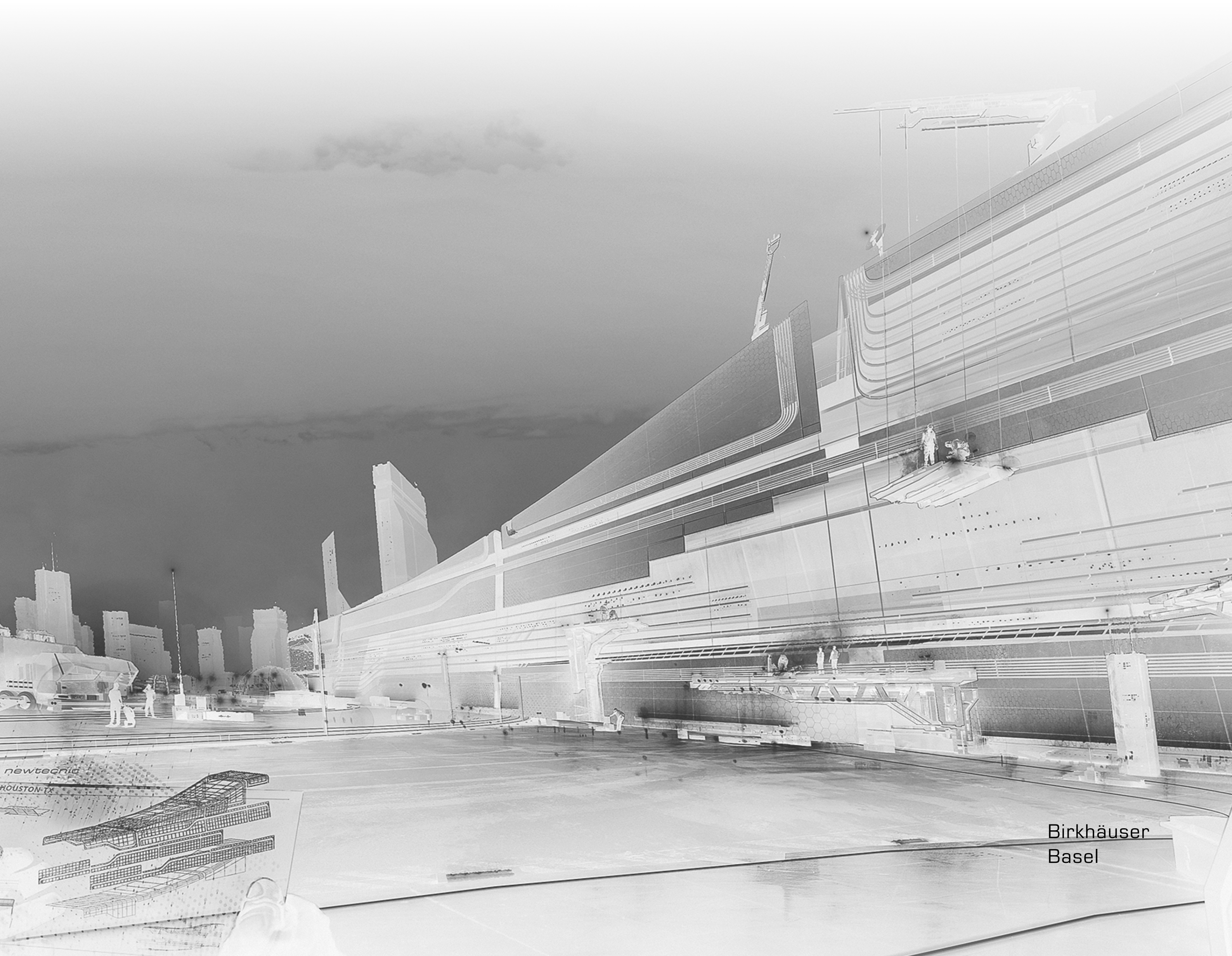
MODERN CONSTRUCTION CASE STUDIES

Emerging Innovation in Building Techniques

Second Edition

ANDREW WATTS



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Since the turn of the 21st century, the linear relationship between architecture/engineering/construction has been slowly dissolving and interweaving into an entirely new workflow, requiring a new kind of relationship between architect, engineer and construction teams in order to achieve the great built works of our age.

Building design has evolved from hand-drawings, hand-calculations and construction-in-the-field to a new process of digital design, engineering analysis/simulation and digital (BIM) construction models. This is not merely a change in medium from paper to computer. It is an entirely new paradigm.

Building envelopes are no longer the exterior wall of the building. The line between facade, structure, lighting, climate-response and mechanical systems begins to blur and suggest new evolutions. The exterior envelope can evolve to also be the structure – it can be an intelligent membrane that not only separates inside from outside but can also engage it.

DESIGN TO PROTOTYPE

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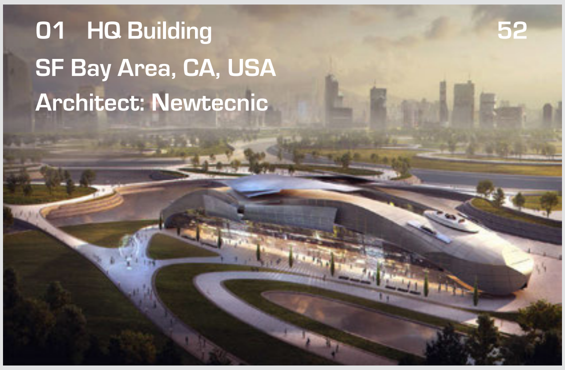

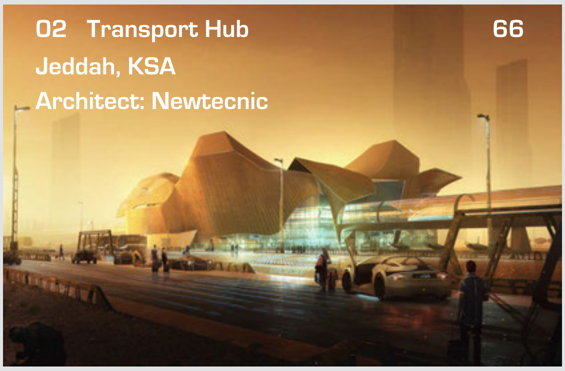

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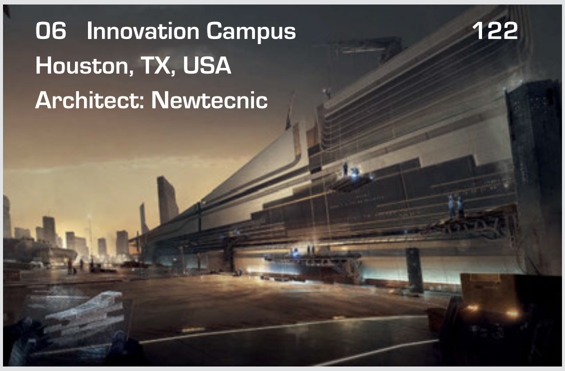

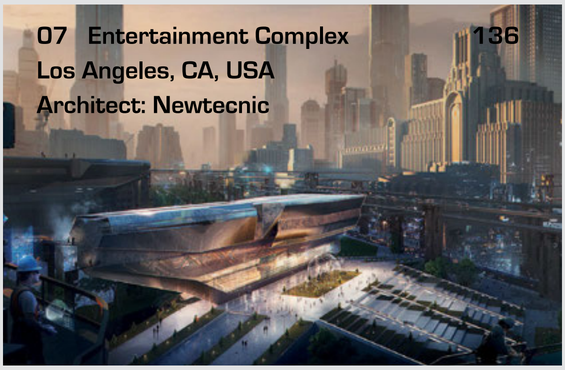

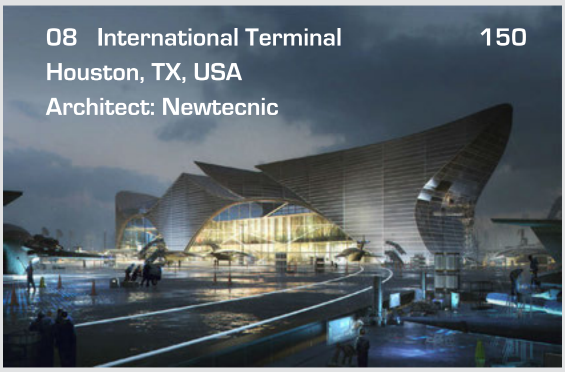

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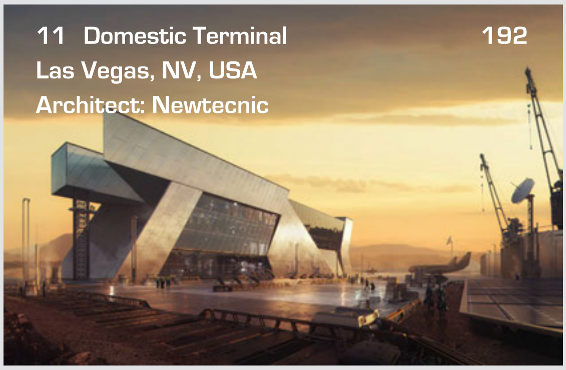


I am writing this introduction as the new edition of 'Modern Construction Case Studies' is about to go to print in April 2019, nearly 20 years into the 21st century. It arrives during a moment of tremendous change in the history of architecture, engineering and construction.

During the 20th century, architecture, engineering and construction were seen as distinct professions – divided into 3 linear steps in the process of making a building:
(20th c.) – Architectural design and documentation.
(20th c.) – Engineering design and documentation.
(20th c.) – Construction.

Since the turn of the 21st century, this linear relationship between architecture/engineering/construction has been slowly dissolving and interweaving into an entirely new workflow, requiring a new kind of relationship between architect, engineer and construction teams in order to achieve the great built works of our age. Building design has evolved from hand-drawings, hand-calculations and construction-in-the-field to a new process of digital design, engineering analysis/simulation and digital (BIM) construction models. This is not merely a change in medium from paper to computer. It is an entirely new paradigm:
(21st c.) – Design/engineering/building a digital version of the building simultaneously.
(21st c.) – Integrated, multi-disciplinary documents for construction.
(21st c.) – Construction.

In this age of digital design and construction, new minds and new mind-sets are emerging. Our new digital tools allow us to explore design forms of greater complexity and simultaneously be informed of the technical issues involved. The result is that as designers, we are able to be more creative, ambitious and intelligent.

Buildings made this way allow for a fully-integrated design that thoroughly considers the architecture, engineering and construction equally from the conceptual stage through construction completion. This holistic, multi-disciplinary approach to design is the engine under the hood of the book that you are holding.

Andrew Watts, as a practicing engineer and architect, has been operating at this high level of design for numerous internationally acclaimed, iconic buildings. With the help of his team at Newtecnic, he is generously sharing his experience and integrated design methods for 12 projects in order for us to better understand this new design workflow for architecture of the 21st century.

Prepare to be immersed in a visually rich and intelligent conversation about state-of-the-art skyscrapers and groundscrapers, ambitious transportation buildings, office buildings, cultural buildings and multi-family housing. The building envelope for each project is the primary focus of the book, as this is where the technical meat of the conversation lies.

Andrew Watts shows us that building envelopes are no longer the exterior wall of the building. The line between facade, structure, lighting, climate-response and mechanical systems begins to blur and suggest new evolutions. The exterior envelope can evolve to also be the structure – it can be an intelligent membrane that not only separates inside from outside but can also engage it.

For the past 20 years I have been leading university-level design courses in the U.S. and the U.K. – teaching design to architecture and architectural-engineering students. It is a rare gift to find a technical book that can communicate content not only clearly but in a manner that is visually compelling and intuitively understandable to both students and experienced designers. 'Modern Construction Case Studies' – in particular, this new edition, is indeed one of these rare gifts to us as designers and helps pave the way deep into the 21st century.

Gregory Brooks
The University of Texas at Austin
Faculty Director, Emerging Technologies program
Associate Professor of Practice, Architectural Engineering program

Modern Construction Case Studies focuses on the interface between the design of facades, structures and environments of 12 building projects. In all cases, Newtecnic have developed innovative aspects of the facade design as architects and engineers.

The primary aim of the book is to compare facade technologies, particularly in the way they interface with structure and MEP (mechanical, electrical, plumbing services) in complex projects, and to provide insights into the design process for building envelopes, by exploring specific themes through case studies of live projects.

Each envelope technology is described with a particular emphasis on one of three aspects:

- Complex geometry
- Innovative construction
- Enhanced performance

For each case study presented in the book, only one aspect is investigated in more detail, although all 12 case studies show strong components of all three aspects of facade technology. The comparative analysis, which follows this introduction, links the 12 case studies by comparing their structural and environmental performance through tables and graphs. These comparisons are used to illustrate trends across complex projects, for which each design is significantly different. This aim is achieved by analysing typical bays which are representative of each project and which illustrate the implications of using different building envelope technologies.

The design methodology, developed by Newtecnic, and used to design each of the case studies, is explained through the introductory essays. These texts explore core themes.

The principles described in this book are presented as a palette of design tools which are applicable to the design process for building projects with external envelopes of complex geometry. The application of this approach to each new design is project-specific and inherently dependent upon the specific function and spatial organisation of each building, and consequently cannot be generalised to a simple set of steps. Newtecnic hopes that the reader will find the content of use in their own engineering design work, as well as benefiting from the project comparisons which are also set out in this book.

Steps to build a working prototype

The purpose of this section is to show the reader how to engage with a fabricator in order to build a working prototype of a facade assembly. This prototype could be used for performance testing in order to obtain certification for its use on a specific building project. The procedures for the fabrication and testing of a working prototype are set out as a series of sequential steps. Such a prototype will typically be made when the contract has been awarded for the construction of the facades, but the prototype can be used during the design development stage in order to eliminate risk of exceeding the budget.

The method of 'steps' described later in this chapter is essential for ambitious or cutting-edge projects in order to remove the uncertainties inherent in the use of current technologies which are combined to form an emerging technology for a building project. At Newtecnic, warranties provided by contractors for pre-tested current technology systems are not relied upon for their combination in an emerging technology.

Cross-referencing MCE3

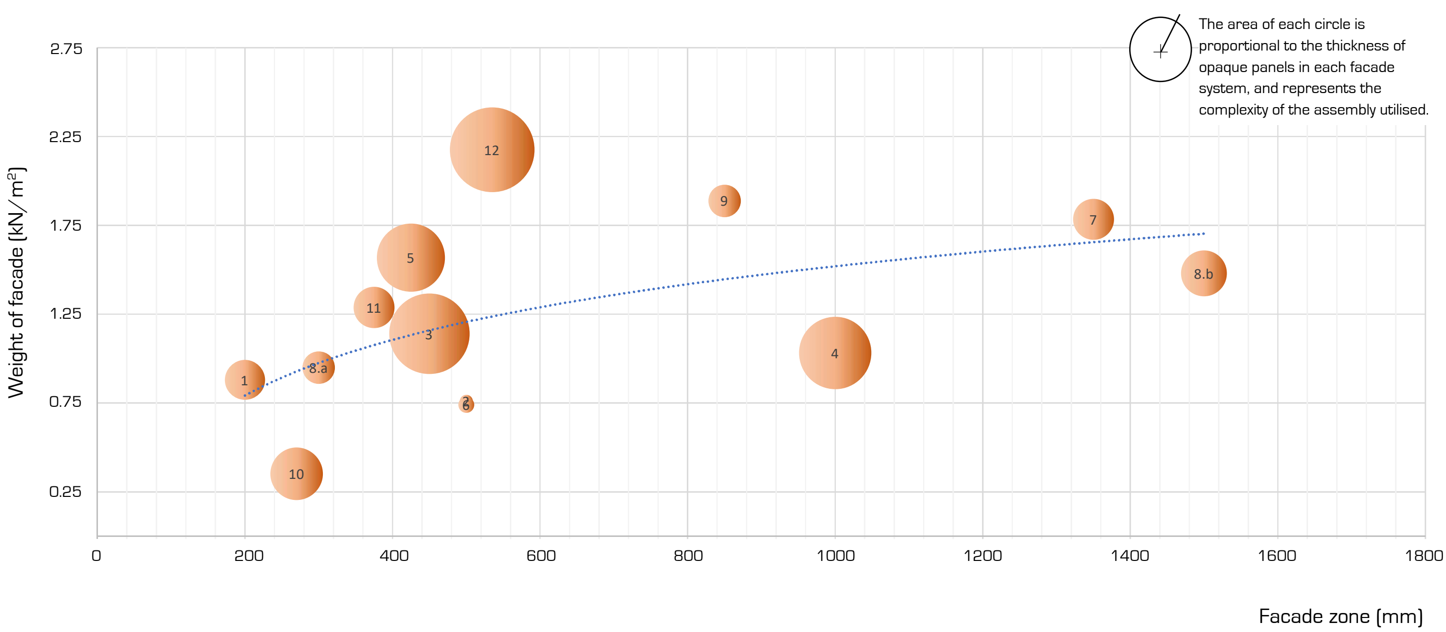
Specific references to materials in this book are to be found in the companion volume Modern Construction Envelopes, 3rd Edition (MCE3). Since it is good practice to not duplicate information across multiple sources, technical information for the specific materials shown on inventory model pages is contained in MCE3 only. As a result, this case studies book is linked directly to MCE3: The case studies featured here are a development of the current technologies set out in MCE3. The prototypes shown in this book are larger in scope than those in MCE3 as the examples here are more suited for performance testing. The prototypes in MCE3 are visual mock-ups that assist the design process. The steps to achieve a small-scale mock-up are set out in MCE3 and those steps should be followed prior to the steps shown in this book.

A development in this new edition is the addition of examples of both structural and environmental engineering analysis that allows the advancement of the systems, shown as prototypes and typical bays, to go beyond the architecture-led approach of MCE3.

A primary objective of the Modern Construction Case Studies is to provide a comparative analysis of different facade technologies used for complex geometry building envelopes, in relation to the climate and environment where they have been implemented on each project. The 12 case studies illustrated in the book have been compared in the tables and graphs below in terms of the environmental and structural performance of their building envelope.

	Project	Facade system	Facade zone	Panel thickness
1	HQ Building	Opaque composite rainscreen with glazing insets	200mm	38mm
2	Transport Hub	Metal rainscreen with full height stick glazing	500mm	4mm
3	Workshop Tower	Opaque and glazing unitized panels	450mm	35mm with 120mm ribs
4	Conference Center	Unitized glazing with UHPC cladding	1000mm	25mm with 100mm ribs
5	Technology Center	Monolithic open-joined GRC rainscreen	425mm	20mm with 90mm ribs
6	Innovation Campus	Metal rainscreen with unitized glazing units	500mm	6mm
7	Entertainment Complex	UHPC open-joint rainscreen with full height stick glazing	Up to 1350mm	40mm
8.a	International Terminal	GRC rainscreen with full height cable-glass facade	300mm	25mm
8.b	International Terminal	UHPC rainscreen with glazing unitized panels	Up to 3000mm	50mm
9	Laboratory Tower	FRP open-joint rainscreen with double skin facade	850mm	25mm
10	Multi-use Design District	Timber boards with stick glazing	270mm	65mm
11	Domestic Terminal	Sprayed GRC used as permanent formwork	375mm	40mm
12	Baku Airport	Precast GRC rainscreen with stick glazing	535mm	50mm with 120mm ribs

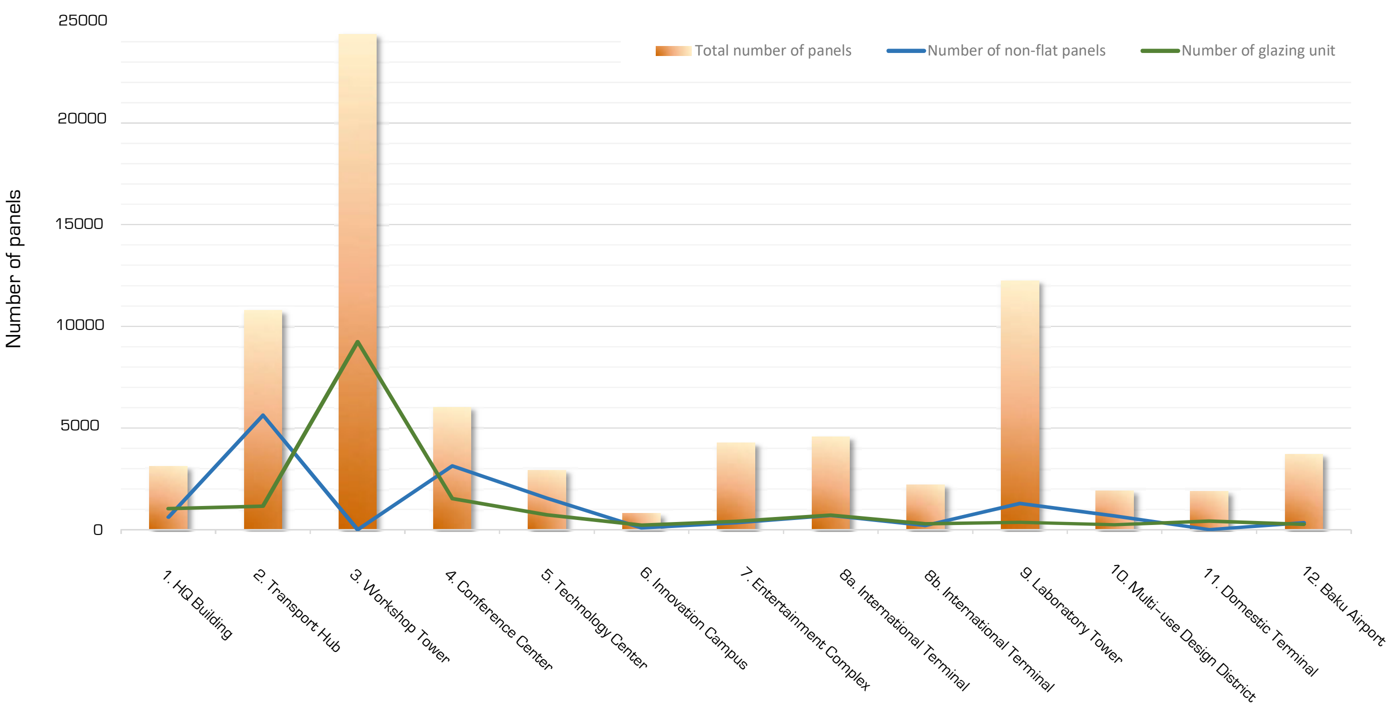
Weight of facade vs. facade zone



The numerical result used for the comparison have been obtained from the analysis performed on each project. Each facade technology, designed to suit all project conditions, has been assessed on a representative typical bay in order to compare facade systems across projects. The numerical values provided in this book are for comparison only and are not directly applicable to other projects.

Number of opaque panels	Number of glazing unit	Number of non-flat panels	Total area of panels requiring unique moulds	Total weight of facade, including secondary structure (kN/m²)	
2076	1026	620	2356	0.88 kN/m²	1
9631	1157	5631	13582	0.76 kN/m²	2
15120	9249	0	0	1.14 kN/m²	3
4488	1527	3141	4909	1.03 kN/m²	4
2208	730	1543	7547	1.57 kN/m²	5
589	222	89	214	0.74 kN/m²	6
3858	402	340	973	1.78 kN/m²	7
3844	720	700	467	0.95 kN/m²	8.a
1920	290	200	1091	1.48 kN/m²	8.b
11885	363	1285	5730	1.89 kN/m²	9
1680	240	672	518	0.35 kN/m²	10
1470	424	0	44	1.29 kN/m²	11
3443	260	344	1032	2.18 kN/m²	12

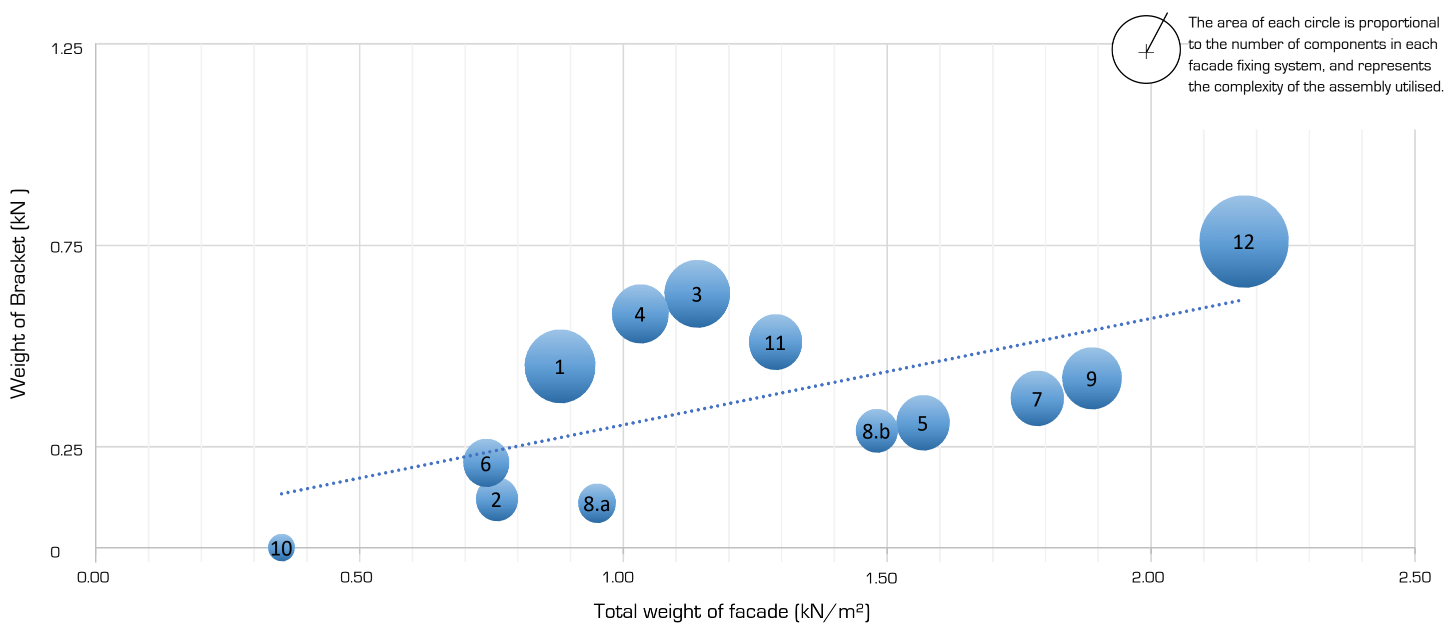
Panel Types Distribution



A primary objective of the Modern Construction Case Studies is to provide a comparative analysis of different facade technologies used for complex geometry building envelopes, in relation to the climate and environment where they have been implemented on each project. The 12 case studies illustrated in the book have been compared in the tables and graphs below in terms of the environmental and structural performance of their building envelope.

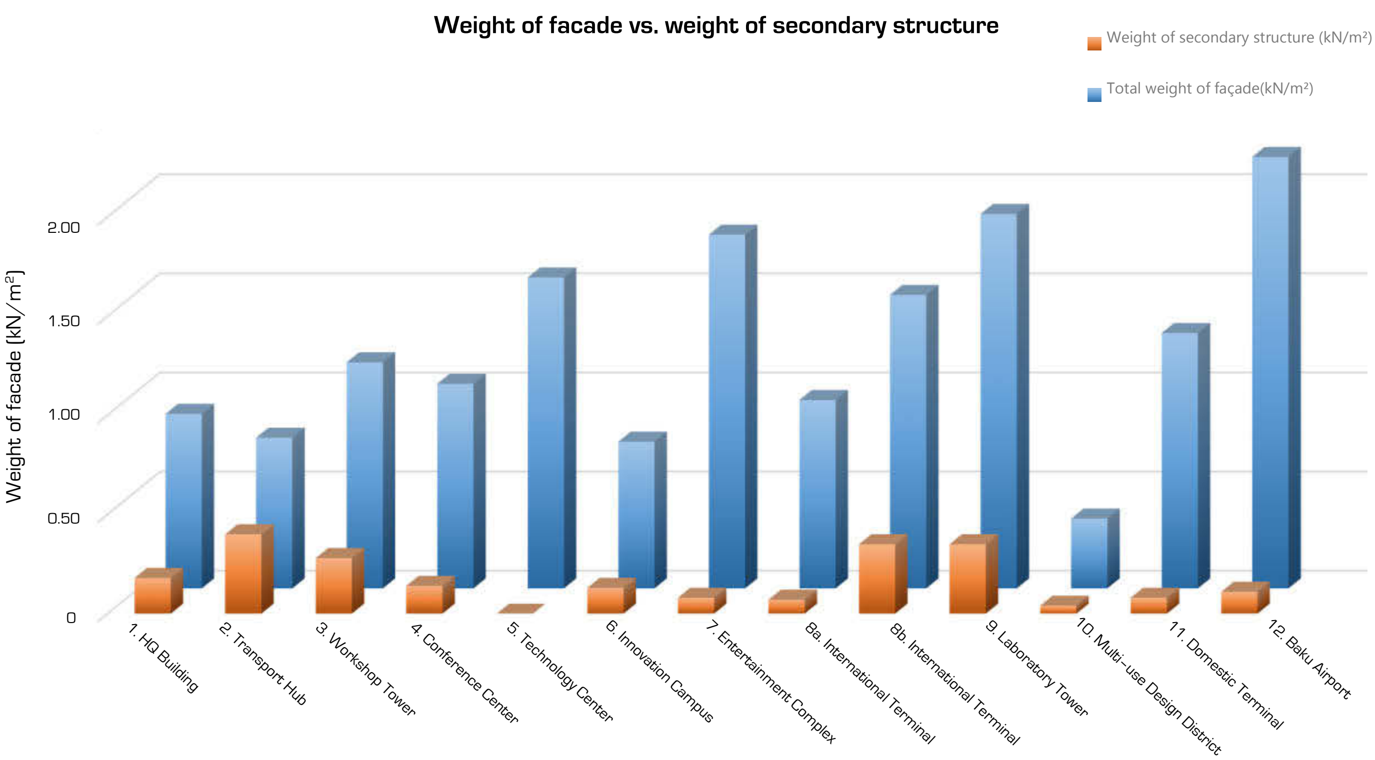
	Project	Primary structure type	Span of primary structure	Secondary structure type
1	HQ Building	Steel gridshell	8800 mm	RHS steel sections
2	Transport Hub	Concrete slab and column	10500 mm	CHS steel sections
3	Workshop Tower	Steel frame	12000 mm	RHS steel sections
4	Conference Center	Steel tensegrity core	–	Steel T profiles
5	Technology Center	Steel shell	–	–
6	Innovation Campus	Steel moment frame	7500 mm	Cold formed steel sections
7	Entertainment Complex	Concrete frame	5000 mm	Extruded aluminium profiles
8.a	International Terminal	Steel arches and cables	Up to 102000 mm	Cable
8.b	International Terminal	Steel arches and cables	Up to 102000 mm	RHS steel sections
9	Laboratory Tower	Bundled tube	3750 mm	RHS steel sections
10	Multi-use Design District	Structural timber frame	1325 mm	Timber battens
11	Domestic Terminal	Steel diagrid	10000 mm	Extruded aluminium profiles
12	Baku Airport	Steel space frame	3500 mm	Extruded aluminium profiles

Facade weight VS bracket weight



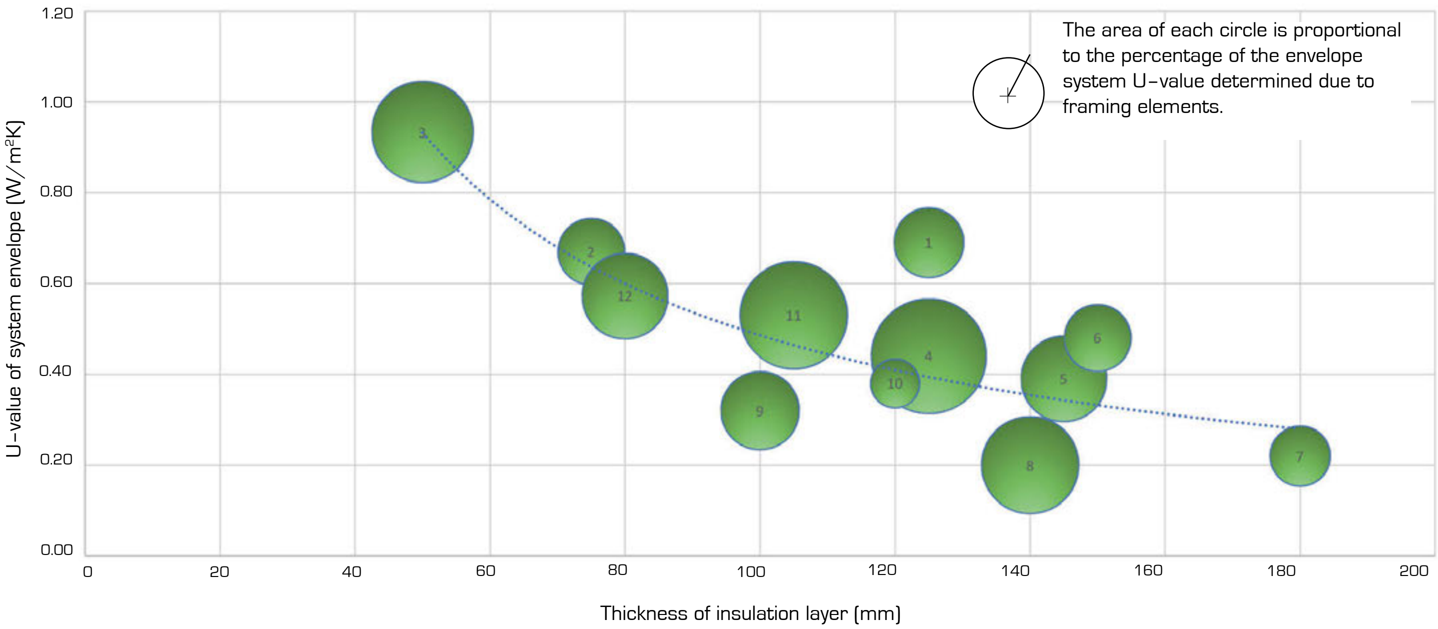
The numerical result used for the comparison have been obtained from the analysis performed on each project. Each facade technology, designed to suit all project conditions, has been assessed on a representative typical bay in order to compare facade systems across projects. The numerical values provided in this book are for comparison only and are not directly applicable to other projects.

Weight of secondary structure	Facade bracket type	Number of components in fixing systems	Weight of bracket	
0.18 kN/m²	Spider bracket with four adjustable arms	14	0.45 kN	1
0.4 kN/m²	Spider bracket with two adjustable arms	5	0.12 kN	2
0.28 kN/m²	Serrated plates; welded and bolted	12	0.63 kN	3
0.14 kN/m²	Standard bolted pieces	9	0.58 kN	4
–	Spider bracket with four adjustable arms	8	0.31 kN	5
0.13 kN/m²	Cast aluminium brackets, bolted through unitised joints	6	0.21 kN	6
0.08 kN/m²	Serrated plates; post drilled anchorages	8	0.37 kN	7
0.07 kN/m²	Spider bracket with four adjustable arms	4	0.11 kN	8.a
0.35 kN/m²	Serrated plates; welded and bolted	5	0.29 kN	8.b
0.35 kN/m²	Spider bracket with two adjustable arms	10	0.42 kN	9
0.04 kN/m²	Serrated plates	2	0	10
0.08 kN/m²	Spider bracket with four adjustable arms	8	0.51 kN	11
0.11kN/m²	Spider bracket with two adjustable arms	22	0.76 kN	12

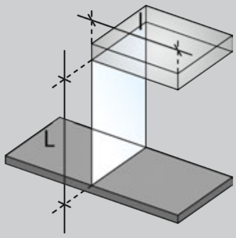
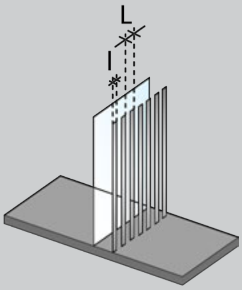


	Project	U-value of system envelope (W/m²K)	Linear thermal bridging effect for system typical detail (W/mK)	Insulation thickness (mm)	Total glazed area (m²)
1	HQ Building	0.69	0.12	125	2727
2	Transport Hub	0.67	0.11	75	15043
3	Workshop Tower	0.93	0.25	50	55860
4	Conference Center	0.44	0.32	125	5705
5	Technology Center	0.39	0.18	145	1010
6	Innovation Campus	0.48	0.11	150	674
7	Entertainment Complex	0.22	0.09	180	961
8	International Terminal	0.20	0.23	140	5613
9	Laboratory Tower	0.32	0.15	100	1545
10	Multi-use Design District	0.38	0.06	120	585
11	Domestic Terminal	0.53	0.28	105	7479
12	Baku Airport	0.57	0.18	80	2671

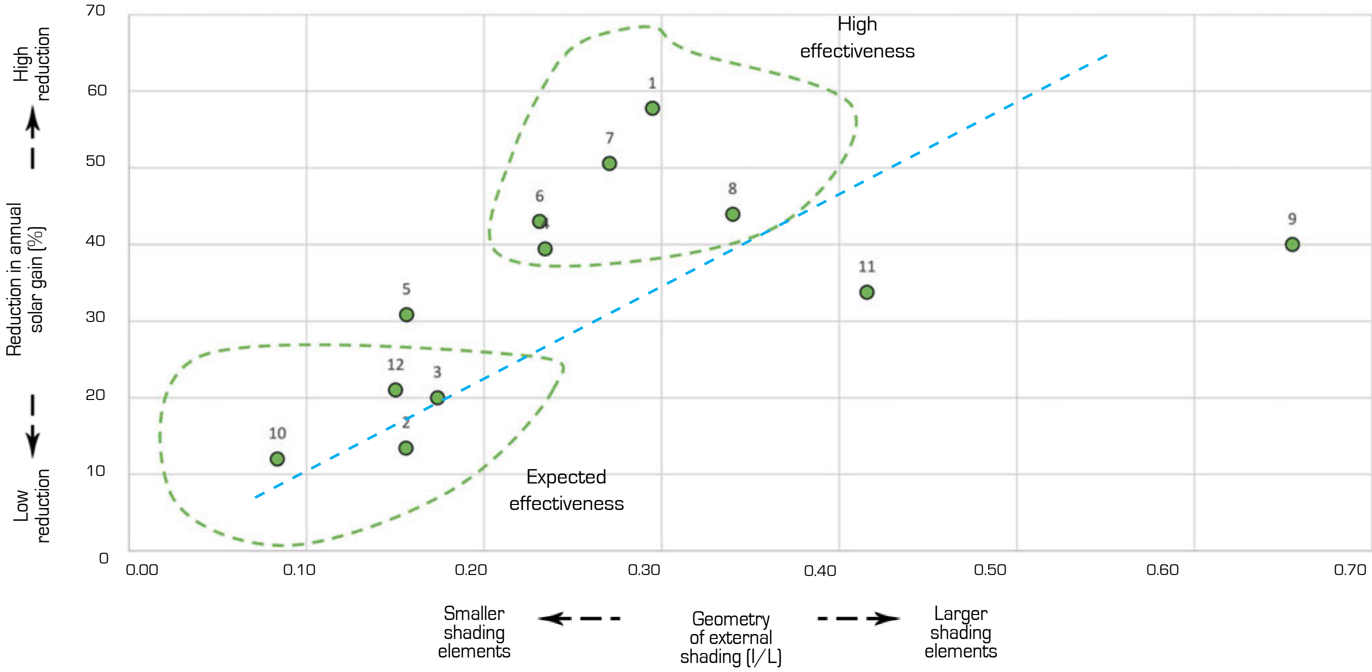
U-value of system envelope vs thickness of insulation layer



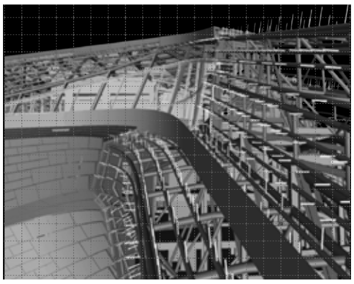
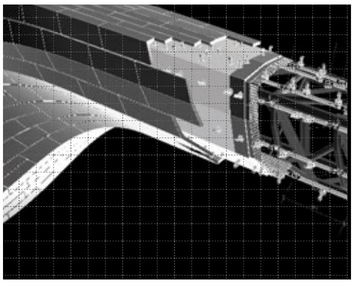
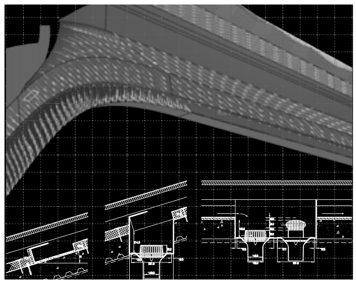
The relationship of inverse proportionality between U-value of each envelope system and thickness of the main insulating layer is illustrated in the graph, which also shows the potential effects of thermal bridging within more complex system assemblies.

Annual cumulative radiation – Total on glazed area (MWh)	Annual cumulative radiation – Average on glazed area (MWh/m²)	Geometry of external shading (l/L)		Reduction in annual solar gain by shading system (%)	
					
1909	0.7	0.29	–	58	1
16548	1.1	0.16	–	13	2
55860	1	0.17	–	20	3
5135	0.9	–	0.23	39	4
1313	1.3	0.16	–	31	5
539	0.8	–	0.23	43	6
1346	1.4	–	0.27	51	7
4491	0.8	–	0.34	44	8
2009	1.3	0.66	–	40	9
351	0.6	0.08	–	12	10
9723	1.3	–	0.42	34	11
1335	0.5	0.15	–	21	12

Effectiveness of external solar shading systems



The linear relationship between the geometry of external shading and the reduction in annual solar gain illustrates the expected effectiveness of external shading systems and allows to identify areas on the graph that represent shading systems with high effectiveness.

Current design methodology

The application of current and emerging technologies for the design engineering of facades is linked to the information available in established technical publications. These sources focus on providing an understanding of the main components within a given building assembly and illustrate the different choices available for the construction of assemblies for the building envelope, as well as construction methods used for the interior of the building. Specific technologies or materials can be selected by the architect or designer as a point of departure in order to select a construction system based on visual, performance or cost criteria. The details contained in these publications are often used by the facade engineer as a point of departure for facade system drawings. These publications typically require an experienced facade engineer to be able to extract relevant knowledge for use on real projects. The information available from these primary sources is also used by architects as a library of visual references and precedent built projects.

Beyond these primary sources, a mix of standards, codes and design handbooks are used for the specific design of components and assemblies, such as those used for connections in steel frames or concrete frames, for example. These design handbooks do not provide guidance for the reader to evaluate the appropriateness of the technology nor do these publications provide a means of validating the choice of a specific technology for a design application. Technical sheets and informal advice from fabricators are also a source of information for current technologies, which are often used as the basis for calculations during the design stage. The design is also often informed by information provided by a specialist contractor and is specific to the project.

Limitations of current methodology

These primary sources of information present information which is focused on the application of current and emerging technologies to specific materials or to specific projects. From the project–specific application of each technology, it is often impossible to extract information about the first principles driving its behaviour. Technical sheets from manufacturers rarely provide sufficient data with the given technology to design from first principles and to verify their suitability for a specific application. Often technical information is presented to satisfy commercial objectives and there is no method in place for the facade engineer to ensure the correctness or completeness of the information utilised.

Direct contact with specialist fabricators, manufacturers or contractors does not often result in the designer developing an understanding of the general principles and common methods used, as manufacturers tend to guard such technical information as being key to the commercial value of their specific product. Fabricators are also often not willing to provide design advice as a result of similar commercial considerations.

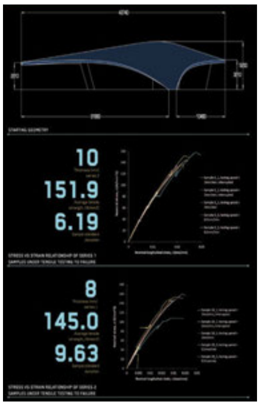
These various sources of information cannot be used directly in the design of complex building envelopes, which require an in–depth understanding of the first principles behind each technology; principles which form the basis of the design with its accompanying cost certainty.

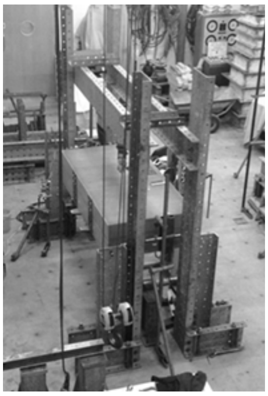
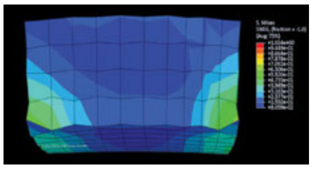
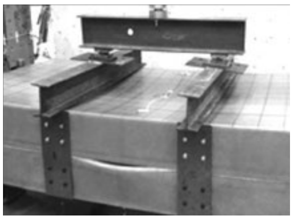
Newtecnic's methodology

In order to develop an understanding of the first principles underpinning the design of current and particularly emerging technologies, a primary source of information is scientific papers published in journals and proceedings from specialist conferences, which are peer reviewed by the engineering community. Peer–reviewed publications are concerned with methods of analysis using a given technology, not on the relative merits of one technology against another. The objective of these publications is to fill in the current gaps in knowledge of the members of the engineering community in the application of current and emerging technologies.

This technical information is combined with project–specific research, in order to assess the appropriateness of each technology and to develop an understanding of constraints related to their fabrication. For emerging technologies, this typically requires physical prototyping and testing to validate their project–specific application, which cannot be validated through desktop analysis only.

For the case studies in this book, the design methodology applied is focused on ensuring the appropriateness of the technology in relation to a series of parameters that go beyond its technical application. In the approach used for the case studies, the technology deployed is linked to the values and culture determined by the geographic location of the project and the common aspirations of that culture; linked to sustainability, justification of the use of resources, local skills in fabrication, but with the global reach of these shared values taken into account. The technology utilised meets the expectations of the client and increases the value of the product delivered. A detailed understanding of local markets and associated fabrication methods builds confidence in the project and ensures its realisation. As part of project–specific research, Newtecnic ensures that for each given project there are always at least two companies that are both capable and interested in realising the project. An important aspect is to generate interest in the design through the construction of proof–of–concept mock–ups and by providing a high level of design resolution, which shows direct engagement with the fabrication process. Part of this approach is to ensure that smaller local companies are able to realise and are willing to construct the design. The technical publications which are used at the primary sources of information on building technology do not typically seek to engage with specific issues of resolution of any completed building but instead make comparisons with other specific design solutions which are based on the adaptation



of available industrial processes to building construction. Emerging technologies are often based on new methods of fabrication. For the case studies presented in this book, the applied technology aims to increase the value of both product and process. New processes for fabrication can only be developed by linking design from first principles, academic research, physical testing and prototyping.

The facade assemblies shown in this book were conceived as a 'product'; a specific design solution with a high degree of resolution. For most projects, the facade assemblies were documented to provide a 'set of instructions' for the construction of those facades, which include a proposed sequence for assembly and installation. As a set of instructions to be followed by a contractor, these designs required validation of the method and outputs that underpin the design for each project.

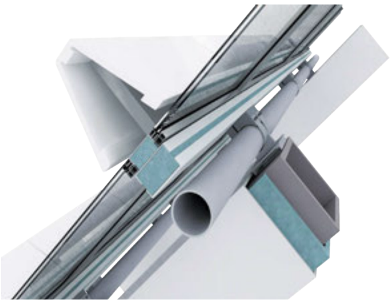
This essay sets out the key issues in the use of current and emerging construction technologies as applied to building envelopes of complex geometry. Designs of this type require a high level of integration between structure, facade and MEP (mechanical, electrical, plumbing services), which often comprises an external envelope with an integrated self-supporting structure that is independent of the building structure that supports floors and service areas, combined with high thermal performance. The design of complex building envelopes with a high level of integration requires a careful selection of suitable technology and its adaptation to project specific facade assemblies, in order to meet a set of different performance requirements for structure, facades and environmental systems.

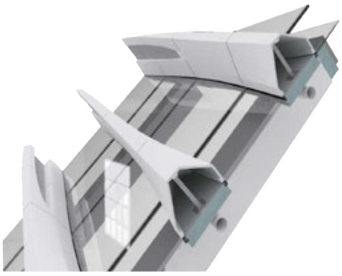
In the context of this book, technologies are tools for generating facade assemblies. In turn, the assemblies generated for a specific facade design determine the components and the connections within each assembly, and therefore affect the assumptions for 3D modelling and associated engineering analysis tasks, such as hand calculations and computational simulations. A facade assembly is made from a set of materials, the fabrication of which will be based on either current or emerging technology, or a mix of the two, as the term 'technology' can apply to both an assembly and the materials used in that assembly. At Newtecnic, complex building envelopes are designed from the point of view of the technology for the assembly, with the specific material used being chosen at a later stage of design development, once the required performance and physical properties of a material have been determined. The choice of a specific material for a facade assembly, such as that used for a solar shading device, is determined later in the design process. The material that will meet the performance criteria of this specific function will often have its own material technology. Consequently, the technology used or developed for the assembly should be interdependent with the materials used in the assembly as well as the technology used for their fabrication. This approach allows 'material selection' to be finalised later in the design process, with the possibility of introducing significant value engineering possibilities without fundamental design changes at that later stage of the project. The alternative approach of using assemblies that are material-specific introduces higher interdependence in the design at an early stage of design development, which would limit the ability of the design to respond to later changes in the design of the external envelope. Consequently, the selection of facade materials is made at a later stage of design development.

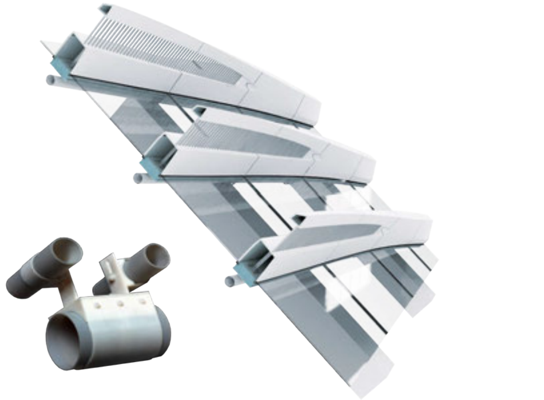
Current technologies in facade assemblies

Current technologies are used in facade assemblies where the project design criteria are typically well-understood, and where alternatives can be provided to the solution proposed by the design team, while still meeting the same project-specific requirements. This approach can lead to facade designs which are more 'generic' in their level of resolution; an approach that allows contractors to propose alternative facade solutions at a very late stage in the design development of the project. Typically, a contractor's alternative solution will be adopted if proven to be substantially cheaper than that proposed by the architect's design team, while still providing the same overall performance as defined in the performance specification for the project. A potential hazard introduced by late design changes from a contractor is the unexpected effects on coordination with other trades or construction packages.

Current technologies require only project-specific performance testing for final validation. Consequently, the expected performance of a well understood technology is validated through physical testing for the specific configuration proposed for the project. Typically, current technologies are optimised for one specific function or a narrow range of functions. For facades, current technologies are typically offered by specialist fabricators and manufacturers as proprietary products which suit the fabricators' own fabrication capabilities. The use of different current technologies across a single project typically leads to a high number of interfaces between each of the facade systems. This approach often leads to a laborious construction methodology which is both difficult to achieve on site and time-consuming to design. Current technologies are typically unable to respond to widely varying conditions of geometry on a single project, making it difficult to enclose the complete external envelope with a single facade system. Current technologies offer fewer opportunities for optimisation and associated cost reductions from reducing the number of interfaces. This makes current technologies less suitable for novel building forms. Typically, current technologies for facades are suited to a 'loose fit' design approach, where a more generic solution is used to provide support to the architect rather than serving to help drive the design forward with innovation. The alternative approach of using emerging technologies allows a project-specific







technology to be brought to the facade design, where it is adapted in a process which resembles that of 'product development'.

Emerging technologies in facade assemblies

Typically, an emerging technology used in facade design is formed by the relationship between a set of novel components within an innovative assembly. Despite associations with the word 'emerging', the engineering basis of an emerging technology must already be demonstrated successfully on previous similar built applications when applied to large-scale projects. Therefore, as part of the design development process, project-specific prototyping and physical testing is required for any facade assembly where an emerging technology is used. This is because an emerging technology requires both proof-of-concept performance testing and final compliance testing, which follows standard procedures. Consequently, emerging technologies are not experimental technologies, but cutting edge applications of proven facade technology. Experimental technologies are considered to be technologies linked to a high degree of uncertainty in their performance and which require further research and development in order to become emerging.

Emerging technologies offer opportunities for significant cost reductions through project-specific design development, while maintaining the high value of the specific technology utilised. These technologies also provide opportunities to innovate for a specific building project, in order to reduce costs of the construction of that project. This approach allows an external envelope to be delivered with both high value and high performance at a cost lower than that of an older technology. However, an emerging technology for a facade system requires a higher level of design development at an earlier stage than a current technology, and consequently is developed as a 'product', for which the emerging technology is tailored to the specific requirements of the project. This approach is key to the design methodology developed by Newtecnic.

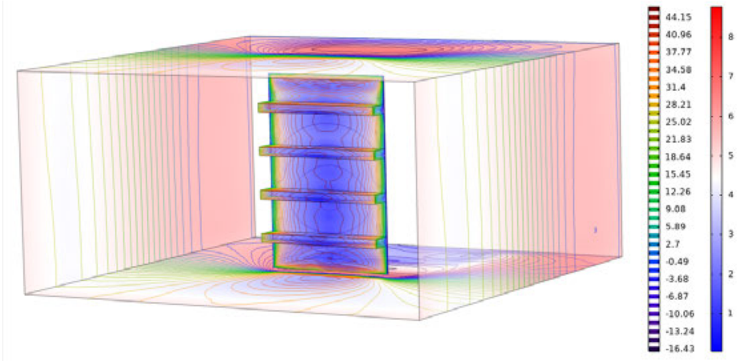
Use of current and emerging technologies in facade design

Both current and emerging technologies require a similar level of documentation when applied to facades for a specific project. For emerging technologies, documentation and supporting outputs is provided earlier in the design process as a tool for problem-solving rather than 'recording choices' in order to provide the same level of cost-certainty as would be expected for an equivalent current technology.

The use of a current technology often leads to project-specific design requirements being set out in a performance specification. The use of an emerging technology usually leads to a specification which sets out a project-specific solution as well as determining the required performance. The use of emerging technology in facade design directs the designer to achieve a set of clear design and performance objectives at an earlier stage of a project, while allowing the choice of key materials within the facade assemblies to be determined at a later stage in design development. This approach allows assemblies that respond directly to project-specific design priorities to be identified, resolved and costed at a much earlier stage of design.

For current technologies used in facade assemblies, a key consideration in the process is the design of interfaces and movement joints between adjacent facade systems. For emerging technologies used in envelope designs, a key consideration is the selection and project-specific development of a single facade system that is optimised to suit all conditions of geometry in the facades. The design of interfaces in facades, which are associated with the junction of current technologies, are slower to implement during the site installation phase than a single system that uses an emerging technology. The design of interfaces between facade systems is also slower to resolve as a result of design changes during design development, as current technologies are not usually optimised for connectivity with other technologies. Consequently, the design development of facades which use a current technology is generally confined to the later stages of a design process when the final design, and associated performance criteria, are determined. The experience of Newtecnic is that the use of current technologies in facade design results in a low level of facade system development for the first 75% of the design time. The remaining 25% of the design time requires an accelerated approach in order to provide the required documentation, but only after the design has been largely determined by the architect. In addition, the documentation of the facade design will be 'generic', almost entirely based on stating the performance requirements of the system, in order to allow for proprietary products to be proposed by contractors to meet the stated performance criteria.

The implementation of both current and emerging technologies in facade design are required to follow a disciplined process of documentation during the early stages of the design process. At the concept design stage, examples of existing assemblies (or existing technologies) are proposed with the purpose of demonstrating the feasibility of each assembly independently. In this process of 'differentiation' of assemblies, options are identified for different technologies that may be applicable to the facade design. At the schematic design stage, precedents of current and emerging technologies applicable to the proposed facade design are brought together as a synthesis, and compared again with the precedents proposed at the concept design stage. The purpose of this process is to clearly distinguish the aspects of the facade design that involve current technology from those that use emerging technology. This method allows the design priorities for the following stage of design development to be determined for necessary prototyping and physical testing.



Current design methodology

For large-scale building envelopes of complex geometry, the design method is often driven by the design of the facade assembly, and with the current or emerging technologies that are associated with that facade assembly. The design method for a building envelope includes all the steps and iterations required to deliver the final design from concept to delivery of a tested and validated physical prototype. The current method for the engineering design of facades for buildings is based on a sequence of steps which attempt to integrate design and manufacturing to ensure continuity from design to construction. This approach attempts to implement an effective project management method in order to control the process in terms of people, time and resources. The project management method facilitates the application of known solutions to supporting tasks in the design process. The current project management method for the design of buildings is based on a linear approach which makes use of Gantt charts to regulate the progress of both tasks and deliverables, as well as to define specific interdependencies between tasks. The assumption of this method is that the time required for each task is well understood from experience of previous projects, and that tasks can be prioritised in terms of amount of time assigned to each task.

The regulation of the design process through a linear project management method is applicable to projects where the design focus is the optimisation of current knowledge, where most of the design aspects are known and where design components which require optimisation can be pre-established. The standard design method for buildings is generally led by an architect, following procedures set out in the work stages of internationally oriented organisations such as the AIA (American Institute of Architects) and the RIBA (Royal Institute of British Architects). On many design projects the role of the building engineer or facade engineer is typically one of providing technical support to the architect rather than one of partnership in the generation of the building design. This approach is based on the building engineer providing a 'service' to support the architect's outputs with knowledge of structural and MEP engineering (mechanical, electrical and plumbing), which is well-established and is provided throughout the duration of the project on a day-to-day basis.

Limitations of current methodology

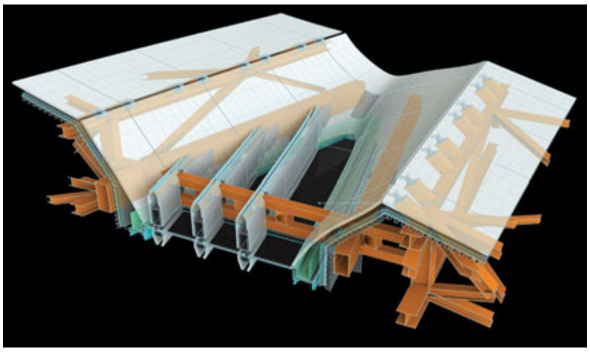
The current approach focuses on the time taken to develop and document a design solution which uses current technology. The current method assumes that current technologies are validated, and attempts to identify, at the outset of the project, the aspects that require a greater effort to be validated. The limitation of using the current method for both design and project management is that only current technologies can be implemented for well-understood applications. This design approach does not apply to complex building projects where the relationship between the parts is not determined. The limitation of the linear approach applied to project management can be a reduction in the ability of the building engineer or facade engineer to provide innovative designs which match the innovation suggested by the architect. This comes as a result of the limited time available to inform the architect's concept with a project-specific facade technology. An innovation by an architect may be based on a novel spatial arrangement in relation to the required function of that space, or may be a visually-driven concept for the form of the building. The engineering design, at the interface of structure, facade and MEP, will not necessarily reach the level of accomplishment anticipated by the architect, as the time scale expected for an innovative architectural design is less than that required for innovation in the corresponding facade engineering design, which typically requires research and development through testing. Consequently, the level of technical ambition in the facade engineering design of a project is reduced to suit the critical path of technical development of the architectural design. This leads to the current trend in facade engineering design of using proprietary systems selected through competitive tender, a process supported by a performance specification and associated drawn or 3D modelled outputs, such as a BIM (building information model).

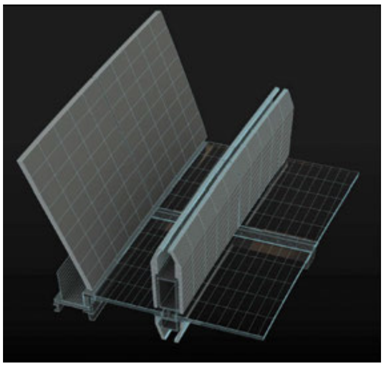
Newtecnic's methodology

The method applied for the case studies in this book is driven by problem-solving, an approach which is applied at each step of the design process. No step in the design sequence is allowed to produce only 'documentation'; the primary output must be a working design which is quantified and costed through 3D models and physical prototypes.

This design approach is non-hierarchical as there are no priorities set on the design criteria or on specific aspects of the design to be innovated or optimised. This method is based on a design engineering approach as applied across other engineering disciplines which are based on the design, fabrication and manufacture of 'products' and is applied to tasks involving the structural, facade and environmental engineering of buildings. This design approach suits engineers who are trained across several building engineering disciplines or, alternatively, have a global understanding of building design beyond their speciality.

This design method assumes that the parts of the design that require innovation emerge as the design develops, the innovation ranging from that of individual components, to creating novel relationships between components that lead to innovative assemblies and a corresponding enhanced performance. This approach to building design is strongly based on first principles and is open from the start of the project to the innovation of any





of the constituent parts of the design. As the design develops, it becomes clear which aspects drive the design and which aspects require innovation to achieve the required enhanced performance. The approach also allows a clear assessment of which parts of a design will most benefit from the application of either a current technology or an emerging technology. This design method focuses on generating quantified, comparable outputs within a short time-frame which will allow the design to progress through a sequence of steps, where the immediate consequences of each step are clearly understood before the next step is taken.

This method is founded on three key principles, which aim at overcoming any restrictions in delivering innovative design solutions:

- Research: University-based research of technologies which integrate facade, structures and MEP, conducted in-house and through academic partnerships. This process is independent of project-specific time scales and is aimed at both gathering knowledge on emerging technologies and developing new knowledge on experimental technologies. This aspect is discussed in the essay 'Design implementation and research method'.
- Digital tools for design and analysis: The use of high performing and calibrated digital tools to perform complex analysis at the early design stages, which is aimed at understanding behaviour. The capabilities of the commercially-available tools are often developed with the software provider as the design progresses. This aspect is discussed in the essay 'Analysis method and scientific foundations'.
- 'Agile' management: 'Agile' techniques provide a method of delivering successful innovation in building design if projects are developed as a 'product' rather than being a process with drawn and written outputs only. This aspect is discussed in the following paragraphs.

On any project, these three aspects enable a set of working facade prototypes to be developed, physically tested and approved through consecutive steps and completed before the stage of competitive tender. These three aspects also allow the design engineering process to generate new knowledge and innovation, which can be applied to subsequent projects.

'Agile' management applied to facade projects

In the delivery of facades of complex geometry for large-scale projects, the design methodology usually drives the management method used by the facade design team. Newtecnic has found 'agile' management techniques to be highly effective in achieving a high level of design resolution within the time constraints typically expected of a building design that would otherwise produce more generic outputs. Agile management techniques have recently spread outwards from the software development industry and are now widely applied across several fields in engineering that require innovation for both design and manufacture. 'Agile' management is highly suited to facade design work on high profile-projects, as the method supports four key aspects of facade design for large-scale projects of complex geometry:

- A multi-disciplinary engineering design approach.
- Short, intense iterations for a team of 8 to 10 engineers with different specialisations.
- Continuous innovation through all stages of design development.
- The creation of new knowledge at all stages of design development.

This 'Agile' approach allows facade design outputs to be communicated and delivered to customers as a highly evolved design 'product', rather than by providing a design 'service' with more generic outputs. This approach allows the focus of a facade engineering team to deliver, quickly, an innovative product which is cheaper, better or easier to construct than an existing product, rather than that team providing a design 'service'. Agile management in facade design provides a method for delivering high quality, innovative 'products', in which the ability to adapt to evolving customer requirements during the course of the design development stages is an essential requirement.

The design engineering of facades of complex geometry is output-oriented and is based on producing design proposals as quickly as possible; increasing the scope and quality of the design with succeeding iterations. The design process is typically 'kick-started' through linear iterations where engineers may be required to work in isolation or in small teams on explorative tasks. These tasks are typically analytical with the aim of identifying the driving design parameters for each discipline. As soon as key design objectives are identified, a large team is tasked with focusing on one specific issue at a time, which ensures that each task benefits from an effective team dynamic.

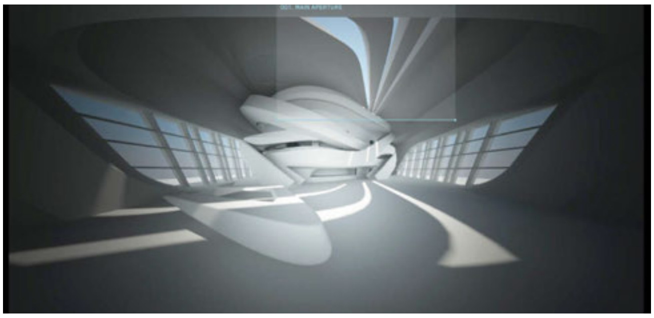
A tangible longer-term outcome of the application of this method is the production of the following outputs:

- Templates for reports.
- Technical notes for procedures and new knowledge.
- Example outputs of innovative solutions for facade engineering.

Templates and procedures provide the basis for the planning of future tasks of a similar nature. Agile management for facade engineering is based on the following core values:

- Collaboration and self-organisation of an engineering design team.
- Empowerment and continuous improvement of an engineering design team.

The principle of continuous improvement is essential for improving design outputs with each new iteration. An essential aspect of the design methodology for complex facades is ensuring that engineers are able to explain, at any given point, the design process to others within the team and to the customer. Every member of the facade engi-



neering team should be responsible for the content of their outputs, ensure the success of the task, and improve the quality of outputs for the next iteration in a process of continuous improvement.

Generating innovation

Innovation is at the heart of this design method for the facade engineering of complex forms. The method aims at generating new knowledge which adds value to the product delivered to the customer, and is usable by facade engineers on other projects. This is achieved through:

- Technical notes: processes developed in–house for projects are documented through technical notes, which are peer–reviewed by external research partners.
- Visible outputs: making outputs visible at every iteration and making the work visible at every stage of the process. This allows gaps in knowledge that require further research to be identified.

Knowledge creation, which is specific to the project, is part of the value the customer gains from this design approach. The customer is able to take ownership of the project–specific part of the technology if they so wish, together with the knowledge and innovation embedded in the design and documented in the project–specific outputs. This means that the client can at any time use the design documentation produced up to that point and continue independently with the design development. This design methodology generates new knowledge through prototyping and physical testing; activities which have seen a greater development in other industries but are not yet conceived as part of the mainstream of design processes for building construction. The creation of key links between building engineers and contractors is an essential step towards collaborating directly with leading fabricators in the construction field and acting as a bridge between design research and project–specific applications.

The approach to optimisation in innovative facade projects is driven primarily by the need to bring facade, structure and MEP together into an integrated solution. Optimisation of specific components cannot be done in isolation, as this can result in the sub–optimisation of other parts of the facade assembly. Components within facade assemblies are not optimised in isolation, but are instead evaluated as part of a matrix of optimisation. Optimisation is not specifically an 'agile' process; it is an iterative process of searching for the removal of unwanted complexity, with the benefit of reducing costs and improving quality for a building project. Optimisation is the 'calibration for economy' of any given facade design. In order to avoid sub–optimisation, an understanding of the cost of individual components is required. For example, the cost of glass in a given assembly can be lowered by reducing glass thickness as a result of decreasing the span of its supporting frame, but the increase in cost of the frame should be no greater than the cost saving achieved from the glass. Innovation in facade engineering design, as distinct from optimisation, is generated through establishing new links between components and facade assemblies.

Application of design method and project management

The aim of this design method for large–scale projects of complex geometry is to bring ambitious concepts to life without basing the design on specific solutions supplied by specialist contractors. This method of project management allows the delivery of facade engineering packages with a high level of technical resolution. These packages are able to be optimised for value and installation time, and would already have received approval for their fabrication and installation. The level of design resolution permits a high level of cost certainty. As part of this approach, each facade assembly deployed on a given project can be conceived as a facade 'system', which can be described in two parts:

- System architecture: The arrangement of functions at the small scale or large scale of a single facade assembly type.
- System engineering: The analysis and performance of a single facade assembly type.

Both 'system architecture' and 'system engineering' are developed through two phases:

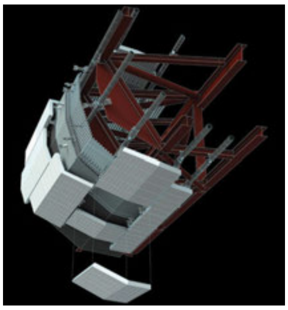
1. 'Differentiation', where each system component is firstly analysed and designed in isolation.
2. 'Integration', where all components are finally made to converge into one design solution.

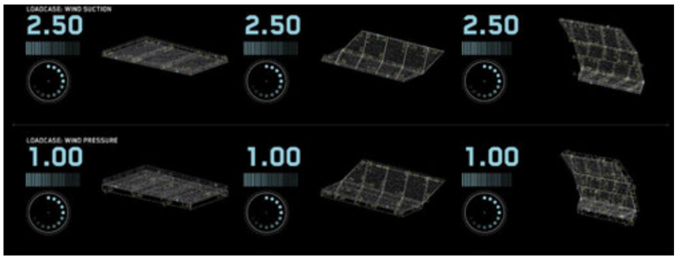
At the schematic design stage, robust concepts and strategies are established and deployed across the scope of the facade design project by exploring in full their applicability to project–specific conditions. The primary objective of outputs at this stage – beyond the design itself – is to obtain preliminary costs based on providing initial quantities, preliminary structural weights and number of components, expected performance criteria and preliminary MEP loads.

At the detailed design stage, or design development stage, analysis is undertaken in order to inform an understanding of each building technology proposed for the project. Outputs are derived from analysis at this stage, rather than from the general considerations of assembly investigated in the schematic design stage. During this stage the facade technology being proposed is developed to suit the visual language of the design as generated from the architect's concept. The following specific analysis tasks are undertaken at this stage:

- Understanding of secondary effects.
- Dimensioning of secondary elements.
- Refining of sizes of primary elements.
- Design of connections.

At the construction documentation stage, drawing outputs are finalised and coordinated with coordination and dimensioning of drawings.





Current design methodology

Analysis is the tool used to demonstrate the validity of a given design concept and is based on the application of a given set of scientific foundations. The current approach to analysis in facade engineering design is to conceive the analysis as a numerical quantification of a proposed design, which is generally conceived by the architect. This approach is based on keeping the scope of the design within codes and standards which provide the scientific foundation for the analysis. Generally, both national and international codes and standards integrate mathematical engineering foundations with empirical data, calculation formulae and procedures. The approach taken aims to ensure an agreed level of design safety for any given facade assembly. The engineer using codes and standards does not have direct access to experimental results or raw empirical data, which are already interpreted in the calculation formulae provided. Codes and standards provide calculation templates for the numerical quantification of current technologies, and ensure that the performance expectations for a current technology are met for a specific design. Calculation procedures from codes and standards are often integrated within design tools provided by specialist manufacturers in order to size specific components for their proprietary products. These tools include tables, software packages and design guides; these are typically provided for commercial purposes and allow the facade engineer to safely integrate proprietary products within the facade design. With the current approach, analysis is based on independent studies that take separate aspects of the design into consideration.

Limitations of current methodology

When using codes and standards, it is difficult to interrogate the first principles behind the calculation formulae utilised. The physical behaviour synthesised through the formulae is often not apparent. The derivations of the empirical factors describing the relative importance of different aspects affecting the behaviour described by the formula are also not apparent. In the current approach, the design process is not informed by digital finite element (FE) tools, which are instead used to provide final numerical validation or as a labour–saving tool. These tools are not in general use for the exploration of design options. This approach suits buildings of rectilinear geometry, for which the analytical basis of the design is well understood.

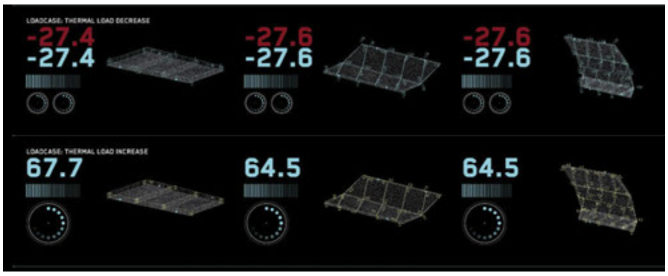
The consequence of the current approach is the generation of separate calculation packages, where the assumptions considered for the analysis are not required to be coordinated in order to ensure a 'loose–fit' design outcome.

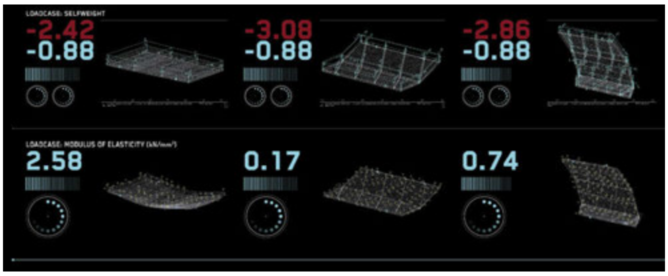
Newtecnic's methodology

In the method used for this book, the design approach aims to understand the first principles behind the analysis, following the academic approach taught at universities with leading engineering departments. In addition, the approach followed is applied by academic research teams attached to these engineering departments, who provide technical support to design engineers. The combination of first principles and physical testing becomes the basis of the scientific foundations when standards are not directly applicable to a design concept, as in the case of emerging technologies. The results are compared with standards and codes which are used to set expectations to verify experimental outputs. The analyses for a complex facade design are of two kinds: geometric and numerical. Geometrical analysis is performed at the beginning and throughout the evolution of the design. This analysis engages with the geometry of the complete building to establish the required complexity of the models required for the numerical analysis. Geometry analysis also ensures that all aspects of the design are tested and integrated into a final design solution following the numerical analysis which splits the design into parts that are calculated following different rules (the 'integration' phase of the design following the 'differentiation' phase).

For complex building designs, the use of first principles through finite element analysis tools is calibrated by physical testing. This approach requires a high level of engagement with institutions that are specialised in the application of first principles to testing of materials, components and assemblies to generate empirical data, which are shared and reviewed by peers. Physical testing is performed in order to calibrate digital models as well as to integrate safety factors into the design. As part of the approach proposed, openness and the sharing of technical knowledge for peer review and evaluation is critical to ensure best practice in the design methods applied, which are validated by the engineering community. In order to be able to effectively share information for peer review, an infrastructure is needed for facade engineering specialist advice, physical testing and peer review of outputs. In order to develop a design, a partnership between the building engineer, or facade engineer, and the architect is required, which is enabled though multidisciplinary team members who also have architectural training. The building engineer should draw a clear boundary around the engineering design, intended as the assistance provided to the technical development of the design concept. This is about realising the design rather than conceiving it: the nature and motivations behind the design concepts are not questioned, and the focus is on finding solutions to a technical problem. The design process allows changes to be absorbed quickly and is used as a tool to develop a deeper understanding of the design and its behaviour.

The design of complex geometry buildings typically requires emerging technology to be deployed in order to construct high performance envelope systems. A complex geometry envelope typically involves an interde-





pendency between supporting structure, enclosing layer and environmental control. These building forms are often conceived as 'wraps' for the internal spaces through a changing relationship between the facade and the floors and voids behind the external wall. Such envelopes are typically self-supporting, as the form of the facades is often independent of the arrangement of floor slabs behind the facade and often forms the external wall of large-scale spaces within the building. The complex geometry facades shown in the case studies within this book are supported either by a self-supporting frame or by load-bearing panels. Where the facade is load-bearing, the structure takes the form of shell structures which are realised with a mix of beam, plate and shell modules, and are distinct from braced frames or load-bearing boxes, as the geometry drives their behaviour. The specific nature of these structures is set out in the Modern Construction Handbook, which forms part of this book series.

The envelope regulates directly the flow of heat energy through the building skin, a factor which determines both peak heating/cooling values used to size mechanical equipment, and the total energy consumptions, which drive the running costs of the heating/cooling installation. Complex facade forms often make use of doubly-curved geometry, which can be exploited to achieve thinner envelope build-ups through shell action.

Analysis method and scientific foundations

The analysis method described here was used to generate early stage engineering designs for the case studies described in this book for the interface of structure, facade and MEP (mechanical, electrical and plumbing services). Through a process of integration of the constituent parts of the facade design, coordination between these components provides an opportunity for optimisation of the facade design. This process of 'integration' aims to achieve material savings, minimise the depth of the facade, and reduce the time required for fabrication of facade components and assemblies.

A current facade engineering approach, based on providing a design 'service' within a strict time-frame, requires the building engineer or facade engineer to apply well-understood technology to specific project conditions and to provide numerical validation of the appropriateness of their use through analysis.

An alternative method of analysis for facades of complex geometry, as used in the case studies in this book, is based around the design of the 'assembly', which is developed like a design 'product' that meets project-specific requirements. The 'assembly' is conceived as the fabric of the building envelope where structure, facade and MEP are integrated. Assemblies respond to specific performance requirements which vary across the building envelope. The numerical analysis involved is a function of the design of the assemblies, which must respond to both structural and environmental performance requirements. This approach results in, for example, varying structural strength and stiffness in adjacent structural members, varying air permeability and solar transmittance, and varying acoustic mass and thermal transmittance. The facade assembly is analysed at different scales by examining local effects at the scale of a typical structural bay, together with global effects at the scale of the entire building. The design of each component in an assembly can be equally driven by local or global effects, and requires a 'multi-scale', 'multi-physics' analysis to identify a global optimum solution. The analyses are typically undertaken in parallel using specialised software packages and the results are compared on the basis of their effect on the design. Sensitivity analyses are conducted on each relevant parameter in order to identify the factors that drive the design.

The scientific foundations for the engineering analysis of complex geometry envelopes are mostly grounded in the finite element, finite volume or finite difference methods, for both structural and environmental design. This approach is implemented in a range of digital tools which allows complex shapes or components to be discretised and analysed. Finite element digital analysis looks primarily at the equilibrium of forces in structural analysis and the flow of energy in environmental analysis and analysis of HVAC (heating, ventilation, and air conditioning). These are investigated through 3D models in both wireframe and surface format, as a method of capturing the geometry of the building form or components. From these models, meshes are generated in order to interface with finite element software platforms. Numerical accuracy in finite element analysis is linked to mesh density and mesh density is linked to computational time. The objective of numerical analysis at the early design stages is to understand behaviour through a simplified but thorough approach. This ensures that robust design concepts are generated which do not depend on a very high level of accuracy of analytical models, which is not achievable within limited project time-scales.

For facade envelopes that integrate structure and skin, optimisation is mainly achieved by reducing the time required for installation on-site, rather than specifically reducing the weight of each assembly. This aim is achieved typically by reducing the complexity of the assembly and the number of components, which attracts a longer installation time and higher costs associated with more time on site. This approach requires a higher level of design input than would be expected for a less ambitious facade design, in order to develop components which are multi-functional rather than having a single function in a facade assembly. The optimisation for weight reduction of each assembly, undertaken in isolation, is of secondary importance in the process of optimisation.

Finite element methods are well-established but, being dependent on the computational power available, have only recently been fully integrated within powerful analytical tools. This has allowed analysis to become a tool for exploring behaviour rather than simply a tool for the numerical quantification of a given design. Numerical analysis during the early stages of the design of facades of complex geometry should be robust

and ensure that the design is functional across a sufficiently wide range of input values. Finite element tools are primarily used to assess behaviour and establish which components can be analysed independently and which cannot be dissociated and must therefore be analysed together. The first iterations of analysis aim at establishing relationships between individual components as well as the magnitude of combined effects.

Finite element analysis (FEA) is based on static equations that resolve the equilibrium of forces, fluxes of fluids or energy in 1D, 2D or 3D. The basic implementation of these equations makes use of the mathematical balance present in an equilibrium steady–state condition. Differential equations are required when analysis is time–dependent and quantities vary over time. The use of FE tools represents an inherent mathematical approximation, which implies a trade–off between accuracy and time in any given analysis. The objective of the analysis is to identify a set of calculation models which are representative of real world behaviour to a sufficient degree of accuracy. The different level of resolution of each design parameter, particularly during early design stages, inherently limits the accuracy of the analysis. Considerations of constructability, construction tolerances and material safety factors are equally important in establishing a design concept. Seen in isolation, the analysis results are not sufficient to ensure the robustness of a design concept. The compatibility between the degree of geometric approximation, the accuracy of input values and the specific use of the analysis outputs, sets the level of accuracy required for numerical analysis. Hand calculations are performed on simpler models in order to set order–of–magnitude values which typically include lower and upper boundaries for the analysis.

A comparison of strategies of analysis is an essential basis of early stage facade design. Comparison between two results is only meaningful if the two terms show the same the level of accuracy. During the concept design stage, a broad range of studies is undertaken and the implications of the design concept for each set of results are assessed against one other. Requirements for design are prioritised on this basis and are directed towards 'convergence' as a single design concept. The prioritisation of requirements is an exercise of judgment by the designer, a judgment which is reviewed in the light of associated costs of fabrication and installation.

A basic implementation of the finite element method is in computational fluid dynamic (CFD) software and structural analysis software packages. CFD is used primarily to explore global behaviour of external and internal flow, in order to understand key relationships between 'parts' and 'quantities' (e.g. between temperature and velocity distributions). CFD is also used to design specific 'parts' of an assembly in order to enhance its global behaviour (modify a diffuser design or external louvres to facilitate air flow). This use of finite element tools during concept design suits 'agile' thinking as applied to project management: the relationship between components may change as a result of decisions made by the customer, resulting in a high level of adaptability required in the process of design. Consequently, the tools must be in place to allow for quick analysis iterations, and the design should be sufficiently robust to have an adequate degree of interdependency between individual components. This allows changes by the customer to be absorbed in the design without impacting the whole concept.

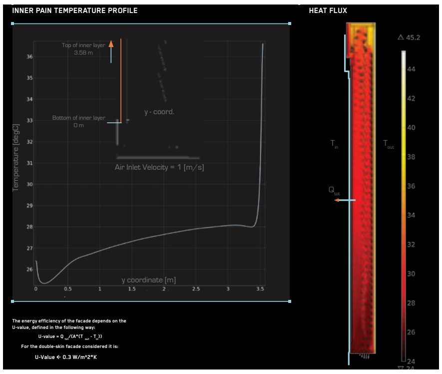
The aim of the design method used in the case studies of this book is to reach a level of 80% cost certainty for the facades and their resolution at the interface with structure and MEP design by the end of the schematic design stage; a level of certainty which would be expected for facade designs that use current technologies rather than the emerging technologies used in innovative facade designs. This approach requires robust design concepts to be in place which integrate the requirements of structural stability, energy consumption and thermal comfort. These concepts inform directly the architectural design; they do not provide only numerical validation. At the concept design stage, a matrix of design recommendations is provided for the customer. This matrix allows different configurations of structure, facade and environmental control system to be assessed against each other. The matrix is used as a decision–making tool to establish the strategies to be developed in the following schematic design stage.

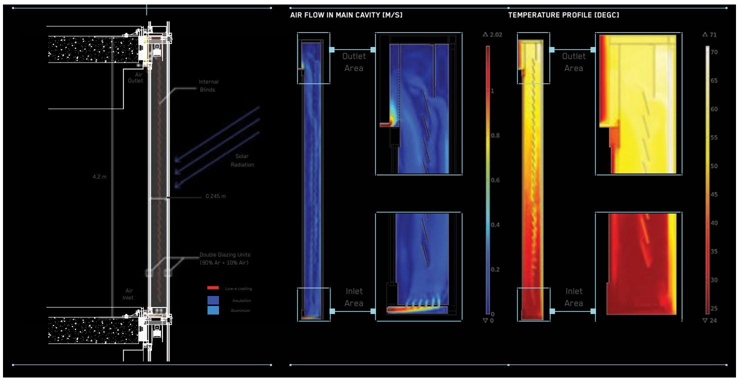
Method for structural analysis of complex facades

The method described here is for the design of structures for facades of complex geometry, which typically follow the structural primitive of a shell. These structural forms typically create large scale enclosures around a more standardised internal structure, made from reinforced concrete or steel, whose purpose is to support floor slabs. The internal structure typically follows the structural primitive of a braced frame or a load–bearing box. The analysis of braced frames and load–bearing boxes is well understood and progresses from the structural design of a typical bay that establishes preliminary sizing, to a final global structural model that allows member sizes to be adjusted and which can account for global static or dynamic effects. The relationship between the internal structure and the external enclosure can vary, primarily as follows:

- The two structures are completely independent, or
- The external enclosure is partially restrained or propped at intermediate locations against the internal structure which requires a high level of coordination between the two, and usually implies a combined analytical/numerical model of the two structures, or
- The external enclosure supports directly the internal structure: the two structures are effectively one and must be considered together.

The first step in the design of a complex geometry structure is to establish a strategy that responds to the architectural programme. The strategy is subsequently deployed across different parts of the building





and is the starting point for the generation of structural concepts. The behaviour of each part of the facade, or building, structure is controlled by a distinct structural primitive. Each structural primitive is combined with the general strategy for the envelope that responds to the architectural programme, in order for a structural concept to be generated. A structural concept for a facade of complex geometry addresses the following primary aspects:

- Structural stability at global and local building scale.
- Robustness of the design proposed.
- Integration of primary, secondary and facade structure.

The structural design of a complex geometry structure follows a process of 'differentiation' and 'integration': all components (connections, constitutive components, modules, etc.) are designed and analysed in isolation but are ultimately assessed in their global behaviour by establishing the load path through the structural elements. For complex geometry structures the 'integration' usually reveals the final structural behaviour, which is driven by the overall geometry. The step of differentiation is nonetheless required in order to integrate the technology required at the level of an assembly.

The general strategy established at the outset of the design is driven by the technology of the proposed facade assembly. To this aim, current and emerging technologies are assessed to establish the strategy for the envelope by examining existing built precedents. These precedents are used to demonstrate the suitability of the technology proposed in relation to either a specific building type, or the project location, climate, etc. During 'differentiation', each assembly is examined independently through simplified calculation models, which range from hand calculations to a finite element assessment of a typical structural bay, whose size is representative of local effects. This is aimed at assessing the robustness of the assembly and its local stability. During 'integration', the structural concept for the load–bearing envelope is analysed through a global finite element model. This is aimed at assessing global stability and support reactions. The stiffness of the building is assessed primarily by estimating natural frequencies and global displacements. Stiffness is typically the driving parameter for the structural design of large–scale enclosures for facades of complex geometry. Global displacements are required to be linked back to local effects in order to obtain preliminary estimates of movement that will have to be accommodated within envelope assemblies, whilst still ensuring weather tightness. The interaction of the structure with the surrounding structures is investigated through support reactions, which are the basis of establishing load paths. The global model allows to assess areas of stress concentrations in order to establish strategies to redistribute internal forces and stresses.

'Integration' and 'differentiation' are developed through iterative loops, where strategies for the technology of the assembly are tested by examining their impact on a global finite element model. This approach captures the geometry–driven behaviour of the envelope. Typically, the behaviour of large steel enclosures is expected to be driven by its global displacements at serviceability. Large concrete shells are likely to be driven by maximum stresses at ultimate limit states. Analytical/numerical models are simplified in order to represent the essence of the object analysed. This is valid from small–scale components to large–scale structures. This ensures that analytical models are robust and do not produce misleading results, in which potential analytical errors are of the same order of magnitude of the results.

Following this design approach, the envelope fabric is optimised in terms of structural stiffness and strengths to match the performance required by the geometry at different locations. The structural optimisation is done through digital analysis, where the global effect of changing the stiffness of one part of the envelope is examined in real time. In this way the assembly is conceived as a flexible set of sub–assemblies and components, so that a single facade system can be used across the project to match the performance required by the envelope geometry. This approach is driven by a thorough understanding of current and emerging technologies used for facades of complex geometry, which inform both materials and assemblies. Assembly technologies are brought into the design process when establishing the general strategy for the load–bearing envelope. The approach in designing complex geometry structures is assembly–driven.

Method for MEP/environmental analysis of complex facades

The approach used to analyse the case studies in this book is based on establishing a balanced set of environmental performance criteria. A commonly used approach sets environmental criteria based on 'best practice'. However, this approach, where each criterion is derived independently, does not allow for an assessment of combined effects, nor for any subsequent optimisation.

The objective of this design method is to produce a balanced set of studies that are coordinated and that document a robust design concept by demonstrating a global understanding of all the implications when choosing a given environmental strategy. This method aims at gaining a basic understanding of the order of magnitude of all the environmental phenomena and their relative importance in the design within a very short time–frame. It departs from a more typical approach where one specific aspect of the design is optimised on the basis of an intuitive 'fit' with the proposed architectural concept. Environmental design covers a wide range of variables. Embedding interdependency between variables is necessary to ensure design robustness, which is achieved by establishing an equilibrium between all the design criteria rather than allowing one criterion to dominate.

The case studies shown in this book have been examined primarily by looking at eight aspects of environmental design (listed below) which affect the performance of both the external and internal environment. Each aspect of an environmental design can be divided into three essential components:

- Natural phenomena. The natural phenomena linked to the specific project climate.
- Analysis type. The effect of natural phenomena can be assessed by means of digital tools and hand calculations, which evaluate specific quantities.
- Design solution. The objective of the analysis is the selection of an assembly or material technology. Different design solutions are able to meet the same performance requirements.

These three categories can be divided further into the following primary categories of environmental study:

Natural phenomena

1. Thermal transmission and condensation.
2. Solar gain.
3. Daylighting.
4. Movement of air inside and outside the building.
5. Heating and cooling loads in relation to external heat gains.
6. Acoustic transmission.
7. Rainwater evacuation.
8. Material design life/fire resistance/corrosion resistance.

Analysis type

1. U-value calculation and calculation of condensation risk internally/interstitially/externally.
2. Calculation of peak solar gain across the year. Calculation of peak radiation, annual cumulative and solar exposure across the year.
3. Calculation of daylight levels (lux) and risk of glare across the year.
4. For the main wind directions, external CFD for cladding pressures (wind speed from codes for structural design) and pedestrian comfort (wind speed from wind rose for a typical year).
5. Estimation of each thermal load (solar gain/losses, conduction gain/losses, internal gain/losses, ventilation gains/losses). Environmental performance simulation tools (e.g. IES-VE) can be utilised for final assessment of the interaction of the thermal loads for the entire building across the whole year.
6. Sound attenuation index calculation for each assembly, by using digital analysis where each material and component can be modelled to assess the overall assembly performance.
7. Water flow digital analysis tracking the direction of water under gravity on curved surfaces. Preliminary 3D drainage layout including gutters and outlets. Preliminary gutter sizing.
8. Material research and selection. Proof-of-concept fire testing if required.

Design solution

1. Selection of insulation material, thickness and position of waterproofing. Design of framing and interfaces to meet requirements on linear thermal bridges.
2. Selection of glass type and external shading strategy in order to meet level of solar control required for peak solar gain.
3. Selection of glass light transmission levels and internal shading strategy to meet internal daylight levels for internal visual comfort.
4. Preliminary cladding pressures for structural and facade design. Velocities around the building at pedestrian level for main wind directions. Internal velocities and temperature profiles for thermal comfort assessment.
5. Breakdown of component values of cooling/heating loads in order to assess the relative importance of each component. Establish environmental zones. Duct and AHU layout and sizes.
6. Amount of acoustic mass required from each assembly to provide the required sound attenuation, establish how mass is distributed across the assembly and which layers provide sound attenuation.
7. Design of drainage system (selection between gravity or siphonic types). Sizing and integration of drainage within facade build-up.
8. Material selection. Material specification. Testing specification.

The undertaking of environmental analysis in a facade design project is essential in order to establish a close relationship between envelope performance and requirements of mechanical ventilation (HVAC). The envelope performance regulates the main thermal gains or losses which require heating or cooling: solar, conduction and ventilation. The following design process is aimed at linking the two together:

a. Thermal loads assessment for a typical bay. Before undertaking any environmental analysis, a basic understanding of HVAC requirements is obtained by means of an estimation of thermal loads for each representative typical bay of the building. This initial assessment uses benchmark values which are based on best practice.
b. Preliminary duct sizes for a typical bay. The thermal loads computed for a typical bay are used to estimate the amount of air and the duct sizes required. As ventilation ducts typically occupy a significant volume of space within a building, this estimate allows zones for both facade and ceiling to be established.
c. Preliminary assessment of global loads. The global loads for the whole building are assessed by scaling-up the loads obtained from the representative typical bays proportionally to surface area.
d. Preliminary estimate of number of air handling units (AHUs). By using the global loads, the amount of air to be provided can be estimated, together with the required number, capacity and size of the AHUs, incorporating the required level of redundancy/back-up.
e. Specialist environmental studies. These studies are aimed at understanding the implications on user comfort of varying envelope performance parameters in relation to HVAC requirements.
f. Final environmental/envelope/HVAC strategy. This is based on a matrix of recommendations where different design solutions are combined to form options. The matrix is used as a decision-making tool.
g. Refinement of calculations. Calculations are refined for thermal loads, energy consumption costs for the building, for determining both the sizes of AHUs and the sizes of ducts for air supply and return.

Current design methodology

The outputs generated through analysis and design require a method of design implementation in order to be transformed into a set of instructions, which is how the design is delivered for construction. Following the current approach in building construction, the building envelope design is delivered through a set of drawings, which represent the design intent, and a performance specification, which contains the performance requirements for the facade systems illustrated in the drawing set. These two outputs can be disengaged from one other.

The use of performance specifications originally comes from other industries where the project requirements are set out at the outset of the project, with limited change expected during the design process. In building construction, this approach assumes that contractors will complete all the detailing of systems and interfaces using the tender drawings as a visual guideline, in order to optimise for cost and ease of construction. The building engineer will check tender returns from bidding contractors based on compliance with what was issued at tender. Since aspects of the design are not described in the tender documentation, the contractor is allowed to propose design changes on the basis of their technical appropriateness. Different tender returns are compared on the basis of their 'quality'. After tender, the engineer is involved primarily in the assessment of visual benchmark mock–ups as well as maintaining a limited involvement during fabrication and construction phases. The role of the 'site inspection' for a building designer is usually limited to checking the visual quality of the construction only.

Project specific research allows the facade engineer to gather all the necessary information to ensure the design can be implemented. Research for most facade design projects is focused on project–specific procedures, mainly in order to unlock approvals and avoid delays in the programme. This approach is structured through a Gantt chart that sets out a series of sequential steps. The research is aimed specifically at understanding the full implications of building regulations, local standards and approval procedures. Research into design topics is limited to the understanding of all the technical requirements for the project. Regarding facade assemblies, the approach is based on obtaining, from specialist contractors, specific information about their products which is understood to be common to all competing manufacturers. This information is added to the performance specification as a way of determining a set of 'benchmark' criteria for assessment at the time of competitive tender. This usually leads to products or specific contractors mentioned in the specification, with the mention of 'or equivalent', in order to define that benchmark.

Limitations of current methodology

The limitations of the current method are that the performance specification does not capture how the various parts of the design are coordinated across the various disciplines. Consequently, there is no method to ensure that all design requirements are both compatible and coordinated. In the drawings, the specific method of assembly is not described. The drawings are organised as a hierarchy of general arrangement drawings, general assembly drawings and typical details, which describe only general design requirements at different scales. These do not engage with interfaces and illustrate only representative parts of the envelope. Similar to specifications, drawings do not validate coordination and compatibility between envelope systems or between different trades. Often, this specific information is thought to be unnecessary, as contractors are considered to possess the required experience in implementing well–known solutions. This approach suits projects where known solutions are implemented and is based on the fact that embedding coordination in the design documentation would increase cost as it would mean being overly prescriptive for certain parts of the design.

With the current approach there is no real mechanism to compare specific parts of the design with alternative proposals, made by contractors, which are not described in the tender package. For these parts, the assessment is limited to a visual comparison with the design intent. The technical aspect of the design does not need to be scrutinised, as the final engineering design is the contractor's responsibility in most construction contracts.

In this context, any project specific research is aimed at defining the scope of the design problem and limiting the opportunities for competing contractors to provide alternatives which do not meet the agreed design criteria. The process is one of collating technical information which is readily available and which is deemed to be relevant to 'define' the requirements of a design solution rather than provide a specific solution to these requirements. The lack of the availability of a specific solution can lead to unexpected consequences for the design if no specific alternatives are available.

Newtecnic's methodology

When the consequences of the proposed design are required to be fully understood at an early stage of project development, the emphasis turns to achieving a high level of design resolution. Early stage design documentation allows costs to be obtained from contractors as the design progresses. In the following design phases that lead to tender, value is added to the design process by undertaking detailed analysis of specific design aspects. The following additional outputs are provided at tender for design implementation: