IT	BH	SW	greenery in flower beds	3248	3g	3	A1	~1000	southern	F,J	~400 x 400	>5	aa ab
33	Seoul New City Hall Green Wall	iArc Architects	2013	Seoul, KOR	BH	W	greenery in interiors	16566	2d2	3	B2	1579	southern	J	~200 x 1000	>5	ac
34	University of Life Sciences	Faculty of Horticulture & Landscape Architecture	2015	Lublin, PL	BK	W	greenery in flower beds	2305	2d2	3	c2	22	southern	J	330 x 650	>5	ac
35	Edifício Santalaia	Paisajismo Urbano, Groncol, Ignacio Solano	2015	Bogota, COL	BM	W	greenery on roof	6061	5i	2	A2	3117	northern, southern, eastern, western	B,C,D, J	~400 x 400	>5	ac
36	ACROS	Emilio Ambasz	1994	Fukuoka, JP	BB, BH, BK	W W	green roof	4754	3g	1	A1	5400	southern	B,C,J	~2000 x 1000	>5	aa
37	Urban Garden	Loizou Architects + Associates	2022	LIMASSOL, CY	BM	N	none	141	3g	2	A1	~450	northern, southern, eastern, western	A,B,E	-	1	ab
38	Venlo Town Hall	Kraaijvanger Architects	2016	Venlo, NL	BB	W	green façade, greenery in interiors	775	2e2.	2	A1	~800	northern, southern, eastern, western	A,J	~800 x 200	>5	ac
39	Liko-Vo	Franek Architects	2019	Slavkov u Brna, CZ	BP	SW	greenery in flower beds, green roof	417	2d2	3	C1	~1000	northern, southern, eastern, western	B,C,D	~800 x 200	4	ac
40	Liko Noe	Franek Architects	2015	Slavkov u Brna, CZ	BK	N	greenery in flower beds, green roof	417	2d2	3	C1	~800	northern, southern, eastern, western	B,C	~1000 x 400	>5	ac

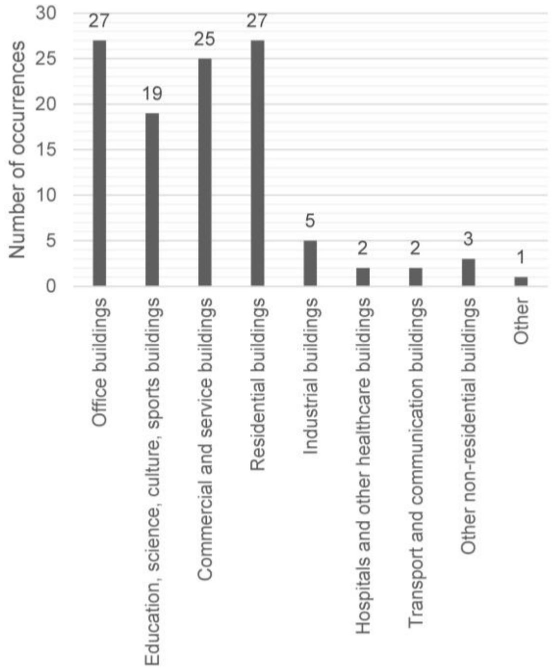
41	Citicape House	Sheppard Robson	2019	London, UK	BB/BH	W	greenery in flower beds, green roof	957	2e2	1	A1	3700	northern, eastern, southern	J	~3000mm [h]	>5	ab, ac
42	Cabin of Curiosities	Emerging Objects	2018	Oakland, CA	BM	N	greenery in pots	431	3f	1	C1	~8	front façade	J	~ 130 x 110	>5	aa
43	Living façade for birds and insect	S. Wu, S. Lapp, Parthner-Buro Happold Cookfox	2021	prototype	BB	SW	green roof	-	2d2	-	C1	-	total exposure	J	~400 x 400	1	ax
44	The Photo Synth Etica	EcoLogic	2018	London, UK	BB	SW	none	5200	2d2	2	A2	224	total exposure	J	2000 x 7000	1	-
45	APHP Saint-Antoine Hospital	Chartier Dalix	2022	Paris, FR	BSI	W	greenery in flower beds	20614	2e2.	2	C1	390	southern	D,F,B	~1000 x 2000	5	aa, ac
46	ASI Reisen	Snøhetta	2019	Natters, AU	BB	N	greenery in interiors	260	2d2	2	B2	~400	northern, southern, eastern, western	B,F	~2000 x 3000	17	az
47	Oasia Hotel	WOHA	2016	Singapore, SGP	BH	WW	greenery on roof, greenery on balcony	6067	5k	2	A2	~30000	northern, southern, eastern, western	B,J	~1000 x 4000	>5	ad
48	FAE Business School	Sakaguti Arquitetos Associados	2016	Curutuba, BR	BK	W	greenery in flower beds	4062	5i	2	C2	~300	eastern	B	~500 x 3000	1	ax
49	Hunziker Areal	Müller Sigrist Architekten	2015	Zurich, CH	BM	N, SW	greenery in pots on balcony	4167	2d2	2	B2	~200	vertical garden	B,F,J	1000 x 2000	2	ad
50	Herstal City Hall	Frederic Haesevoets Architecte	2016	Herstal, BE	BK	SW	green roof	1686	2d2	1	A1	2500	northern, southern, eastern, western	F,J	1000 x 1000	>5	ab
51	School of the Arts	WOHA	2009	Singapore, SGP	BK	WW	greenery in interiors, trees in pots, greenery in flowerbeds	6067	5k	2	B2	5800	northern, southern, eastern, western	B,C	~1000 x 2000	2	ab
52	Parkroyal Collection Pickering	WOHA	2013	Singapore, SGP	BM/BB	WW	green walls, horizontal gardens, greenery in interiors	6067	5k	2	B1	~3000	northern, southern, eastern, western	B,D,J	-	>5	aa.
53	Humboldt University, Physics Institute	Augustin + Frank	2005	Berlin, DE	BK	SW	rain gardens, green roofs	3891	2d2	2	A2	~5000	southern, in the patio	B,F,D,J	~800 x 2000	>5	aa.
54	Tower 25	Jean Nouvel	2013	Nicosia, CY	BM	WW	greenery in pots	69	3g	2	A2	~4000	northern, southern, eastern, western	B,E,D	~500 x 500, 1000 x 1000, 2000 x 2000	>5	ac
55	Fountain House	Raumlabor	2014	Montreal, CA	BK	N	greenery in pots	898	2d2	1	A1	~400	northern, southern, eastern, western	B,E	~3000 x 2000	1	aa, ab
56	Bosco Verticale	Boeri Studio	2014	Milan, IT	BM	WW	green roof	7311	3g	3	B1	~20000	northern, southern, eastern, western	J	~1000 x 6000	>5	ac
57	Tony Fruit Office	TAA DESIGN	2020	Ho Chi Minh, VNM	BB	SW	green roof	14424	5i	2	A2	250	southern	B,D	3000 x 3000	>5	aa
58	Green cast	Kongo Kuma & Associates	2011	Odawara, JP	BH, BM	SW	none	1705	3g	2	A1	200	western	D,B	~500 x 500	5	aa
59	USA Pavilion Milan Expo	Biber Architects	2015	Milan, IT	BH	SW	trees in pots	7311	3g	3	A1	840	-	B	~1000 x 1000	>5	ac
60	Lausanne-Flon Metro Station	Bernard Tschumi Architects	2008	Lausanne, CH	BT	N	green roof, greenery in flower beds	3400	2d2	2	A1	~50	eastern	B,C	~10000 x 1000	5	aa
61	Pasona Urban Farm	Kono Designs	2010	Tokyo, JP	BB	SW	greenery in interiors, pots, green roof, on balcony	11961	3g	1	D1	11961	eastern, western, southern	B,J	~3500 x 3500	>5	ad

62	TONIPark garage	TONI KG	2021	Augsburg, DE	PB	SW	greenery in flower beds	1856	2d2	1	A1	700	eastern, western, northern	J	635 x 555	>5	ab
63	Menara Etiqa	Verias Architekci	2018	Kuala Lumpur, MY	BB	W W	greenery in flower beds	6696	5k	3	A2	1000	southern, western	J	~400 x 400	34	af
64	Musee du quai Branly in Paris	Jeana Nouvela	2006	Paris, FR	BB/BK	SW	greenery in flower beds	21888	2e2	2	C1	2400	northern, western	B,C,J	~500 x 500	>5	ac, az
65	L'Oasis d'Aboukir	Patric Blanc	2013	Paris, FR	BM	SW	greenery in flower beds	21888	2e2	2	C1	251	southern	J	~1000 x 3000	>5	ac
66	Calwer Passage	Ingenhoven Architects, Tennigkeit Architects	2018	Stuttgart, DE	BK-U, BB, BM	SW	greenery in flower beds	3000	2d2	2	B1	~3600	northern, southern, eastern, western	B,C,J	~500 x 3000	4	ad
67	Terminal 3, Changi Airport	Tierra Design, CPG Corporation, SOM	2008	Singapore, MY	BT	SW	greenery in interiors	8687	5k	2	B1	4144	-	B,C,J	~500 x 1000	>5	ad
68	Gardenhouse	MAD Architects	2020	Los Angeles, USA	BM	SW	greenery on patio, greenery in pots, flowerbeds on balconies	3072	3f	2	A1	~1000	northern, eastern	B,C,J	~1000 x 3000	>5	ac
69	A cafeteria within a green wall	Antonio Macia, Rebeca Cebrian	2015	Elche, ES	BH	N	greenery in interiors	706	3f	2	A2	150	southern	J	~500 x 500	>5	ab.
70	Asr Headquarters	Team 5 Architects	2016	Utrecht, NE	BB	SW	green roof	845	2e2	2	A1	17000	northern, eastern, western	J	~1000 x 3000	1	ac
71	Green Walls Jakob Saigon Factory	Rollimarchini AG Architecten, Bern & G8A Architects	2020	Ho Chi Minh, VNM	BP	SW	green patio	14424	5i	3	B1	30000	northern, southern, eastern, western	2xJ	~2000 x 3000	>5	af
72	Athenaeum Hotel	Patric Blanc	2009	London, UK	BH	W	16 small trees	5598	2.e.2	1	B2	329	southern	J	~1000 x 2000	>5	ac
73	Universidad del Claustro de Sor Juana	Verde Vertical, initiative: Garnier, Ministry of the Environment	2012	Mexico, MX	BK	N	green patio	63	3f	6.	B1	400	on patio	2xJ	~1000 x 1000	>5	aa, ad
74	K11 Museum	K11 Group	2019	Hong Kong, HK	BK	SW	green balconies	6542	3g	6	A1	-	northern, southern, eastern, western	B,C,J	~500 x 500	>5	aa, ac
75	Atlas Hotel Hoian	VTN Architects	2016	Hoi An, VNM	BM	SW	greenery in pots on balcony	2500	5i	2	B1	~2400	northern, southern, eastern, western	B,C,D, J	~3000 x 500	>5	ad
76	Naman Retreat Pure Spa	MIA Design Studio	2015	Da Nang, VNM	BSI	N	greenery in interiors, greenery or roofs, in pots	4087	5i	2	B2	1600	-	B,C,D, J	~1000 x 3000	>5	ae.
77	MFO Park	Burckhard + partners AG architekten	2007	Zurich, CH	BH	SW	greenery in flower beds, greenery in pots	4167	2e2	4	C2	4900	northern, southern, eastern, western	B,J	4500x4500	>5	ab
78	Electrical substation, Barcelona	Rahola vidal arquitectes	2007	Barcelona, ES	BP	SW	none	15992	2e	2	C2	~2000	northern, southern, eastern, western	B,C,J	3000x1000	>5	ab
79	Sky Green Residential & Retail Tower	WOHA	2019	Taichung City, TW	BM	W	greenery on balconies	1196	4g	3	B1	~30000	northern, southern, eastern, western	B,C,J	~500 x 3000	2	ac, ad
80	Jeven Sp. z o.o.	4Nature System	2022	Sady, PL	BP	N	green internal wall	210	2d2	2	B2	20	along stairs	J	~390 x 195	>5	ac
81	Generation Park Y	Skanska S.A.	2021	Warsaw, PL	BB	W W	green internal wall	3602	2d2	3	C1	330	lobby by main entrance	3xJ	~300 x 300	>5	ac
82	Nanobiome Building Skin	Michael K Chen Architecture	2016	New York, NYC	BM	N	none	10000	2e2	1	C2	~18	wall by entrance	2xJ	~200 x 400	>5	aa az

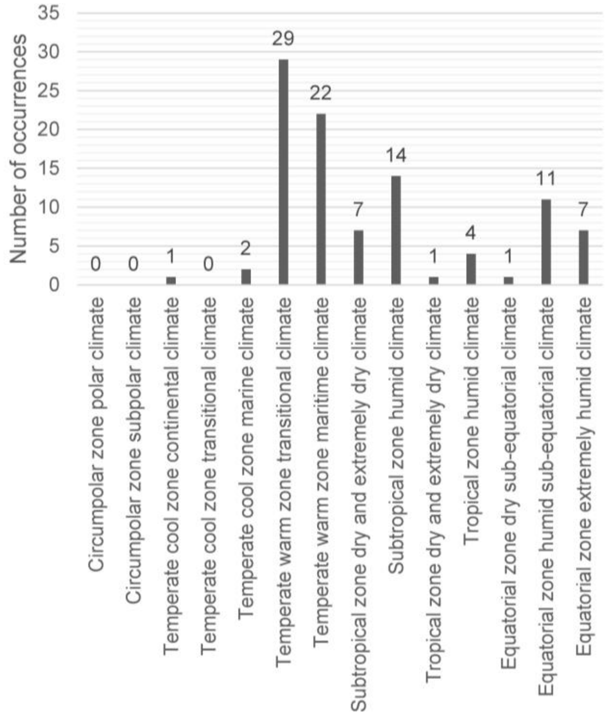
83	Garden house	Seasonal Landscape	2020	LA, USA	BM, BH	SW	trees in pots	3206	3f	1	A1	-	northern, eastern	C,F	-	-	ac ae
84	Botaniczna Residential Estate	Pracownia Insomia	2018	Poznań, PL	BM, BH	SW	green flowerbeds	2100	2d2	3	B2	~15000	northern	E	~3000 x 3000	?	ac
85	Żabka Eko Smart	Żabka Group (no further information available)	2022	Poznań, PL	BH	N	ecomat, PV bench, perovskite structures, flowerpots	2100	2d2	3	C1	~20	northern	C	~300 x 300	>5	ac
86	Taras Concordia Design	MVRDV, Q2Studio, Greenarte	2019	Wrocław, PL	BB	SW	green flowerbeds	2302	2d2	3	C1	360	southern, eastern, western	2xJ	~400 x 400	>5	ac
87	Wrocław City Hall	Greenarte	2014	Wrocław, PL	BB	SW	greenery in pots	2302	2d2	3	C1	`100	western	B,C,F	~400 x 400	>5	ac
88	Katowice Town Square	Greenarte	2014	Katowice, PL	O	N	none	1765	2d2	3	A2	250	northern, southern, eastern, western	B,J	~400 x 400	>5	ac
89	Office building, FNP	FAAB Architektura	2014	Warsaw, PL	BB	N	green flowerbeds	3467	2d2	3	A1	260	western	B,C,J	~400 x 400	>5	az
90	Building at Planken 07	Schmucker u. Partner Planning Company mbH, Aufgabe	2014	Mannheim, DE	BB, BH	SW	greenery in front of building	2160	2e2.	2	A1	170	northern	B,C,J	~500 x 500	>5	ac
91	Waste Management Department	(BOKU) University of Life Sciences	2020	Vienna, AT	BB	SW	green flowerbeds	4069	2d2	2	D1	850	southern, western	B,C,J	~1000 x 300	>5	ac
92	Train station	Greenery in interiors	2019	Wodzisła w Śląski, PL	BH	N	green flowerbeds	911	2d2	2	C1	~100	western	B,C,J	~1000 x 1000	>5	ac
93	Turó de la Peira Sports Center	Architecture Anna Noguera, J2J	2018	Barcelona, ES	BH	SW	green flowerbeds	15992	2e	2	B2	~800	northern, southern, eastern, western	B,C,J	~400 x 800	3	az
94	Bat Trang House	Vo Trong Nghia Architects	2020	Bat Trang, VNM	BM	SW	green flowerbeds	3824	5i	4	D1	~1000	northern, southern, eastern, western	B,C,D, J	~400 x 400	>5	ad
95	Standing Garden	NEXIT architects and Poelmans Reesink landscaping	2010	Arnhem, NE	PB	N	green flowerbeds	1694	2e2.	2	C1	~100	northern, southern, eastern, western	B,C,J, F	~200 x 200	>5	ab, az
96	N1/N2 Stadthaus, Parkhaus	no information	no information	Mannheim, DE	PB	N	green flowerbeds	2160	2e2.	2	B1	~900	southern, western	B,F	~1000 x 500	1	ac
97	Complex with SKA Type modules	module by: Shang Kai Steel's SKA Type	no information	Singapore, SGP	-	N	green flowerbeds	6067	5k	2	B2	~1000	northern, southern, eastern, western	A,B,F	~500 x 2000, ~500 x 3000	3	ac
98	Q20 – NeckarPar	Wernersobek	2024	Stuttgart, DE	BB, BH	SW	green flowerbeds	3000	2e2	2	B1	~4000	northern, southern, eastern, western	B,C,D	~1000 x 500	>5	ad
99	Baubotanik: Platanen-Kubus	Nagold	2012	Nagold, DE	BK	N	none	2178	2e2	1	B1	~1000	northern, southern, eastern, western	B,F	~1000 x 2000	1	ax
100	S Nine: Cultivated Envelope	PMA madhushala	2022	Pune, ID	BB	SW	greenery in pots	603	4g	5	B2	~750	northern, southern, western	B,F,J	~1000 x 3000	>5	ac, az

2.3. Analyses of data in tables

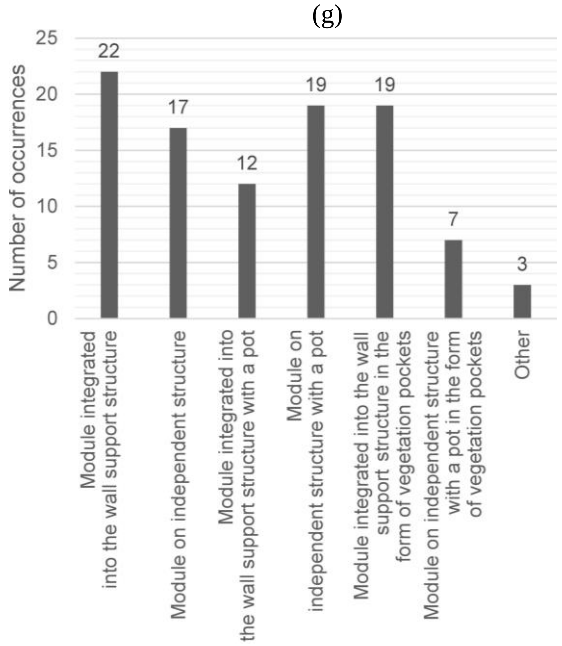




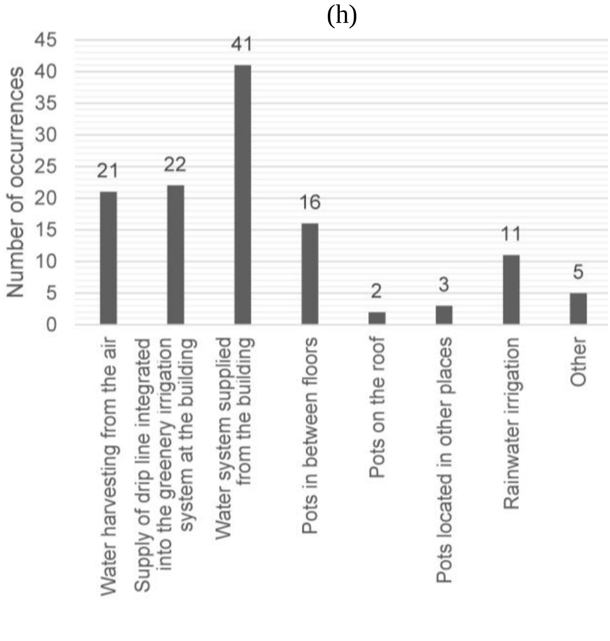
(g)



(h)



(i)



(j)

Fig. 2. Figures depicting case study data (Tab. 1): (a) Number of façade functions vs. population density, (b) Number of solutions with greenery on and around the building vs. degree of air pollution, (c) Number of other examples of greenery around the building vs. development period in years, (d) Module area vs. building height, (e) Number of different species on a façade vs. façade area, (f) Exposure of modules on a façade, (g) Functions of buildings with green façades, (h) Climate at the location of a buildings with green façades, (i) Type of green wall, (j) Irrigation of green façade vegetation

The data presented in Table 1 made it possible to identify current trends in the design and implementation of green façades. A thorough analysis of the data was visualised in the form of graphs (Fig. 2a-j), showing relationships between the presented values and the variability of data over time.

The first graph (Fig. 2a) presents an analysis of the relationship between the number of different functions that a modular façade performs and the local population density. Most often, modules perform two functions and multifunctional shells are used in less densely populated areas. As part of the research, we also analysed the correlation between urban air quality and the amount of indoor and outdoor greenery solutions used (Fig. 2b). Air pollution has a slight impact on the use of more solutions with vegetation when planning an investment site. Often, greenery is organised in flowerbeds next to the building as well as inside the building itself. Graph three shows a noticeable difference in the amount of greenery solutions used for investment projects and inside buildings with vegetation on the façades over a 30 year period. There is a noticeable gradual increase in new greenery elements in the interiors and on the investment plot (Fig. 2c). A comparison of the average area of modules with building height showed no correlation. The average size of modules on the façades is 1.3 m2 (Fig. 2d). Graph five (Fig. 2e) shows the quantitatively diverse selection of plant species depending on the façade dimensions. One as well as two, three, four, five or more plant species regardless of the façade dimensions are installed on green walls. Another analysis (Fig. 2f) shows the statistics for green module façade locations according to the cardinal directions. The greatest use of modules is noted on all building façades or only on one, the south facing. The table was also used as basis for research on the function of buildings whose façades are most often covered with modules with plants. Office, residential, commercial and retail buildings are most numerous (Fig. 2g). Graph eight (Fig. 2h) shows the climate where the largest number of buildings with green façades from the surveyed sample were constructed. Similar investments are most likely to be executed in the warm temperate transitional and maritime climate zones and the temperate cool transitional climate zone. The structure of a green façade module was also analysed (Fig. 2i). Solutions integrated into the building's load-bearing structure, including modules integrated into the main structure with plant pockets or solutions placed on an independent structure with pots are the most commonly designed and implemented elements. Vegetation irrigation is ensured by systems integrated into the building's plumbing systems. Many plants on modules collect additional water from the air; the use of rainwater for watering was recorded in more than 10 % of cases (Fig. 2j).

2.4. Detailed analyses of selected examples from the table

The data shown in Table 1 concerned sites that were known from first hand only to a few people and only in a few cases, which may represent some limitation for the method used. One of the basic elements of architectural research is a site visit and the ability to inspect a building [23], therefore, in subsequent parts, in order to illustrate the many technological possibilities in the shaping of green façades in architecture, examples from Poland[2] and the neighbouring Germany, also investigated first-hand by the authors, featuring different types of modular solutions have been cited.

[2] The small number of green façade projects in Poland in relation to, for example, European projects is clear. In the opinion of the article authors, the interpretation of the definition of biologically active area set forth in the Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions to be met by buildings and their location Journal of Laws. 2019.1065 i.e., of 07.06.2019: § 3, para. 22 may be the problem here. Even though it is possible to implements a biologically active area on a plot: on a building part of a plot - 100%, on roofs and terraces - 50% and on other surfaces, including in the form of vertical greenery on condition that the natural vegetation of plants and water retention are ensured, this last aspect is little used by investors due to the cost-intensive nature of such solutions. (Authors' footnote: interpretation of the definition based on Opinion No.

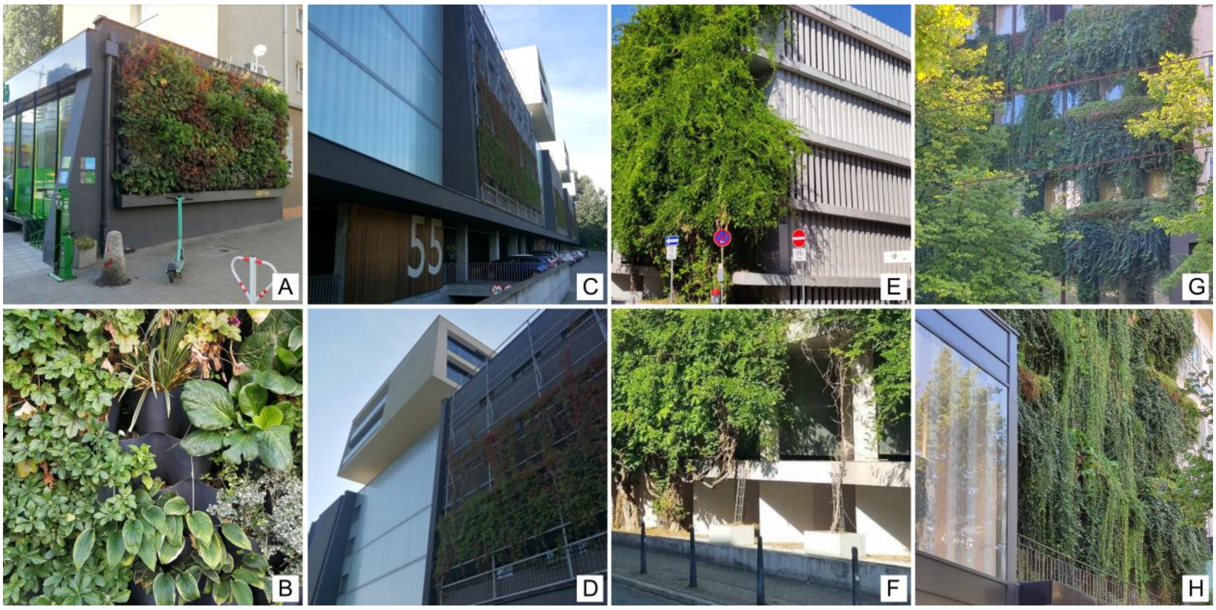


Fig. 3. Examples of buildings with green façades: a) Żabka Eko Smart (tab. 1. item 85), b) Żabka Eko Smart – green façade element, c) Botaniczna Residential Estate (tab. 1. item 84), d) Botaniczna Residential Estate – green façade element, e) N1/N2 Stadthaus, Parkhaus (tab. 1. item 96), f) N1/N2 Stadthaus, Parkhaus – green façade element, g) building at Planken 07, Mannheim (tab. 1. item 90), h) Building at Planken 07, Mannheim – green façade element, Source: authors' own photographs

The technology used for the Żabka Eko Smart retail building in Poznań (Fig. 3a, 3b), developed by the Żabka Group, is a solution in which plants in the substrate are placed in specially shaped pockets using an additional substructure integrated into the façade's load-bearing structure. Żabka's innovative Eko Smart project introduces many other environmentally friendly solutions, including a perovskite structure, a solar bench with phone charging capacity as well as a bottle and can collection device. The façade of a building on the Botaniczna Residential Estate in Poznań designed by Insomia Architectural Studio (Fig. 3c, 3d) is an example of a green façade in the form of an independent substructure attached to the main load-bearing system of a building with pots. The design uses climbing plants on an additional frame offset from the façade, creating a periodically vegetated second skin of the building. Greenery on the N1/N2 Stadthaus, Parkhaus in Mannheim (Fig. 3e, 3f) building represents a well-known and widely used solution for locating vegetation in modular pots next to a building and flowerbeds, allowing plants to grow freely and directly on the standard façade of the building. The exposed façade of a building located by the pedestrian area at Planken 07 in Mannheim (Fig. 3g, 3h) is an example of the use of modern green wall technology. The existing façade of the 1950s building has been revitalised according to a design by the Schmucker und Partner architectural studio. An additional substructure was mounted to the building façade, and then a square-shaped modular Hydroflora system was installed between the frames. The fact that individual modules can be exchanged quickly is an advantage of this solution. Shade-loving species have been planted on the façade. The system allows water to be stored and evaporated, improving the micro-climate.

ZR 189 of the Team of Experts at the Council of the Małopolska Regional Chamber of Architects of the Republic of Poland [41]).

2.5. Summary of analyses and research

Several arguments were raised on the basis of the research carried out to indicate the need for innovative eco-friendly façade solutions. According to the data collected, air pollution, with changing parameters at different times of the year or day, only slightly affects the amount of greenery used on a building and in its immediate surroundings. Therefore, more greenery on façades, which can effectively improve the overall air quality and protect against possibly worsening conditions seems justified. The analysed cases indicate that there are no restrictions related to orientation (cardinal directions) when it comes to green façades due to the possibility of selecting an appropriate plant species.[3] Rainwater to feed the plants is additionally stored in only 10% of the cases, which means that designers should pay more attention to the need to store it outside the root system. The use of recycled materials to build façades is still not widespread enough. These could then potentially be recycled and used again.

3. DISCUSSION

A review of the literature on the subject and the data collected showed a great diversity of issues related to the façades in question. According to the authors, the search for modern solutions should be directed towards multifunctional façades that, with the use of modern technologies, will perform to all the requirements that are feasible in a given location, starting with consciously selected, recyclable, durable materials which generate the smallest possible carbon footprint in the production process; construction materials associated with greenery through their many functional qualities (rainwater collection and use, shading, insulation against wind, sun, rain, snow and temperature), air purification, combined with other functions of the components used (e.g. energy production, anti-smog coatings, etc.), all the way to aesthetic requirements (composition, colour, texture, etc.). Economic factors related to both material expenditure in the spirit of vernacularism and costs of use should also be taken into account. The development of a modular façade design adaptable to any façade size by multiplying elements, the possibility of exchanging components and placing a variety of infill materials in the substructure are key aspects in the design of innovative concepts for a sustainable tomorrow. Eco-friendly façade designs should be developed for application in buildings of various functions. Our research shows numerous construction methods and systems in use, which should form the basic and initial knowledge before the design process begins.

In order to develop the best possible solutions, green façade system designers should take into account the latest materials, such as: aesthetically pleasing, flexible and thin perovskite structure [3, 34]; bamboo which has remarkable strength and irrigation properties, and is biodegradable [20]; rammed earth which is resistant to vibration [27], noise and fire; the biomass generated by the algae oxygen production reaction which can be periodically harvested, then collected and used, for example, as fertiliser or as an energy source [31]; new raw materials from used plastic products [24] or ornamental or utility plants, selected to suit street-like conditions [4].

Green façade systems, significant for the implementation of sustainable construction technologies [15], should not only be put forward for new buildings but should also be an option for renovations of existing buildings, for example in large-panel blocks of flats [12, 17], facilitating an adaptation of the existing architectural features to the needs imposed by the changing climate [6].

[3] In modern buildings, green modules are integrated with the load-bearing structure, forming an integral part of the building. For older buildings selected for revitalisation (including Polish high-rise apartment buildings), it is worth developing better methods than those used so far (usually climbers on old façades, or building renovation entailing thermal insulation and painting) which would entail additional pro-environmental functions

4. CONCLUSIONS

The research, analysis (presented in this article) and additional examples of future solutions (presented as an appendix to this article) have shown the validity of developing modern, green and environmentally friendly façade technologies, and were used to identify the latest design and implementation trends. In particular the orientation, tasks and functions which modern façades should fulfil have been demonstrated.

- A review of existing solutions implemented around the world has identified relationships between the decision to implement a green façade and external factors: climate, population density of the site, or sun exposure of the façade [29, 33]. There is a need for green façades across most inhabited areas of the world on buildings performing various functions. Modular façade elements are readily used on all the walls of a building, on every functionally available surface, with some selected additional functions requiring the right orientation and exposure.
- Detailed analyses of the complex construction of modular solutions have shown a trend towards the implementation of a number of different technologies in the creation of green façades, different ways of irrigating vegetation with a plethora of floral species, which makes it possible to adapt the form, the way the façade is used, to the design possibilities, the individual needs of the investor, economic assumptions and climate factors [38].
- The creative new solutions for the future should present new design possibilities using innovative materials, including materials and substances capable of producing energy; purifying air; regulating humidity; reducing mould and fungal growth; preserving and self-cleaning elements; increasing or decreasing light flow; promoting biodiversity; protecting against insects; and improving aesthetics.
- There is a discernible need to design and implement more green and environmentally friendly façades in Poland.
- According to the guidelines set out after the research on currently existing façades was carried out, newly designed facades should be constructed as multifunctional green modules, which in most cases can be dedicated to buildings located in different parts of the world, adapted to climatic conditions and multiplied in form depending on the façade dimensions.
- The research by design (on the basis of the students' solutions shown in an appendix), proved the potential for more research to develop further innovative solutions based on already implemented, developed and proven technologies and systems. The analysed designs (appendix to the article) confirm the validity of the developed “Model for creating innovative green façade solutions in architecture”.
- Available modern materials, the state of research, inspiration in the form of existing buildings, the possibility of building 3D models and carrying out computer calculations enable researchers from all over the world to develop the idea of green façades and to develop fully eco-friendly solutions for the future [8, 9], as shown by the present article.

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APPENDIX TO THE ARTICLE – SOLUTIONS FOR THE FUTURE

Innovative solutions in architecture are one of the research directions pursued at the Institute of Architecture and Spatial Planning at the Faculty of Architecture at Poznań University of Technology. New study concepts are intended to indicate directions for improving the aesthetics of designed or existing architectural or engineering structures, but also to serve the purpose of optimisation, above all in terms of increasing functionality using the latest technical, technological and material environmentally friendly solutions. In the 2020/21, 2021/22, 2022/23 academic year, modular building façades become the subject of research within the scope of subject of innovation during term 1 of a second cycle programme. Selected design concepts developed on the basis of a simplified model (Fig. 1, in the article) and constituting yet another contribution to the discussion in question are presented below.

Fig. 1. Students concepts: a) Block Full of Energy design by Susan Zawadzka, Maciej Wiśniewski; b) DE-HYDRATION designed by Kinga Wleklak, Zuzanna Zdanowicz, c) HEX Panel designed by Joanna Sitak, Jakub Sokołowski, d) LeafyShade – green modular facade designed by Karina Prajs, Martyna Ruszała, e) ECO-FAÇADE designed by Kamila Gajda, Natalia Fedko; f) BASE. Bio Assimilated Soil Elevation designed by Agnieszka Dopierała, Marta Frankel; g) Botanic Diamond designed by Oliwia Frydryk; h) ALGTUBE designed by Barbara Domaradzka, Antonina Frieske; Fig. 1a-d supervised by Hanna Michalak; Fig. 1e-h supervised by Patrycja Kamińska

The presented design concepts (Fig. 1a-h), by students of the Faculty of Architecture, show possibilities and solutions for creating eco-friendly architectural solutions in the form of green façades.The designs draw inspiration from some of the most interesting innovative examples of green façades already constructed around the world, use modern materials and technologies, and perform a range of functions to help cities adapt to climate change and work towards protecting the environment. Multi-functional solutions were employed in all the designs. The developed modules can be used on most new builds or buildings in progress with a variety of façade sizes and exposures, depending on the individual preferences of the designers and the investors as well as economic considerations and environmental requirements. Methods for water retention, waste treatment or the use of natural materials to reduce the carbon footprint of façade elements have been developed as part of many solutions.