

WOODHEAD PUBLISHING SERIES IN CIVIL AND STRUCTURAL ENGINEERING



RETHINKING BUILDING SKINS

TRANSFORMATIVE TECHNOLOGIES AND RESEARCH TRAJECTORIES



Edited by
EUGENIA GASPARRI, ARIANNA BRAMBILLA,
GABRIELE LOBACCARO, FRANCESCO GOIA
ANNALISA ANDALORO, ALBERTO SANGIORGIO



Documents
Document Storage Hub

Rethinking Building Skins

This page intentionally left blank

Woodhead Publishing Series in Civil and
Structural Engineering

Rethinking Building Skins

Transformative Technologies and
Research Trajectories

Edited by

Eugenia Gasparri

Arianna Brambilla

Gabriele Lobaccaro

Francesco Goia

Annalisa Andaloro

Alberto Sangiorgio



WP
WOODHEAD
PUBLISHING
An imprint of Elsevier



Documents
Document Sharing Hub

Woodhead Publishing is an imprint of Elsevier
The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, OX5 1GB, United Kingdom

Copyright © 2022 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-822477-9 (print)

ISBN: 978-0-12-822491-5 (online)

For information on all Woodhead Publishing publications
visit our website at <https://www.elsevier.com/books-and-journals>

Publisher: Matthew Deans

Acquisitions Editor: Glyn Jones

Editorial Project Manager: Rachel Pomery

Production Project Manager: Anitha Sivaraj

Cover Designer: Matthew Limbert

Typeset by MPS Limited, Chennai, India



AA **Documents**
Document Sharing Hub

Contents

List of contributors	ix
Foreword	xv
Preface	xvii
Acknowledgements	xxi
1 Façade innovation: between ‘product’ and ‘process’	1
<i>Eugenia Gasparri, Arianna Brambilla, Gabriele Lobaccaro, Francesco Goia, Annalisa Andaloro and Alberto Sangiorgio</i>	
2 Façade innovation: an industry perspective	15
<i>Alberto Sangiorgio</i>	
Part A Product Innovation	59
3 Urban overheating mitigation through facades: the role of new and innovative cool coatings	61
<i>Mattia Manni, Ioannis Kousis, Gabriele Lobaccaro, Francesco Fiorito, Alessandro Cannavale and Mattheos Santamouris</i>	
4 The pursuit of transparency	89
<i>Lisa Rammig</i>	
5 Advanced fenestration—technologies, performance and building integration	117
<i>Fabio Favoino, Roel C.G.M. Loonen, Michalis Michael, Giuseppe De Michele and Stefano Avesani</i>	
6 Embedding intelligence to control adaptive building envelopes	155
<i>Fabio Favoino, Manuela Baracani, Luigi Giovannini, Giovanni Gennaro and Francesco Goia</i>	
7 Biomimetic adaptive building skins: design and performance	181
<i>Aysu Kuru, Philip Oldfield, Stephen Bonser and Francesco Fiorito</i>	

8	Building integrated photovoltaic facades: challenges, opportunities and innovations	201
	<i>Francesco Frontini, Pierluigi Bonomo, David Moser and Laura Maturi</i>	
9	Unitized Timber Envelopes: the future generation of sustainable, high-performance, industrialized facades for construction decarbonization	231
	<i>Eugenia Gasparri</i>	
10	Industrialized renovation of the building envelope: realizing the potential to decarbonize the European building stock	257
	<i>Thaleia Konstantinou and Charlotte Heesbeen</i>	
11	Vertical farming on facades: transforming building skins for urban food security	285
	<i>Abel Tablada and Vesna Kosorić</i>	
12	Interactive media facades—research prototypes, application areas and future directions	313
	<i>Martin Tomitsch</i>	
Part B	Process Innovation	339
13	The building envelope: failing to understand complexity in tall building design	341
	<i>José L. Torero</i>	
14	Resilience by design: building facades for tomorrow	359
	<i>Mic Patterson</i>	
15	Inverse design for advanced building envelope materials, systems and operation	377
	<i>Roel C.G.M. Loonen, Samuel de Vries and Francesco Goia</i>	
16	Towards automated design: knowledge-based engineering in facades	403
	<i>Jacopo Montali, Michele Sauchelli and Mauro Overend</i>	
17	Additive manufacturing in skin systems: trends and future perspectives	425
	<i>Roberto Naboni and Nebojša Jakica</i>	
18	Mass customization as the convergent vision for the digital transformation of the manufacturing and the building industry	453
	<i>Gabriele Pasetti Monizza and Domink T. Matt</i>	

19	Automation and robotic technologies in the construction context: research experiences in prefabricated façade modules	475
	<i>Kepa Iturralde, Wen Pan, Thomas Linner and Thomas Bock</i>	
20	Life cycle assessment in façade design	495
	<i>Linda Hildebrand, Kim Tran, Ina Zirwes and Alina Kretschmer</i>	
21	Circular economy in facades	519
	<i>Mikkel K. Kragh and Nebojša Jakica</i>	
22	Facades-as-a-Service: a business and supply-chain model for the implementation of a circular façade economy	541
	<i>Juan F. Azcarate-Aguerre, Annalisa Andalaro and Tillmann Klein</i>	
	Afterword by Ulrich Knaack	559
	Index	561

This page intentionally left blank

List of contributors

Ajla Aksamija Department of Architecture, University of Massachusetts Amherst, Amherst, United States

Annalisa Andaloro Energy Efficient Buildings Group, Institute for Renewable Energy, Eurac Research, Bolzano, Italy

Stefano Avesani Energy Efficient Buildings Group, Institute for Renewable Energy, Eurac Research, Bolzano, Italy

Juan F. Azcarate-Aguerre Department of Architectural Engineering+Technology, Chair Building Product Innovation, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

Manuela Baracani Department of Energy, Polytechnic University of Turin, Torino, Italy

Thomas Bock Chair of Building Realization and Robotics, Technical University of Munich, Munich, Germany

Pierluigi Bonomo University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Manno, Switzerland

Stephen Bonser School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, Australia

Keith Boswell Skidmore, Owings & Merrill LLP, San Francisco, CA, United States

Arianna Brambilla School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia

Alessandro Cannavale Polytechnic University of Bari, Bari, Italy

Andrew Cortese Grimshaw Architects, Sydney, NSW, Australia

Giuseppe De Michele Energy Efficient Buildings Group, Institute for Renewable Energy, Eurac Research, Bolzano, Italy

Samuel de Vries Department of the Built Environment, Eindhoven University of Technology, TU/e, Eindhoven, The Netherlands

John Downes Lendlease, London, United Kingdom

Fabio Favoino Department of Energy, Polytechnic University of Turin, Torino, Italy

Francesco Fiorito School of Built Environment, University of New South Wales, Sydney, NSW, Australia; Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Bari, Italy

Francesco Frontini University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Manno, Switzerland

Eugenia Gasparri School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia

Giovanni Gennaro Department of Energy, Polytechnic University of Turin, Torino, Italy

Luigi Giovannini Department of Energy, Polytechnic University of Turin, Torino, Italy

Francesco Goia Department of Architecture and Technology, NTNU Norwegian University of Science and Technology, Trondheim, Norway

Charlotte Heesbeen Department of Architectural Engineering+Technology, Chair Building Product Innovation, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

Linda Hildebrand Chair for Reuse in Architecture, Faculty of Architecture, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, Aachen, Germany

Kepa Iturralde Chair of Building Realization and Robotics, Technical University of Munich, Munich, Germany

Nebojša Jakica Department of Technology and Innovation, University of Southern Denmark (SDU), Odense, Denmark; Section for Civil and Architectural Engineering, University of Southern Denmark (SDU), Odense, Denmark; FACETS lab, Odense, Denmark

Tillmann Klein Department of Architectural Engineering+Technology, Chair Building Product Innovation, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

Ulrich Knaack Institute of Structural Mechanics and Design, Chair of Façade Structures, Department of Civil and Environmental Engineering, Technical University of Darmstadt, Darmstadt, Germany; Department of Architectural Engineering+Technology, Chair Design of Construction, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

Thaleia Konstantinou Department of Architectural Engineering+Technology, Chair Building Product Innovation, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

Vesna Kosorić Balkan Energy AG, Starrkirch-Wil, Switzerland; Daniel Hammer Architekt FH AG, Olten, Switzerland

Ioannis Kousis Department of Engineering, CIRIAF—Interuniversity Research Center on Pollution and Environment ‘Mauro Felli’, University of Perugia, Perugia, Italy

Mikkel K. Kragh Department of Civil and Architectural Engineering, Aarhus University, Aarhus, Denmark

Alina Kretschmer Chair for Reuse in Architecture, Faculty of Architecture, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, Aachen, Germany

Aysu Kuru School of Built Environment, University of New South Wales, Sydney, NSW, Australia; School of Architecture, Design and Planning, University of Sydney, Sydney, NSW, Australia

Thomas Linner Chair of Building Realization and Robotics, Technical University of Munich, Munich, Germany

Gabriele Lobaccaro Department of Civil and Environmental Engineering, Faculty of Engineering, NTNU Norwegian University of Science and Technology, Trondheim, Norway

Roel C.G.M. Loonen Department of the Built Environment, Eindhoven University of Technology, TU/e, Eindhoven, The Netherlands

Mattia Manni Department of Engineering, CIRIAF—Interuniversity Research Center on Pollution and Environment ‘Mauro Felli’, University of Perugia, Perugia, Italy

Domink T. Matt Faculty of Science and Technology, Free University of Bozen-Bolzano, Bolzano, Italy

Laura Maturi Energy Efficient Buildings Group, Institute for Renewable Energy, Eurac Research, Bolzano, Italy

Michalis Michael Engineering Department, Glass and Façade Technology Research Group, University of Cambridge, Cambridge, United Kingdom

Jacopo Montali Algorixon Srl, Parma, Italy

David Moser Energy Efficient Buildings Group, Institute for Renewable Energy, Eurac Research, Bolzano, Italy

Roberto Naboni CREATE, Odense, Denmark; Section for Civil and Architectural Engineering, University of Southern Denmark (SDU), Odense, Denmark

Philip Oldfield School of Built Environment, University of New South Wales, Sydney, NSW, Australia

Mauro Overend Department of Architectural Engineering+Technology, Chair of Structural Design & Mechanics, Delft University of Technology, Delft, The Netherlands

Wen Pan Chair of Building Realization and Robotics, Technical University of Munich, Munich, Germany

Gabriele Pasetti Monizza Process Engineering in Constructions, Fraunhofer Italia Research, Bolzano, Italy

Saverio Pasetto Skanska, London, United Kingdom

Mic Patterson Façade Tectonics Institute, Newington, CT, United States; University of Southern California, Los Angeles, CA, United States

Sophie Pennetier Enclos, Los Angeles, CA, United States

Lisa Rammig Eckersley O'Callaghan, Los Angeles, CA, United States; Delft University of Technology, Delft, The Netherlands

Kieran Rice Aecom, Melbourne, VIC, Australia

Damian Rogan Eckersley O'Callaghan, London, United Kingdom

Davina Rooney Green Building Council of Australia, Sydney, NSW, Australia

Alberto Sangiorgio Grimshaw Architects, Sydney, NSW, Australia

Mattheos Santamouris School of Built Environment, University of New South Wales, Sydney, NSW, Australia

Michele Sauchelli WSP UK Ltd, London, United Kingdom

Haico Schepers ARUP, Sydney, NSW, Australia

Dominic Shillington Laing O'Rourke, Sydney, NSW, Australia

Abel Tablada Faculty of Architecture, Technological University of Havana J.A. Echeverría, Havana, Cuba

Martin Tomitsch School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia; Central Academy of Fine Arts, Beijing Visual Art Innovation Institute, Beijing, P.R. China

José L. Torero Civil, Environmental and Geomatic Engineering, University College London, London, United Kingdom

Kim Tran Chair for Reuse in Architecture, Faculty of Architecture, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, Aachen, Germany

Ina Zirwes Chair for Reuse in Architecture, Faculty of Architecture, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, Aachen, Germany

Marc Zobec Permasteelisa, Sydney, NSW, Australia

This page intentionally left blank

Foreword

Building skin is one of the most significant contributors to the energy budget and the comfort parameters of any building. As energy and other natural resources continue to be depleted, it has become clear that technologies and strategies that allow us to maintain our satisfaction with interior environment while consuming fewer of these resources are major objectives for the contemporary facade designs. Moreover, life cycle considerations for facade design, engineering, production, installation, maintenance and disassembly are integral for the future of building skins. Therefore systematic and integrated approach for design, engineering, construction and operation is essential, and collaboration between different stakeholders is paramount for this endeavor.

Building facades perform two primary functions: first, they are the barriers that separate a building's interior from the external environment; second, more than any other component, they create the image of the building. High-performance facades can be defined as exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and well-being of buildings' occupants. This means that high-performing facades are not simply barriers between interior and exterior; rather, they are building systems that create comfortable spaces by actively responding to the building's external environment and significantly reduce buildings' energy consumption. In high-performance facade design, it is crucial to consider climate and environmental factors, materials, components, building function, methods for improving occupants' comfort, fabrication, construction, impacts on other building systems, operation, and ultimately deconstruction and/or refurbishment. Therefore emerging building technologies, systems, tools and production methods are essential in our quest to improve building skin performance and consequently performance of buildings and the built environment.

This book presents strategies, technologies and research trajectories associated with contemporary building facades. The primary goal of the book is to discuss trends that can transform facade industry, including design, engineering, fabrication, construction, operation, maintenance and end-of-life considerations. The book is organized into introductory section that outlines the role of building facades in the built environment and current challenges, followed by an overview of state-of-the-art technologies and methods. Then, two major parts present different global perspectives on product innovation (Part A) and process innovation (Part B). Product innovation refers to new materials, technologies and systems, new concepts and forms, and new needs and performance requirements. Process innovation considers

new design methods, fabrication and construction techniques, and operational modes.

Chapters in *Part A: Product Innovation* discuss relationships between facades and urban design, coatings and transparency, advanced fenestration systems, adaptive facades and intelligent systems, biomimicry and building skin design, energy-producing facades, modular timber envelopes, retrofitting strategies for existing buildings, vegetated systems and interactive media facades.

Chapters in *Part B: Process Innovation* present complexities in tall building facade design, resiliency, inverse design methods, automated design and knowledge-based engineering, additive manufacturing, mass customization and digital transformations, robotic technologies for prefabrication, life cycle assessments and circular economy as it relates to building skin and supply-chain model.

The remarkable aspect of this book is that it provides different viewpoints and perspectives from faculty members, researchers and industry professionals around the world. It sets the course of action for transforming the design, engineering and construction of facade systems. Innovation requires intense research and development, and the current challenges facing our industry can only be solved by dedicated research, technological developments and solutions that improve the performance of building skin and ultimately our buildings and the built environment. Strategies and methods that are presented in this work can certainly help us in our quest to create better performing, environmentally sensitive enclosures of the future.

I hope that you will enjoy reading this important book and that you will find inspiration for further innovations in facade systems. Ultimately, we are designing our buildings for people – to be inhabited, used for learning, working and all other aspects of our lives. Future innovative building skins can create beautiful, well-performing, inspirational buildings that improve our environment and our well-being and perhaps even impact our happiness. Perhaps in the future, we might start measuring our buildings according to the level of happiness that they provide to their occupants – until then, let us focus on improving their performance through innovative design, production and collaboration.

Ajla Aksamija

*Department of Architecture, University of Massachusetts Amherst,
Amherst, United States*

Preface

The world we live in today is facing unprecedented challenges which are shaking our society and communities at their core. The health and economic crises caused by the global pandemic together with the incremental demand for climate action have been urging many industries to reconsider the way they operate and function towards more sustainable models, efficient approaches and equitable and safe practices.

Building construction is the largest industry in the global economy and one of the great accomplishments and incremental sustained innovation. Over the last few decades, building construction has been significantly underperforming showing on average very modest productivity growth. The industry is highly fragmented and risk-averse, which make it less responsive to adaptation and transformational change. It is less digitised than nearly any other industry and historically reliant on manual labour, both factors contributing to amplify its vulnerability to present and future disruptions, such as, for instance, the recent COVID-19 global disruption pandemic. The building construction sector is also responsible for considerable resource depletion and greatly contributes global energy consumption and carbon emissions.

The way buildings are designed, assembled, used and maintained and ultimately disassembled needs to undergo a profound transformation in the very near future. Recognising the complexity of the sector ecosystem is central to promote better practices of knowledge sharing and cross-disciplinary collaboration. Systemic innovation and sectoral digitalisation are key factors in driving the change and reframing the construction paradigm for the industry to meet global sustainability goals towards decarbonisation, keep up with the ever-changing needs of our society and grow prosperously.

Building skins play a pivotal role in architecture. They determine the aesthetic appearance of a building, its relationship with the surrounding context, and they are the interface between the built and human dimensions of our cities. They mediate between the indoor and outdoor environments, largely contributing to the overall building energy performance, and to occupants' comfort and well-being. Ultimately, facades dramatically influence the construction process efficiency and safety of a building, particularly in high-rises that have established a relevant presence in our highly urbanised cities. Therefore façade technologies have enormous potential to drive change in the construction sector and represent a perfect incubator to explore opportunities for transformative innovation.

Rethinking Building Skins: Transformative Technologies and Research Trajectories builds up on these premises by showcasing major research trends in



Documents

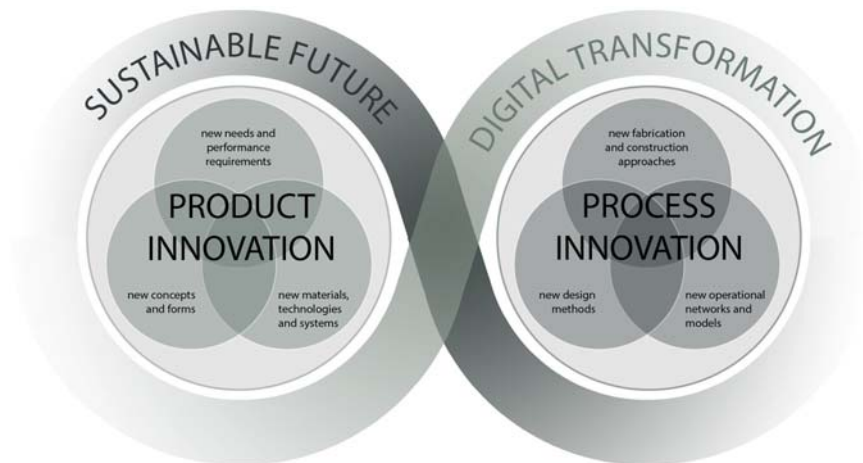
Document Sharing Hub

the field of façade technology throughout its entire life cycle, including design, fabrication, construction, operation and maintenance and, ultimately, end of life. The book opens with the editors' critical analysis on the development of façade technologies through the 'fil-rouge' of innovation, identifying main stepping-stones for advancement over the last century and future trajectories to rethink the facades of tomorrow. The second chapter gives voice to a rich array of highly influential experts from the different sectors of the industry, who share their views on the future of façades and discuss major challenges and opportunities to innovation. The main body of the book presents a compelling and highly diverse collection of the most forward-looking research projects in façade design and applied technologies from top-tier international research groups. The research themes are organised into two main domains, one dealing with *product* innovation and the other with *process* innovation. The dichotomous structure is deemed functional to the narrative, but the two proposed domains are not to be intended as separate entities, rather as bodies of knowledge meant to inform and complement one another.

Part A: Product Innovation focuses on the interpretation of façade as a tangible asset, providing an overview of the most advanced products, components, technologies and systems, being them close to market or experimental rising star innovations.

Part B: Process Innovation focuses on the façade project life cycle and value-chain development, providing insights into different phases of a project and showcasing novel cross-industry approaches to current and perspective challenges in the façade world.

The look at innovation within each domain is bifocal. It includes studies which thoughtfully address current challenges to guarantee a more sustainable, resilient, and environmentally conscious future, as well as studies exploring new opportunities brought about by the digital era to achieve a more efficient, transparent, collaborative and connected future.



The book is not a theoretical or technical manual nor a specialist guide for the practice. It rather aims to be a platform for innovation, creating a fertile ground for a multilevel, multidisciplinary discussion and contributing to the definition of an international research agenda in this sector for the years to come. Our intent is to reach a wide audience, encompassing academics, practitioners and students from different discipline background and expertise, as well as innovation enthusiasts.

To date, this book is unique in its genre. It brings together the expertise, creativity and critical thinking of more than 60 global innovators and leading experts in the field of façades, both from academia and the industry.

We hope this is only the beginning of a participatory discussion on the topic that opens wide the doors of a future where the principles of ‘collaboration’ and ‘knowledge sharing’ are central in catalysing innovation in construction. Let us start ‘Rethinking Building Skins’!

***Eugenia Gasparri, Arianna Brambilla, Gabriele Lobaccaro, Francesco Goia,
Annalisa Andaloro and Alberto Sangiorgio***

This page intentionally left blank

Acknowledgements

We would like to express our gratitude to all authors who contributed with their time, commitment and energy by delivering high-quality chapters on their most forward-looking research works and to the industry experts who have enthusiastically shared their views about future trends in façade innovation.

We also acknowledge those industries and public entities that contributed, either technically or financially, to the development of the research featured in the book's chapters.

A heartfelt thank you to Ajla Akšamija and Ulrich Knaack who have endorsed the value and relevance of this book, respectively, through their foreword and afterword.

***Eugenia Gasparri, Arianna Brambilla, Gabriele Lobaccaro, Francesco Goia,
Annalisa Andaloro and Alberto Sangiorgio***

This page intentionally left blank

Façade innovation: between 'product' and 'process'

1

Eugenia Gasparri¹, Arianna Brambilla¹, Gabriele Lobaccaro²,
Francesco Goia³, Annalisa Andoloro⁴ and Alberto Sangiorgio⁵

¹School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia, ²Department of Civil and Environmental Engineering, Faculty of Engineering, NTNU Norwegian University of Science and Technology, Trondheim, Norway,

³Department of Architecture and Technology, NTNU Norwegian University of Science and Technology, Trondheim, Norway, ⁴Energy Efficient Buildings Group, Institute for Renewable Energy, EURAC Research, Bolzano, Italy, ⁵Grimshaw Architects, Sydney, NSW, Australia

Abbreviations

AEC	Architecture, Engineering and Construction
AR	augmented reality
BIPV	Building Integrated Photovoltaics
BIST	Building Integrated Solar Thermal
GDP	Gross domestic product
LCA	life-cycle approach
LCC	Life-cycle cost
OLEDs	Organic Light Emitting Diodes
R&D	Research and Development
RES	Renewable Energy Sources
SME	Small and Medium Enterprises
VR	virtual reality

1.1 Introduction

Building construction is the largest industry in the global economy, accounting for 13% of the world's gross domestic product and employing around 7% of the global workforce. However, its annual productivity has only increased by 1% on average over the last 20 years, highlighting a sectoral resistance to change and adaptation (Barbosa et al., 2017).

Innovation in construction has been a highly debated topic for decades. However, nowadays more than ever, it is becoming pivotal worldwide as current social and environmental challenges request rapid and far-reaching measures. Pressing concerns around climate change and resource depletion have put the building construction sector under the spotlight, as responsible for more than 35% of global energy consumption, nearly 40% of global carbon emissions, as well as

ranking amongst the most wasteful industries (IEA, 2019). The magnitude of the problem is further exacerbated by the steep growth of global population, expected to increase by over 2 billion in the next 30 years, together with the fast-paced urbanization that contributes to further congest our densely populated cities (United Nations, 2019). Finally, the present COVID-19 pandemic has been shaking the world population and is forcing to reconsider the way people live and ‘inhabit’ spaces, toward more sustainable, equitable and safer built environments.

These unprecedented and multifaceted challenges come at a time where advances in digital technologies are opening up a whole new world of possibilities toward automation of manufacturing and industrial processes, the so-called Fourth Industrial Revolution (Industry 4.0). New materials and technologies are rising at the horizon, with the fields of nanotechnologies and robotics gaining momentum. New strategies and models for value creation through circularity have started to be implemented across the market. Global digital trends uptake and cross-sectoral knowledge contamination offer enormous potential to revitalize the construction and building sector, creating favourable conditions for transformational change (Ribeirinho et al., 2020).

In this vibrant panorama, where new vast potentials meet traditional resistance toward change, it becomes natural to question how the façade industry will contribute to shaping the future of the architecture, engineering and construction sector. Indeed, the building envelope, other than the aesthetical, is key to the climate performance, occupant’s health and well-being, construction process efficiency and overall environmental impact. Therefore facades represent the ideal playground to explore innovation in construction and play a pivotal role in scaling up the change.

Building on this premises, this chapter—*Façade Innovation: between ‘product’ and ‘process’*—presents a critical analysis of the façade sector through the ‘fil-rouge’ of innovation. It is organized in two main sections:

- ‘Facades today’ presents an overview of the main technological advancements in the field of facades to date, provides a picture of the façade industry status quo and examines present challenges and barriers to sectoral innovation.
- ‘Facades tomorrow’ discusses new opportunities and drivers for the sector to embrace transformational change and defines main research trajectories and pathways for innovation to rethink the facades of tomorrow.

1.2 Facades today

Facades, as we intend them today, have dramatically changed over the history of building design and construction, acquiring stand-alone prominent architectural roles with respect to the structural part of the building fabric. Over the last century, façade design has become a central and independent technical discipline in the construction industry, attracting the interest of many and initiating a series of new roles in the field where façade experts have different backgrounds and specializations, being them architects or designers, building technologist and engineers and sometimes also modern critics as ‘web-influencers’ (Fig. 1.1). Nowadays, the façade industry is a fully formed, mature sector with dedicated market products.

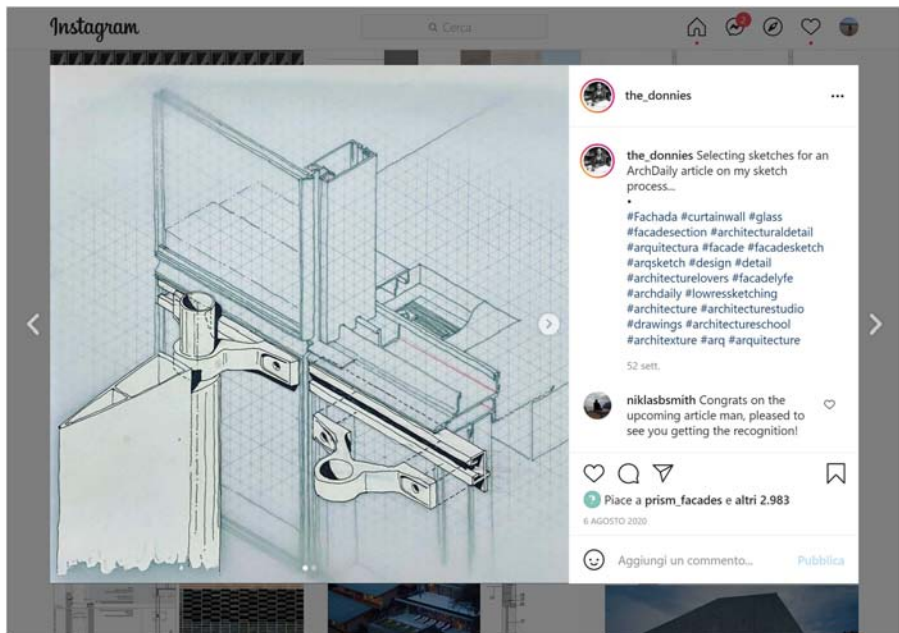


Figure 1.1 Façade sketches from @the_donnies. Credit: Troy Donovan. Troy is Principal at Prism Facades (Sydney, Australia) and has more than 300k followers on Instagram.

technologies and systems as well as an ecosystem of established professionals and entities eager to contribute to sectoral innovation and development.

This evolutionary climax has taken place in a relatively short time frame, thanks to the advancements in material science and production techniques brought about by the industrial revolution. At the same time, the sudden market growth and sector specialization has resulted in an extremely competitive environment, characterized by process scattering and fragmentation that hinder innovation momentum. This section draws upon these considerations in two steps:

- It navigates through major technological advancements occurred during the last centuries that contributed to redefine and transform the façade as a 'product'. It discusses and reflects upon the major drivers to innovation in relationship with their enabling factors.
- It presents the 'process' of façade design and construction today, by identifying the relationship among main actors and activities. It discusses and reflects upon major barriers to innovation and opens the floor to new perspectives and ideas for the sector to prosper and thrive moving forward.

1.2.1 Façade technological advancements: a 'product' innovation narrative

Façade systems classification is today vast and multifaceted and terminology encompasses a wide range of definitions. The juxtaposition between opaque

multilayer and transparent envelopes is acknowledged by the market and is employed within this section for the purpose of the narration. Both groups have been evolving through history pursuing improved energy efficiency and comfort performance, enabled by technical advancements in the field of material science, design and industrialization.

The façade was initially a solid structural wall supporting the roof, optionally equipped with holes for letting air or light in. Made of a single material, product, or product combination, such as stone or bricks and mortar, it provided for structural resistance and shelter. Rain and wind were kept out from apertures by moveable elements, such as windows, doors, or shutters. The need for optimized use of resources brought in a transition from stacked to infill walls, which set the basis for the disassociation of the façade from the sole load-bearing function. Along with novel indoor environment comfort requirements and energy consumption concerns, the façade system developed into a more complex system where multiple layers ensured the achievement of better performance and climate control levels (Knaack, 2014).

The uptake of new structural concepts favouring open floor plan configurations and higher flexibility of spaces allowed the façade to develop further as an independent element, the architectural and technological identity of which spans beyond any load-bearing duty. This brought to a progressive increase of envelopes' glazed surfaces, from window to wall size, which soon became a global trend in high rises as a way to optimize daylight penetration, therefore maximizing floor plates' depth and increasing buildings' value.

Transparency in façade evolved continuously starting from the 19th century in America, where mass production techniques, such as the invention of the Bessemer process, introduced the use of timber for window frames and some use of wrought iron frames for larger industrial buildings where buildings' own weight have been carried by structural steel frames in place of masonry walls. Furthermore, the Industrial Revolution witnessed the exponential growth of new factories with larger glazing area (Condit, 1975). However, stone, bricks and iron, the structural resistance of which is counterbalanced by heavy weight, limiting building height, were still being used to form the spandrels or solid sections of wall, yet no longer load bearing. During the skyscraper boom of the 1930s, steel engineering unleashed the potential of high-storied buildings characterized by lighter weight and this form of construction has been widely employed and developed until present times. In parallel, the advent of modernist architecture brought a gradual elimination of glazed decoration areas and moved the focus on their functionality. In that regard, architects began to explore how the façade could be disassociated from its structural function to achieve higher transparency.

From the post-Second World War, architectural styles pulled together several new materials facilitating three major stages of the modern curtain wall developments. The first stage (1970–80) sees simple designs, mainly stick systems and on-site assembly and visible aluminium frame. Aluminium became increasingly common in construction due to its robustness and ductility as well as the advantage to be extruded into fine and precise shapes and then tempered for higher strength, making it an ideal material to form window sections. The following decade, 1980–90, witnessed an increased application of systems designed and built according to standards

and manufacturer recommendations, with stick systems still dominating on others. Only from 1990, given the challenge of more and more high-rises construction, American manufacturers developed stick curtain wall systems by employing the third new component, widely available gaskets and seals, to form complete curtain wall systems. This, coupled with new glass processing techniques on float glass (eg, glass fins, point support glazing), has enabled a further push for transparency and lighter construction wall systems. Furthermore, unitized systems started to take over in larger buildings due to their economic benefits and ease of installation, as well as improved energy performance. The economic driver is the main difference in development drivers against opaque façades, where cost logics have not been so prominent in driving façade system evolution.

Unitized glazed systems have recently been evolving into advanced active or adaptive façade systems that enable increased comfort control in indoor environments. As a matter of fact, the integration of shading systems within or outside the cavity, coupled with energy systems or distribution ducts installation in the spandrel part of the unitized façade cell, enabled a brand-new construction concept, saving room in the enclosed space thanks to effective allocation of active components above and under floor slabs, leveraging through-floor connections located in the façade space. The same space-saving driver is also being developed in opaque envelopes, especially in the retrofit sector.

Alongside the postwar developments, façade systems continued to evolve in complexity. The current century is characterized by multifunctional and multiperformance building envelopes, designed and developed to optimize building occupants' comfort together with operation costs. The façade system is now asked to work harder than ever before: it should be able to stand up, bear horizontal loads (ie, wind and any earthquakes), adapt to building movements, guarantee air and water tightness, keep air contaminants out, guarantee thermal insulation and avoid overheating, let natural ventilation through (ie, warming sun and cooling breezes), offer views out and daylight, protect from outside noise, fire spreading through the building, intrusion and blasts. The complex integration of all these performance requirements, coupled with aesthetic ambitions, calls for the use of a wide range of materials, technologies and systems, as well as the need for cross-disciplinary, integrated design approaches.

1.2.2 Façade design and construction: a 'process' innovation barrier

Architecture and building construction are complex and dynamic systems. The process of designing, assembling and managing a building involves a consistent amount of different interdependent activities, several actors and technical skills. The façade discipline reflects perfectly the complex and dynamic nature of the building construction sector. As a matter of fact, façade design has become a highly specialized, multifaceted technical discipline characterized by fast progress and evolution. New regulations, norms and standards in the field are continuously

established, new technical competences and expertise required and an increasing number of professionals from different backgrounds and knowledge domains involved across the whole process of façade design and construction.

The role of the façade expert (or façade engineer) has become prominent in building construction projects, as the one who is aware of each product's technical specifications and individual component's performance requirements and, at the same time, accountable to deploy optimal façade technological solutions through function integration and holistic design approaches. The façade engineer is also involved in the process of façade design and construction, overseeing all project stages and engaging with the different actors across the value chain, including architects and other design specialists (Fig. 1.2), as well as suppliers, fabricators, installation teams and contractors (Fig. 1.3).

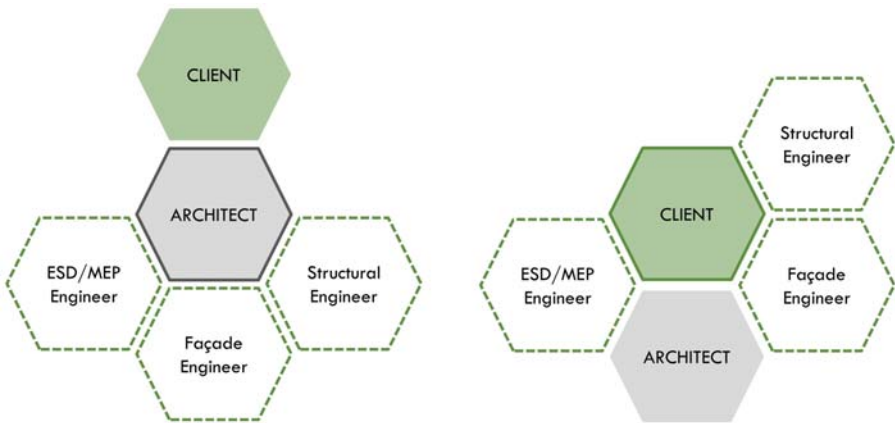


Figure 1.2 Typical contract organization chart—design phase (on the left: engineers employed by the architects; on the right: engineers employed by the client).

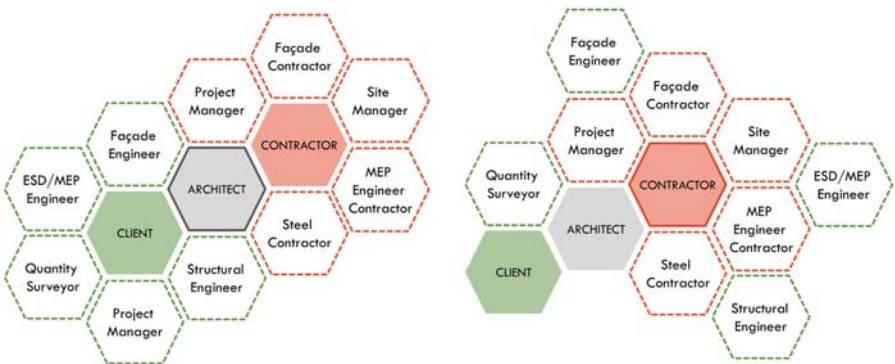


Figure 1.3 Typical contract organization chart—design and construction phase (on the left: tender; on the right: novation).

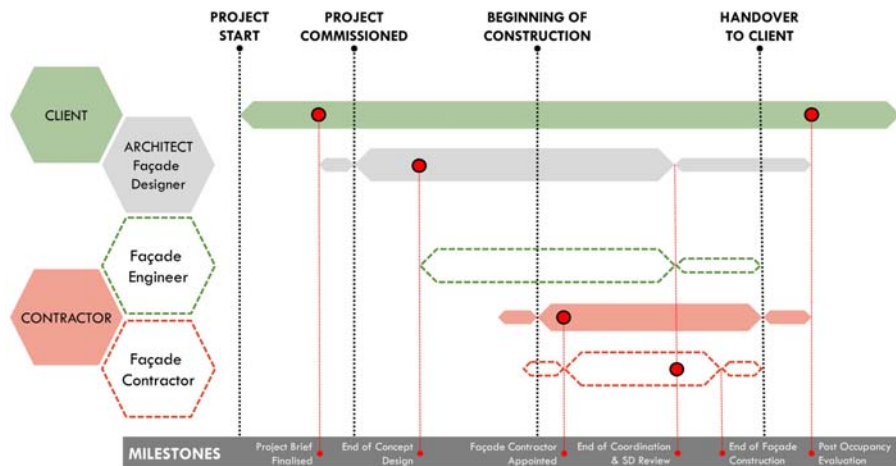


Figure 1.4 Typical project timeline with actors' early-stage involvement in the design and construction phase.

In this context, it seems evident how the organization and management of interactions among the various experts at the different stages of a project is highly challenging and requires substantial efforts in coordination. However, at the current stage, the fragmentation of the design scope among the various designers and consultants involved in façade projects, who are often scattered and/or working in isolation, results in significant process inefficiencies and frictions. As shown in Fig. 1.4, the different actors involved in the process of façade design and construction come into play at different stages of a project, often at a point in time when their efficacy in guiding critical decisions is very limited, or design changes would require substantial investments in time and cost. From an environmental perspective, for example, early-stage involvement of façade engineers and technical experts can enable an integrated façade design outcome. This guarantees high energy performances on a building scale, together with reduced environmental impact and positive contribution toward more comfortable indoor spaces and sustainable urban environments.

Today, the endemic fragmentation of the industry and the related lack of transparency, knowledge isolation and productivity stagnation constitute the main barrier to optimization and innovation in facades and building construction more broadly. The 'one-off' nature of construction projects adds a second dimension to fragmentation, where the lack of knowledge transfer not only happens within the different phases of a project, but also among different projects. Another factor hindering innovation can be identified in the risk-averse nature of the business, particularly affecting the large multitude of small and medium enterprises characterized by negative cash-flow patterns and low margins. This necessarily results in general underinvestment in technical skills development and research and development, with nonhomogeneous growth patterns across the sector in favour of few players who

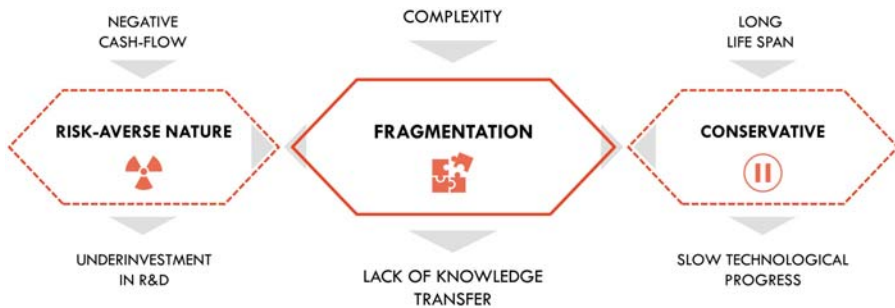


Figure 1.5 Barriers to construction innovation.

can afford large capital investment. Finally, conversely to other technology-based industries, the products of which are oftentimes ‘designed to fail’, the construction sector is conservative as its assets must serve extended life spans. This logically results in slower technological advancements and more ‘cautious’ innovation attempts (Fig. 1.5).

In this scenario, it is clear how ‘isolated’ and ‘incremental’ innovation widely adopted in construction so far become inadequate to guarantee the sector’s sustainable development and economic growth in the years ahead. The construction industry will need to look at the problem holistically and move toward ‘systemic-radical’ innovation approaches (Blayse & Manley, 2004) where ‘business-as-usual’ practices are coherently integrated within novel platform models and networks to enable the creation of collective value.

Today, a significant shift in mindset is already permeating the industry at different levels, with several actors embracing sustainable development goals and green practices. Moreover, new digital megatrends introduced by Industry 4.0 seem to offer enormous potential to overcome present barrier to innovation and open the floor to an announced ‘construction revolution’, also known as ‘Construction 4.0’.

1.3 Facades tomorrow

1.3.1 Transformational change: drivers and opportunities

The process of innovation is generally driven by the rise of new needs, being them of ‘economical’ nature (for instance related to productivity/profitability optimization) or ‘sociopolitical’ nature (for instance, aiming at the improvement of societal/environmental conditions) (IEA, 2019). In modern capitalistic economies, these two domains are often misaligned or entwined in cost–benefit logics, as the pursuit of the common good can become an obstacle or restrain the pursuit of private profit.

As discussed in the previous sections, facades developments so far have been primarily characterized or enabled by material-related or technological innovations (Knaack, Klein, Bilow, & Auer, 2007), pertaining to the broader domain of

'technical' innovation, either 'product-' or 'process-based' (Blayse & Manley, 2004). Over the last few decades, since the Kyoto protocol agreement was signed in 1997, sustainability has represented the major 'sociopolitical' driver to innovation in construction. However, the idea of sustainability in buildings was mainly bound to the concept of 'operational energy' reduction and occupants' comfort, achieved through better climate control. This contributed to bring a wide range of new façade products, technologies and systems to the market, with the purpose to maximize the performance of the building envelope. However, the increasing demand for more stringent requirements has today reached a point where incremental improvements are either not sufficient or even uneconomical and unsustainable (eg, the thickness of thermal insulation in certain climatic regions). Moreover, the concept of 'embodied energy' across the entire building life cycle has now become prominent, bringing process-based innovation logics at the centre of present and future facades technological developments.

Sustainability in construction has evolved (United Nations Framework Convention on Climate Change UNFCCC, 2015) and acquired different nuances that can lead to the realignment of 'economical' and 'sociopolitical' drivers according to win-win logics, favouring the implementation of 'systemic-radical' innovation pathways that bring entirely new perspectives to the façade (and construction) industry.

The view that negative impacts are an inevitable consequence of development has blinded us to the obvious. We could design development to increase the size, health and resilience of natural systems, while improving human health and life quality.

Janis Birkeland.

Today, the idea of sustainability goes beyond the net-zero energy or carbon paradigms. The reduction of the sector environmental impact is not enough anymore. Instead, the goal of future sustainable design and construction practices is to add or create value through the introduction of innovative platform models where economic, environmental and social goals can thrive simultaneously and harmoniously.

Future sustainability and innovation approaches will not only be 'systemic', thus embracing holistically all the different phases of a project (cradle-to-gate), but they will have to be 'ecosystemic', spanning beyond the traditional life cycle of a project to nourish future developments (cradle-to-cradle). This vision is encompassed in the regenerative and circular economy theories, which aim at decoupling the concept of growth from consumption, rather grounding itself on virtuous models such as resilience and adaptability (UNEP, 2006).

As mentioned in the previous section, Industry 4.0 and digital megatrends uptake represent the key to success and can be major enablers for the construction sector transformation. Despite being at its embryonic stage, industry digitalization has already started and research in the field has been demonstrating huge potential in accelerating innovation processes toward breakthrough, disruptive approaches to the way we design, build and operate facades. Digital platforms will also enable the actualization of new design approaches that will reshape the building construction

industry at its core, by leveraging expertise in technology, favouring knowledge sharing and transparent processes, redefining business models for value creation and paving the ground for transformational change through both ‘product’ and ‘process’ innovation.

1.3.2 Rethinking building skins: pathways to innovation

In light of what explained throughout this chapter, *Rethinking Building Skins* would imply the exploration of new concepts and forms, advanced materials and technologies, novel approaches to design, more efficient fabrication and construction techniques, innovative operating networks and models. We have envisioned a future that will be profoundly transformed by the digital era, where new innovation models will enable integral economic, environmental and social sustainability to thrive.

With a two-step approach, we aimed at identifying the main research trajectories in façade design and technology, pertaining to the proposed domains of ‘product’ and ‘process’ innovation (Fig. 1.6). First, we present a simple and intuitive classification for ‘the façade product’ of tomorrow, through the identification of four main macro-categories. Currently, there is no clear classification of the different façade systems that is representative of their main functions and characteristics and terminology in the field is rather contextual and often confusing (Carlucci, 2021; Romano, Aelenei, Aelenei, & Mazzucchelli, 2018). As a second step, we illustrate the opportunities for ‘the façade process’ to uptake digital transformation across each different stages of a project (design, fabrication, construction) and, holistically, by looking at the entire value chain.

Part A: Product Innovation

We have imagined a future where ‘the façade product’ can be classified in:

A.1 Eco-active facades—adopting active strategies to ‘give back to’ or to ‘repair’ the ecosystem they work within. This might include conversion and exploitation of energy or biofuel from renewable energy resources, water capture or food harvesting, CO₂ capture and air purification. Among the technologies that could serve these functions are building-integrated photovoltaics, building-integrated solar thermal, wind turbines, algae, hydroponic systems for vertical farming, nanocoatings and/or bioinspired systems for water capture.

A.2 Re-active facades—reacting and adapting to changing environmental conditions—such as changes in temperature, wind patterns, atmospheric moisture levels and sunlight, or even extreme weather events—to minimize buildings’ energy consumption, optimize occupants’ comfort and well-being and guarantee safety and security. This façade systems mimic biological systems adaptation strategies and involve different levels of user intervention, from manual to fully automated control strategies. Technologies that could serve these functions might include the use of smart materials and nanocoatings, photo- or electrochromic devices, dynamic shadings, built-in sensors, artificial intelligence and machine learning for improved building–environment interaction.

A.3 Inter-active facades—interacting, informing and communicating via interior or exterior environments with humans, being them, respectively, building’s occupants or citizens. This offers new and exciting opportunities for collaboration across the fields of

architecture and neuroscience, so far mostly unexplored. Among the technologies that could serve these functions might include the use of media screens for placemaking, data feeds and sensors, organic light-emitting diodes for whole-surface illumination, augmented reality (AR) and virtual reality (VR) for immersive user experience, IoT technologies, cyber-physical systems, artificial intelligence and machine learning for improved building–human interaction.

A.4 Circular facades—reducing consumption of finite resources and designing-out waste. This could be enabled for instance by using renewable or carbon-negative materials (eg, timber technologies), products that can be reused or recycled at the end-of-life, plug-and-play and reversible connection systems, modular facades and flexible components that can be easily assembled and disassembled for programmed maintenance and repair across their life-cycle.

The abovementioned identified categories are not meant to be exclusive. Instead, the integration of different functions, methods and operating models is desirable (or perhaps necessary in certain contexts) to maximize benefits and enable ‘systemic-radical’ innovation in façade design and technology. The technologies listed for each category are not exhaustive and they might have different levels of maturity. Categories A.1, A.2, A.3 define the ‘façade product’ throughout a set of functionalities guaranteed during operation, while the A.4 category refers to systems materiality and characteristics of assemblies or technologies throughout their life cycle – being therefore inclusive of the former three.

Part B: Process Innovation

Similarly, we have imagined a future where ‘the façade process’ will integrate:

B.1 Design methods—using strategies for knowledge integration through the use of digital twins and pushing the boundaries of automated design through artificial intelligence and machine learning.

B.2 Fabrication processes—adopting advanced industrialized processes, which involve for instance the use of additive manufacturing technologies, advanced prefabrication and mass-customization methods, robotics for high-quality and efficient assembly.

B.3 Construction practices—applying advanced digital tools to increase site efficiency and safety, such as smart helmets integrating AR and VR technologies for site activities real-time monitoring and activities forecasting, drones providing real-time on-site control and tracking, Building Information Modelling and robotics for efficient and safe control and installation.

B.4 Life cycle approaches (LCA)—designing for systems’ resilience, adopting LCA and life cycle cost approaches and implementing service platforms and business models that aim at extending the façade service life over the traditional cradle-to-grave approach, for instance, using the façade as a ‘material bank’.

The abovementioned identified categories are not to be considered as independent but rather deeply intertwined, particularly when looking at new digitalization horizons. Here again, the technologies listed for each category are not exhaustive and they might have different levels of maturity. Categories B.1, B.2, B.3 deal with three different stages of the ‘façade process’, while the B.4 category looks at the whole-life process holistically – therefore aiming to ‘oversee’ and integrate the former three.

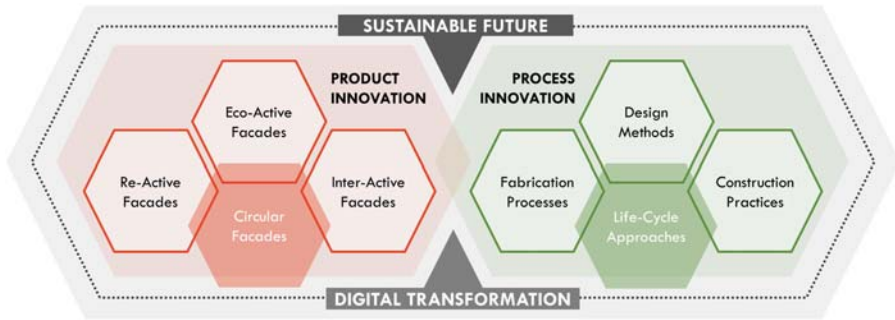


Figure 1.6 Façade Innovation – between ‘product’ and ‘process’.

1.4 Conclusion

This chapter provided an overview of major barriers, drivers and opportunities to innovate the façade industry. It framed the current ecosystem looking at technological advancements throughout recent history which shaped its looks and organization, defining the main challenges ahead for the sector.

Future pathways for innovation are presented according to two domains, the ‘product’ and the ‘process’ of facades. As technical and technological innovation has already reached very high momentum, the optimization of processes and industry organizational structure are expected to gain further strength in the years to come, thanks to the disruption brought about by digital transformation and the adoption of Industry 4.0 approaches.

Total sustainability of future façade will be the driver for industry development and economic growth, enabled by radical life cycle approaches to design, construction and fabrication. In this frame, advanced sectoral digitalization will unlock the potential for façade increased integrability, adaptability and climate resilience to meet global targets toward decarbonization, keep up with the ever-changing needs of our society and grow prosperously.

This chapter is a progressive introduction to the book conception, organization and innovation topics, through the narrative of ‘product’ and ‘process’ innovation in the field of facades. These two pillars are gradually investigated within the book, benefitting from contributions by a wide group of established experts from academia and the industry toward the definition of an international research agenda for the façade industry to uptake transformational change in future.

References

- Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., ... Brown, S. (2017). *Reinventing construction: A route to higher productivity*. McKinsey Global Institute.

- Blayse, A. M., & Manley, K. (2004). Key influences on construction innovation. *Construction Innovation*, 4(3), 143–154.
- Carlucci, F. (2021). A review of smart and responsive building technologies and their classifications. *Future Cities and Environment*, 7(1), 10.
- Condit, C.W. (1975). *Designing for industry: The architecture of Albert Kahn*.
- IEA. (2019). *Global status report for buildings and construction*. Paris: IEA.
- Knaack, U. (2014). Potential for innovative massive building envelope systems – Scenario development towards integrated active systems. *Journal of Façade Design and Engineering*, 2(3–4), 255–268.
- Knaack, U., Klein, T., Bilow, M., Auer., T. (2007), *Fassaden. Prinzipien der Konstruktion*, Birkhäuser: Basel, <<https://doi.org/10.1007/978-3-7643-8319-0>>.
- Ribeirinho, M. J., Mischke, J., Strube, G., Sjödin, E., Blanco, J. L., Palter, R., ... Andersson, T. (2020). *The next normal in construction: How disruption is reshaping the world's largest ecosystem*. McKinsey & Company.
- Romano, R., Aelenei, L., Aelenei, D., & Mazzucchelli, E. S. (2018). What is an adaptive façade? Analysis of recent terms and definitions from an international perspective. *Journal of Façade Design and Engineering*, 6(3), 65–76. Available from <https://doi.org/10.7480/jfde.2018.3.2478>.
- UNEP. (2006). *Circular economy: An alternative for economic development*. Paris: UNEP DTIE.
- United Nations. (2019). *World urbanization prospects: The 2018 revision (ST/ESA/SER.A/420)*. New York, NY: United Nations.
- United Nations Framework Convention on Climate Change (UNFCCC). (2015). *The Paris agreement*. New York, NY: UNFCCC.

This page intentionally left blank

Façade innovation: an industry perspective

2

Alberto Sangiorgio

Grimshaw Architects, Sydney, NSW, Australia

Abbreviations

BIM	Building Information Modelling
CWCT	Centre for Window and Cladding Technology
DfMA	Design for manufacturing and assembly
DGU	Double Glazed Units
EC	Embodied carbon
ECI	Early contractor involvement
EPD	Environmental Product Declaration
LCA	Life cycle assessment
LCIs	Life cycle inventories
NZC	Net-zero carbon
PV	photovoltaic
TB	Text boxes
TGU	Triple Glazed Units

2.1 Introduction

Innovation is seldom a unidirectional process. On the contrary, it is usually a convoluted process involving different drivers, players, stakeholders and constraints. The interaction between these factors determines the pace and the potential for innovation to flourish and spread.

Construction projects have always been characterized by a high level of complexity and recent studies indicate that both technical and organizational complexities are gradually increasing (Luo et al., 2017). The effects are already visible within the construction industry, as well as in its relationships with other sectors, from manufacturing to information technology.

Compared to other markets, the construction industry, including the façade sector, comprises a large and growing number of stakeholders: clients, urban planners, architects, engineers, consultants, contractors, subcontractors, fabricators, regulators and certifiers, to name just a few. Stakeholders have different and sometimes competing agendas, targets, risks and contingencies, focus on different aspects of the process (such as design, installation, maintenance and end-of-life), have different expertise and are regulated by a great variety of national and regional building codes. This landscape results in a highly fragmented industry which, as a whole,

moves and innovates slowly, often focusing on an incremental and field-specific innovation process in which major opportunities to create radical and cross-field innovation processes are less likely to occur.¹

The process of ‘rethinking building skins’ has to start with an understanding of the factors that drive and limit innovation within the façade industry, taking into consideration its relationships with other industries, academia and state government. This chapter presents a wide-ranging overview of the façade industry’s perspective on present and future drivers, challenges and opportunities for innovation in building envelopes through contributions from leading experts and companies in the façade design and construction industry. Its purpose is to provide fertile ground for a multilevel discussion across disciplines and fields, to assess the engagement of the façade industry in different research streams and to serve as a catalyst for the development of synergic collaborations.

2.2 Method

Considering the great variety of players and stakeholders involved, the task of rendering an overview of the façade industry in relation to innovation is challenging. The method adopted to meet this challenge was to collect the insights of 11 selected experts affiliated to global tier-one companies, leaders in the façade design and construction industry. These companies, due to their size and revenue, are major players in R&D activities, since big projects and big contracts are necessary to meet the initial costs of development and testing of new ideas and, potentially, generating the benefits of economy of scale. These global companies can be considered the highways on which innovation is developed, tested, applied and, most importantly, spread across the market to other smaller entities and stakeholders and, eventually, across the globe, including developing countries.

This analysis does not claim any statistical relevance, as it interrogates a limited number of purposefully selected experts. However, it creates a multidimensional overview of façade innovation that takes account of the great variety of roles and expertise that characterize the façade industry and includes recognized leaders in different sectors, such as architecture and design, engineering and consultancy, façade contractors and general contractors, as well as policy makers. Further, it acknowledges the importance of differences in geographical context by inviting authors from Australia, the United Kingdom and the United States.

Table 2.1 shows the complete list of industry experts, their affiliated company, the field of expertise and country of operation.

¹ Incremental innovation is defined as ‘small and based on existing experience and knowledge’; radical or disruptive innovation is defined as ‘a breakthrough in science or technology’ (Blayse & Manley, 2004).

Table 2.1 List of industry experts.

Ref	Façade expert	Company of affiliation	Field of expertise	Country
TB01	Andrew Cortese	Grimshaw Architects	Architecture-Design	Australia
TB02	Keith Boswell	Skidmore, Owings & Merrill	Architecture-Design	United States
TB03	Kieran Rice	AECOM	Engineering	Australia
TB04	Damian Rogan	Eckersley O'Callaghan—Engineers	Engineering	United Kingdom
TB05	Haico Schepers	ARUP	Engineering	Australia
TB06	Marc Zobec	Permasteelisa	Façade contractor	Australia
TB07	Sophie Penetier	Enclos	Façade contractor	United States
TB08	Saverio Pasetto	Skanska UK	Contractor	United Kingdom
TB09	John Downes	Lendlease	Contractor	United Kingdom
TB10	Dominic Shillington	Laing O'Rourke	Contractor	Australia
TB11	Davina Rooney	Green Building Council of Australia	Policy maker	Australia

TB, Text boxes.

The experts were asked to provide a written contribution, with an indicative limit of 1000 words, addressing the following two questions:

Question 1: What are the most relevant innovations that you foresee will play a major role in shaping the way the next generations of building envelopes will be designed, procured, built, maintained and dismantled?

Question 2: In your current practice, what are the future innovations you are actively fostering/exploring and how do you expect these innovations to change your role, your approach to design, engineering, fabrication, procurement, construction and the outcome of the design?

The experts were asked to use these questions as guidelines, focusing on their specific field of expertise and personal experience. The structure of the response was intentionally flexible, leaving the contributors free to combine the answers or address them separately.

The following section scaffolds on the industry experts' contributions, summarizing their feedback and providing a snapshot of present and future drivers, challenges and opportunities for innovation in the façade industry. In it, the author provides a commentary that discusses the main points made by the industry experts and contextualizes them in relation to the broader industry and relevant literature to create a mental map of the key themes and topics that are discussed by each expert. The 11 contributions from the experts are included in full in the 'Industry insights'.

section in the form of ‘text boxes’ (TB) and are presented in the same order as shown in [Table 2.1](#).

2.3 Façade innovation: drivers, challenges and opportunities

2.3.1 What drives innovation? Why do we innovate?

These questions are apparently simple, but their answers are complex and embedded in the way our global economy and society operate. During his career the Italian design Master, Bruno Munari, championed creativity and radical innovation and proposed an interesting theory: ‘Laziness is the engine of progress. It is the stimulus that pushes us to obtain what we desire with the minimum of physical effort; the maximum result with the minimum effort is now a law of economics’.² ([Munari, 2018](#)).

In more general terms, industrial innovation aims to improve the operations of a specific field with reference to specific targets. In the façade construction industry, these targets are as follows:

Economic/productivity growth: This is the type of innovation to which Munari refers it is driven by what he playfully calls laziness, but which can be related to the more conventional ideas of efficiency, optimization and competition between

SUSTAINABILITY	TB01, TB02, TB09, TB11
Operational Energy Embodied energy	TB01, TB03, TB04, TB05 TB06, TB09
Circular economy	TB03, TB04, TB08
Durability and Comfort Resilience and Adaptation	TB01, TB07, TB10
Policies and Framework	TB07, TB11
ORGANISATIONAL INNOVATION	TB01, TB04, TB05, TB06 TB07, TB08, TB09, TB10
INNOVATION BY DESIGN	TB01, TB06, TB07, TB08 TB10, TB11

Figure 2.1 Summary of the main topics and contributions from the industry experts cited in the text.

² ‘La pigrizia è il motore del progresso. È lo stimolo che ci spinge a ottenere ciò che desideriamo facendo il minimo di fatica fisica; il massimo risultato col minimo sforzo è ormai una legge di economia’.
Translated by the author from [Munari \(2018\)](#).

companies. One example is the innovation that aims to find new fabrication processes to improve a product or reduce its time and cost of production (Slaughter, 1998).

Social/environmental drivers: In this case, innovation aims to improve humans' personal and social conditions with respect to comfort, safety, health and well-being. It is enabled by the adoption of policies or codes. Innovation as a means to achieve higher targets in sustainability and building performance can be included in this category (Slaughter, 1998).

Creativity: There are innovations that do not target growth from an economic perspective, nor from a social/political one. A good example related to façade construction is research that focuses on the achievement of new architectural languages, including free forms and which is justified by aspects of our society that have more in common with fashion and creativity than with the rationality that characterizes the previous two categories.

In the process of rethinking the facades of the future, innovation will find its *raison d'être* in one or more of the three categories listed earlier. The same applies to all the innovations mentioned by the industry experts in their contributions.

The following sections summarize the key topics and concepts mentioned by the industry experts and divide the discussion into themes. It starts from the most popular topic—sustainability—and moves to the other recurrent themes, linking them with one another in a continuous discussion. References are given to the respective TB in which these topics are mentioned (Fig. 2.1).

2.3.2 Sustainability

Today, buildings are responsible for up to 39% of global emissions, a figure that is expected to grow by 50% by 2050, despite the global effort to minimize their impact (D. Rooney TB11). In this context, facades are pivotal in determining the final energy and carbon consumption of a building. This fundamental role is acknowledged by all industry contributions, which indicate that sustainability is a trending topic and driver for future innovation. The major role played by sustainability comes as no surprise, considering that the market has been increasingly focusing on this topic over recent decades, due to the growing impact of environmental policies. This awareness found new strength during 2019 and 2020, when increasing temperatures and the unprecedented spread of bushfires ramped up the discussion on effects, causes and solutions to climate change, while the global pandemic put health and well-being in the built environment under the spotlight.

The aftermath of the Paris Agreement and the Sustainable Development Goals released in 2015 saw an increase in global awareness of sustainability across all fields and especially in construction. In a strong response, most of the signatory countries committed to delivering net-zero carbon (NZC) new constructions by 2030 and to operate within a completely NZC by 2050.

To facilitate this process the private industrial sector and, more specifically, the construction industry reacted with the creation of voluntary organizations such as the World Green Building Council and Architect/Engineers/Contractors Declare, among others. The aim is to raise awareness of climate and biodiversity.

emergencies, to advocate for faster change in the industry toward sustainable and regenerative design practices and to promote the exchange of knowledge and research. The ultimate goal is to reduce greenhouse gas emissions in the construction industry, in alignment with the international commitments.

The success and relevance of these initiatives across the construction sector and the increasingly tight building codes and certification requirements, demonstrate a growing social responsibility toward the environment, which is reflected in the industry experts' contributions: today and in the next 30 years, innovation in building skins will primarily focus on reducing energy and carbon emissions. 'Creating a pathway to net carbon zero is most likely the biggest challenge that the property industry has ever faced' (J. Downes—TB09), but not enough has been done in designing toward the NZC goals. However, the industry as a whole is slowly moving in the right direction, acknowledging the urgency of the problem and upskilling to reach the set targets.

From a building and façade design perspective, the journey toward NZC is already creating a paradigm shift, gradually moving away from a *design-for-compliance* approach—where a building's energy and carbon performances are assessed and eventually adjusted only after the completion of the concept design phase—to an *integrated design* approach. In the latter, architects and consultants work together to achieve a holistic balance among performance against all targets, optimizing the consumption of energy and carbon 'without losing focus on the other fundamental qualities of buildings and facades, such as amenity, variety, experience, visual connection, etc'. (A. Cortese—TB01).

In this context, innovations that focus on only one of these aspects, overlooking the others, will be unlikely to succeed (K. Boswell—TB02). Finding a balanced approach to innovation will require novel early-stage data-based design methods and workflows, as well as multidisciplinary environments and procurement routes to allow designers and engineers to work together with contractors. In such a truly integrated design approach, it is possible to make informed decisions and align design and construction performances.

This new arrangement will be necessary to achieve good and holistic zero-energy building design and it will require a reassessment of the role of the architect and the design team in general. These will have to extend their scope of work from concept to completion, expanding their knowledge and expertise to include deeper awareness of performative design, construction processes and advanced methods of research (K. Boswell—TB02). The advent of new high-performing envelopes will also be an opportunity for architects to renovate the façade design language, so that 'the array of architecture and sustainability elements [...] are rationalized and used to build the tectonic and the filigree of the facades' (A. Cortese—TB01).

In any analysis of the relationship between sustainability targets and innovation with a focus on the NZC goals, it is important to identify the main parameters in the façade design and construction process that have an impact on carbon emissions. These are as follows:

- operational energy and embodied energy;
- 'circular economy', that is, the use and disposal of resources;
- durability and comfort, resilience and adaptation; and
- policies and frameworks.

Operational energy and embodied energy

In the last 20 years, one of the primary objectives of building policies and, consequently, of façade design, has been to improve the thermal performance of the building skin as a means of reducing the heating and cooling energy consumption. However, very little focus has been given to a whole-of-life carbon approach (K. Rice—TB03; D. Shillington—TB10).

This has resulted in a focus on the development and diffusion of a new generation of high-performance facades, designed to suit the new challenging targets in operational energy. Different strategies have proved successful in addressing low energy targets, leading to the development of new façade typologies that include, for example, high-performance defensive, reactive and active (A. Cortese—TB01), as well as dynamic facades. Dynamic facades in particular are repeatedly cited in most industry contributions, which acknowledge their great potential in managing and optimizing daylight and solar gains under changing weather conditions. This is due to their responsive behaviour, which works similarly to human skin (M. Zobec—TB06).

In the future, this new generation of high-performance dynamic facades will require sensors, motors, moving components and, ultimately, integration with the building management system and smart home appliances, or the Internet of things (H. Schepers—TB05). These components will allow the façade to meet the needs and comfort requirements of the building occupants while decreasing the building's operational energy usage and carbon emissions. The development of smart solutions to manage the increasing complexity of future static and dynamic facades will be a fundamental step to ensure the success of these technologies, especially when the operational energy benefits are compared to the potential downsides in relation to service life, maintenance costs and increased embodied energy (D. Rogan—TB04).

In recent years, growing interest in embodied energy and carbon has prompted new policies and pathways intended to limit the CO_{2e} embedded in building components, especially facades and structures, which are recognized as the main contributors to the total embodied energy content (Azari & Abbasabadi, 2018). This has allowed new tools for carbon accounting to be implemented and led to the development of new life cycle inventories (LCIs).

Today, the use of life cycle assessment (LCA) software as a design tool is still subject to debate, due to its limitations. Indeed, LCA software and embodied calculators are limited by many factors that can jeopardize their use, especially in the early stages of façade design. The first factor is represented by the market's limited knowledge of embodied energy (J. Downes—TB09). A second limiting factor is the low accuracy of the input and the lack of accurate, consistent, local-specific data and standard methodology. Both factors affect the reliability of the tools: assessing the same design with the different tools that are available can lead to great differences in the embodied energy accounting (Dixit et al., 2012). To respond to these challenges, the next generation of building skins will need more precise and local-specific LCIs, a shared definition of the scope of investigation (scopes 1, 2 and 3 of embodied energy as defined by the Green House Gas protocol) and an agreed method of accounting.

Last but most importantly, one of the great issues associated with the use of embodied energy accounting as a design tool is the number of assumptions required at an early design stage, whereas decisions about materials procurement are finalized only at a later phase, when the contractor is involved (D. Rogan—TB04). This issue touches the foundations of the design process and its resolution will require a deep organizational shift, forcing designers and contractors to work closely to determine façade systems and procurement much earlier in the process.

In the path toward a more informed and truly energy- and carbon-sensible design resolution, another issue that must be addressed during the design phase is the sometime competing nature of embodied and operational impacts. Kieran Rice (TB03) provides a practical example in the form of a project-specific research undertaken by AECOM Victoria (Australia), which aimed to compare the use of triple-glazing unit (TGU) and double-glazing unit (DGU) on a full LCA, measuring the costs/benefits in relation to operational factors and embodied carbon (EC) consumption for both alternatives. The results showed that, for that specific project and climatic context, despite the fact that the TGU seemed to offer operational advantages, the additional glass panel would take 33 years to offset its additional embodied energy, leading to a negligible carbon emission saving over the design life of the building.

The design of future facades will have to address this problem through a whole-of-carbon design approach which relies on multivariable optimization processes necessary to achieve the lowest energy and carbon intensity in the LCA and, ultimately, a zero carbon design.

Circular economy

Another sustainability-related concept that has emerged in recent years will likely be a major driver of future innovation and research in buildings and facades. This concept, the ‘circular economy’, represents the shift from a linear pattern of consumption that starts with material extraction and ends in disposal to a circular approach, where materials are reemployed at the end of their life (MacArthur, 2013). This shift has the potential to minimize both waste disposal and the demand for new materials (D. Rogan—TB04), with significant benefits for the environment.

The basic principles of circularity were embedded in the economy and construction as long ago as the Middle Ages, or even earlier in the architecture of the Roman Empire. Due to the high cost of materials and craftsmanship, construction materials were a valuable resource, so recycling was most often cheaper than the use of new resources. For this reason, buildings were designed and built to last and their components often reused at the end of the building’s life (S. Pasetto—TB08).

The industrial revolution contributed to an increase in the availability of construction materials through the employment of a highly engineered mass production chain, resulting in a reduction in the cost of new materials for the end client. As a consequence, the strategy of ‘reuse and recycle’ became a less appealing solution, breaking the circularity and opening the door to the current consumerist ‘throw-away’ model. Of course, this is a crude simplification of a process that took a century to change the way our economy and society work.

The presence of ‘loops’ in the economy was formally theorized for the first time in an EU report commissioned in 1976, called ‘Jobs for Tomorrow: the potential for substituting manpower for energy’, which focused on car manufactory and building construction (Stahel & Reday-Mulvey, 1981). Some 30 years later, new ideas in relation to ‘circularity’ and ‘cradle to cradle’ were introduced, but very little has been done to implement them in the industry (Braungart & McDonough, 2009).

Some steps have been undertaken on the recyclability front, with increasing the use of recycled material in the fabrication of aluminium, steel and glass. However, most current façade systems employ a variety of materials with unique provenance, making it very difficult to deploy a responsible reuse and recycle process at the end-of-life of the façade elements (D. Rogan—TB04).

A simple example is again provided by DGUs, whereby glass is processed and combined with other components and materials (such as solar control/low-e coatings, sealant, space bar) to improve its thermal performance. Although glass is generally recyclable, its use in a complex product makes the recycling process more complex, expensive and less convenient. A similar point can be made in relation to durability performance: simple float glass has a much longer design life compared to the more complex multiple-glazed products that are the market’s standard and which have a lifespan of only 25–30 years (Patterson et al., 2016).

Considering that a more durable and easy-to-recycle product has a higher potential to save energy for fabrication and reduce the amount of material that needs to be disposed of, it can be concluded that the increased complexity necessary to achieve higher targets on operational energy competes with the targets on circular economy and embodied energy.

As a consequence of these intercorrelations between operational energy, embodied energy and circular economy, the façade industry will have to make a ‘fundamental reappraisal of what constitutes a carbon efficient building skin’, shifting the present focus on operational energy to a more ‘nuanced appreciation of what gives the most optimal overall carbon foot print across the building’s lifecycle’ (K. Rice—TB03).

Durability and comfort, resilience and adaptation

In this fast-changing reality in which the façade systems or ‘species’ appear to be in competition to increase their success in the market in some kind of Darwinian model, ‘threat, adaptation, survival’ will be other important drivers for innovation (S. Pennetier—TB07). In the process of ‘rethinking building skins’, considerations of durability and comfort, resiliency and adaptation of facades will be central in efforts to reduce embodied energy and optimize the use of resources. A durable façade is capable of matching all minimum performance targets established during the design phase, from the beginning to the end of its intended service life.

Today more than ever, we live in an environment characterized by unprecedented rates of change in economic and climatic conditions. In imagining the façade of the future, designers and researchers will have to foresee these factors and take them into account to extend the adequacy and durability of façade solutions.

making them resilient and capable of adapting to constant and sudden changes within and outside the building construction industry.

An example of a long-term trend that is already impacting the durability of facades and buildings is the pursuit of higher energy efficiency. Increasingly tighter provisions have confronted indoor environmental health and quality with unprecedented challenges, not always successfully. Evidence can be found in the dramatic increase over the past 50 years in the number of cases of ‘sick building syndrome’ and mould growth. It has been estimated that the proportion of buildings currently damaged by mould is 45% in Europe, 40% in the United States, 30% in Canada and 50% in Australia ([Brambilla & Sangiorgio, 2020](#)). These statistics are the result of multiple factors that include the rapid uptake of new façade systems and materials in the absence of sufficient understanding of their hygrothermal performance, the increase difference in the hygrothermal conditions between internal and external environments due to the broad diffusion of air conditioning systems and more generally poor design practices that fail to address the mid-long-term consequences of these problems.

Over the design life of a building, all these factors have a negative impact on the durability of materials and building components, with consequences for the financial, energy and carbon budgets and a detrimental effect on the building’s air quality ([Brambilla & Sangiorgio, 2020](#)). Future research will have to address these problems not only to increase the durability of the envelopes but also to improve the health and well-being conditions for the building’s users.

An example of sudden change outside the industry that has heavily impacted our lives and the way in which we utilize our buildings is the global pandemic of COVID19, which has escalated discussion around resiliency and adaptation of spaces and facades to suit different functions and occupation patterns. A further source of long-term impact is represented by climate change, which will heavily impact the selection of the new ‘species’ of building envelopes. In the next 50 years, new buildings and facades will have to respond to restrictions on energy/carbon consumption, while dealing with a range of environmentally related emergencies, such as the increase in temperature and urban heat island effects, the growing level of urbanization and the problem of food security, together with the likely scenario of new global pandemics and economic crises. In this fast-changing environment, design and innovation for ‘resilience’ will be fundamental for the new generation of facades and, more generally, for the future of façade industry operations (A. Cortese—TB01; D. Shillington—TB10).

Policies and frameworks

All experts agree on the major role that increasingly aspirational sustainability targets will play in reshaping building skins. Nonetheless, high-performance facades, which employ innovative and advanced technologies and materials and sophisticated investigative and data-based design processes, usually imply higher initial costs, which can conflict with the industry’s basic principles of competitiveness. Although in most cases this initial investment is balanced if not exceeded by the

savings in operational costs—something that is well understood by inspired and well-informed clients—the systematic development, diffusion and success of innovation driven by sustainability/energy performance is still strictly dependent on building codes and policies.

For example, a building developer is less interested in reducing the operational energy and carbon of the building if it is intended for sale or rental after construction. In this kind of scenario, among others, sustainable policies are essential to regulate the construction industry and will play a major role in improving the energy performance of future facades, increasing the minimum standards and then incentivizing the industry to do better (D. Rooney—TB11). A recent example is provided by Sophie Pennetier, who witnessed an instantaneous change in façade glazing from DGU to TGU when New York's Law 97 passed in 2019, placing carbon caps on roughly 50,000 residential and commercial properties across NYC. This case is a perfect example of adoption issues, rather than the lack of technology and knowledge (S. Pennetier—TB07).

Innovation of appropriate technologies driven by sustainability depends on the ability of institutions to respond progressively to climate change (Rodima-Taylor et al., 2012). Regulators and policy makers have a primary role in reestablishing the complex balance between 'economic/productivity' and 'social/environmental' drivers and in the definition of the innovation agenda, including targets and implementation strategies.

In accordance with the recent trends identified by the industry experts, it is certain that future envelopes will have to comply with increasingly stringent regulations and policies, which will not only provide tighter operational energy consumption targets but also thresholds for embodied energy (or carbon emissions) and more specific metrics to measure performance related to the circular economy.

In the future the current so-called green or sustainable design approach, which focuses on the mitigation of a building's environmental impacts, will be implemented with the new regenerative design principles, which interpret buildings as a whole in their social—cultural and environmental context (Cole, 2012). Hence, as part of this trend, we will witness the rise of new regenerative design policies, frameworks and tools aimed at encouraging innovative design solutions capable of shifting the focus from 'green' and 'sustainable' toward regenerative design thinking.

In conclusion, the reappraisal of all sustainability design and construction metrics and parameters has the potential to drive and promote innovation in architectural expressions, materials, fabrications and construction processes. The magnitude of this potential will depend on how well researchers, policy makers and industry work together to define targets, frameworks and pathways to achieve them.

2.3.3 Organizational innovation: collaboration and education

The façade construction sector and the building industry in general innovate at a slow pace (S. Pasetto—TB08). Slow innovation and operational inefficiencies have common causes and these must be identified both within and outside the façade

industry. From an internal perspective the fragmented supply chain, the lack of coordination between design, supply chain and construction and the low level of investment in R&D are definitely among the major problems (Dubois & Gadde, 2002; Dulaimi et al., 2002). This fragmentation is the result of multiple factors, including the multidisciplinary design process typical of façade design, the typical one-off nature of the projects and the use of multiple products/materials assembled in complex and highly customizable systems, which involves a highly specialized supply chain with several different stakeholders, such as designers, consultants, contractors and subcontractors, organized in a compartmentalized chain of separated entities. In this panorama, every player in the game has a limited scope of work and, at the same time, has to rely on the work of many other stakeholders; this increases the risks and contingencies while reducing efficiency at every step of the design and construction process.

This environment also reduces the parties' ability and willingness to innovate (Blayse & Manley, 2004), curtailing any opportunity of collaboration along the design/supply chain. The result is a systematic failure of cross-field innovation, which increases the risks and constrains the development of novel facades (M. Zobec—TB06). Risk management will be key to the success of innovation (H. Schepers—TB05) and reducing the inherent risk of innovation will require (1) a reconsolidation of the market toward the development and coexistence of new forms of collaboration and cross-fertilization between different parties; and (2) new standardized digital management tools and workflows. The first is often defined in the literature as 'organizational innovation' (Blayse & Manley, 2004), as it aims to change the organizational structure by introducing advanced management techniques and implementing new corporate strategic orientations. Changing the inner structure of the market to foster a positive climate of change is an essential step to enhance opportunities for exchange and, ultimately, support a paradigm shift in the way the market works (Demircioglu, 2016).

Further research in this field will be fundamental to define the new generation of business models, project management strategies and tools, tendering processes, contracts, scope-of-works and responsibilities, insurance schemes and procurement systems. These will bridge the gap between designers, contractors and subcontractors, minimizing the existing barriers to innovation.

In the future, new contracts and project management schemes will transform the design methodology, paving the way for the achievement of ambitious sustainability goals in relation to EC and circular economy by forcing procurement choices at earlier stages of the design (D. Rogan—TB04). An example is provided by prefabricated mega-panels, which have the benefit of supporting local manufacturing and reducing transport costs, but which cannot be developed without an 'earlier coordination of designers and contractors' and an 'earlier engagement with the client' (D. Shillington—TB10). Hence, it is clear that new strategies for involving all stakeholders from the early design stage will be key to a radical transformation of the market.

A first step in this direction is represented by the increasing use of early contract involvement (ECI) practices, although these are not sufficient on their own to drive change. A more radical shift will require a deeper integrated design approach and

will represent, for example, a new opportunity for architects to play a fundamental role in this transition (A. Cortese—TB01).

Another notable direction in policy change is represented by the shift toward the façade-as-a-service model, where the façade is ‘leased or offered as a service, rather than bought’ (S. Pasetto—TB08). This might also be an interesting way of encouraging the reuse and recycling of façade elements and, ultimately, reduce buildings’ environmental impact.

Nevertheless, organizational innovation must be supported by the development of new management tools that can facilitate the change. In the construction sector, this may include a holistic integrated design, fabrication and management tool that can be employed across the field, allowing a more effective and standardized platform for collaboration between different parties. Current R&D projects are working in this direction, aiming to develop ‘total façade management systems’ (M. Zobec—TB06), ‘digital twins’ (J. Downes—TB09) and the technical tools necessary to support design for manufacturing and assembly (DfMA).

To support multidimensional and multidisciplinary information flows within the industry and across different sectors, it will be necessary to establish new highways for data and knowledge exchange. Indeed, the fragmentation of the façade market is reflected in a discontinuous knowledge development process, both within and between organizations, which prevents the development of an ‘organizational memory’ (Blayse & Manley, 2004). In the past, little effort has been devoted to transmitting data, knowledge and experience between projects, disciplines and companies, resulting in a system that penalizes the spread of advantageous mutations to standard products and processes (Dubois & Gadde, 2002).

However, the development and diffusion of innovations resonates with the way ‘we develop our skills, our knowledge and our relationships’ (H. Schepers—TB05). Today, intellectual capital is becoming as important as financial capital as the basis of future economic growth (Etzkowitz, 2003) and institutions, such as Arup University, are already investing in the creation of innovative internal learning platforms to bring global experts together and enable the creation of an ‘organizational memory’.

External learning platforms and opportunities are also key to sharing knowledge and innovation between companies (J. Downes—TB09; S. Pennetier—TB07) and, therefore, enabling innovation. Examples include the involvement of Lendlease UK, Skanska UK and other contractors in the Centre for Window and Cladding Technology (CWCT) and the strategic committee on Sustainability and Embodied Carbon (J. Downes—TB09), or the growing number of industry—academia research programmes that constitute ‘a very fertile soil for open source, tax supported collaboration and innovation’ (S. Pennetier—TB07). The development of internal knowledge-capture platforms and external knowledge-generation opportunities will increase the already compelling need for the identification of more efficient ways of extracting/distilling codified knowledge from experience, overcoming the problems given by the project-specific nature of the market and making this knowledge easily accessible and transferable.

Today, the main opportunities for cross-field multidisciplinary innovation are found in temporary coalitions of firms enabled by large-scale projects and in the