Hugo Hens

Performance Based Building Design 1

From Below Grade Construction to Cavity Walls

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To my wife, children and grandchildren

In remembrance of Professor A. de Grave
Who introduced building physics as a new discipline
at the University of Leuven (KULeuven), Belgium, in 1952

Contents

Performance Based Building Design 1. From Below Grade Construction to Cavity Walls.
First edition. Hugo Hens.

Preface

Overview

Just like building physics, performance based building design was hardly an issue before the energy crises of the nineteen seventies. Together with the need for more energy efficiency, the interest in overall building performance grew. The tome on applied building physics already discussed a performance rationale, and contained an in depth analysis of the heat, air, moisture performance requirements at the building and building enclosure level. This third tome builds on that rationale although also structural aspects, acoustics, fire safety, maintenance and buildability are considered now. The text reflects thirty eight years of teaching architectural, building and civil engineers, coupled to more than forty years of experience in research and consultancy. Where and when needed, input from over the world was used, reason why each chapter ends with a list of references and literature.

The book should be usable by undergraduates and graduates in architectural and building engineering, though also building engineers, who want to refresh their knowledge, may benefit. The level of discussion assumes the reader has a sound knowledge of building physics, along with a background in structural engineering, building materials and building construction.

Acknowledgments

A book of this magnitude reflects the work of many, not only of the author. Therefore, first of all, we like to thank the thousands of students we had. They gave us the opportunity to test the content and helped in upgrading it.

The text should not been written the way it is, if not standing on the shoulders of those, who preceded. Although we started our carrier as a structural engineer, our predecessor, Professor Antoine de Grave, planted the seeds that slowly fed our interest in building physics, building services and performance based building design. The late Bob Vos of TNO, the Netherlands, and Helmut Künzel of the Fraunhofer Institut für Bauphysik, Germany, showed the importance of experimental work and field testing for understanding building performance, while Lars Erik Nevander of Lund University, Sweden, taught that application does not always ask extended modeling, mainly because reality in building construction is much more complex than any simulation can reflect.

During the four decennia at the Laboratory of Building Physics, several researchers and PhD-students got involved. I am very grateful to Gerrit Vermeir, Staf Roels Dirk Saelens and Hans Janssen who became colleagues at the university; to Jan Carmeliet, now professor at the ETH-Zürich; Piet Standaert, a principal at Physibel Engineering; Jan Lecompte, at Bekaert NV; Filip Descamps, a principal at Daidalos Engineering and part-time professor at the Free University Brussels (VUB); Arnold Janssens, associate professor at the University of Ghent (UG); Rongjin Zheng, associate professor at Zhejiang University, China, Bert Blocken, professor at the Technical University Eindhoven (TU/e) and Griet Verbeeck, professor at KHL, who all contributed by their work. The experiences gained by working as a structural engineer and building site supervisor at the start of my career, as building assessor over the years, as researcher and operating agent of four Annexes of the IEA, Executive Committee on Energy Conservation in Buildings and Community Systems forced me to rethink the engineering based performance approach every time again. The many ideas I exchanged and got in Canada and the USA from Kumar Kumaran, Paul Fazio, Bill Brown, William B. Rose, Joe Lstiburek and

Performance Based Building Design 1. From Below Grade Construction to Cavity Walls.
First edition. Hugo Hens.

Anton Ten Wolde were also of great help. A number of reviewers took time to examine the book. Although we do not know their names, we like to thank them.

Finally, I thank my family, my wife Lieve, who managed living together with a busy engineering professor, my three children who had to live with that busy father and my many grandchildren who do not know their grandfather is still busy.

Leuven, February 2012 *Hugo S. L. C. Hens*

0 Introduction

0.1 Subject of the book

This is the third book in a series on building physics, applied building physics and performance based building design:

- Building Physics: Heat, Air and Moisture
- Applied Building Physics: Boundary Conditions, Building Performance and Material Properties
- **Performance Based Building Design 1**
- Performance Based Building Design 2

Both volumes apply the performance based engineering rationale, discussed in ‘Applied Building Physics: Boundary Conditions, Building Performance and Material Properties’ to the design and construction of building elements and assemblies. In order to do that, the text balances between the performance requirements presumed or imposed, their prediction during the design stage and the technology needed to realize the quality demanded.

Performance requirements discussed in ‘Applied Building Physics: Boundary Conditions, Building Performance and Material Properties’, stress the need for an excellent thermal insulation in cold and cool climates and the importance of a correct air, vapour and water management. It is therefore logical that Chapter 2 starts with a detailed overview of insulation materials, waterproof layers, vapour retarders, airflow retarders and joint caulking, after Chapter 1 recaptured the performance array at the building assembly level. In the chapters that follow the building assemblies that together shape a building are analyzed: foundations, basements and floors on grade, the load bearing structure, floors and massive facade systems. Each time the impact of the performance requirements on design and construction is highlighted. For decades, the Laboratory of Building Physics at the K. U. Leuven also did extended testing on highly insulated massive facade assemblies. The results are used and commented.

0.2 Units and symbols

The book uses the SI-system (internationally mandatory since 1977). Base units are the meter (m), the kilogram (kg), the second (s), the Kelvin (K), the ampere (A) and the candela. Derived units, which are important, are:

Unit of force: Newton (N); $1\ \text{N} = 1\ \text{kg} \cdot \text{m} \cdot \text{s}^{-2}$
Unit of pressure: Pascal (Pa); $1\ \text{Pa} = 1\ \text{N/m}^2 = 1\ \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$
Unit of energy: Joule (J); $1\ \text{J} = 1\ \text{N} \cdot \text{m} = 1\ \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$
Unit of power: Watt (W); $1\ \text{W} = 1\ \text{J} \cdot \text{s}^{-1} = 1\ \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-3}$

For the symbols, the ISO-standards (International Standardization Organization) are followed. If a quantity is not included in these standards, the CIB-W40 recommendations (International Council for Building Research, Studies and Documentation, Working Group ‘Heat and Moisture

Performance Based Building Design 1. From Below Grade Construction to Cavity Walls.
First edition. Hugo Hens.

Transfer in Buildings') and the list edited by Annex 24 of the IEA, ECBCS (International Energy Agency, Executive Committee on Energy Conservation in Buildings and Community Systems) are applied.

Table 0.1. List with symbols and quantities.

Symbol	Meaning	Units
a	Acceleration	m/s^2
a	Thermal diffusivity	m^2/s
b	Thermal effusivity	$W/(m^2 \cdot K \cdot s^{0.5})$
c	Specific heat capacity	$J/(kg \cdot K)$
c	Concentration	kg/m^3, g/m^3
e	Emissivity	–
f	Specific free energy	J/kg
	Temperature ratio	–
g	Specific free enthalpy	J/kg
g	Acceleration by gravity	m/s^2
g	Mass flow rate, mass flux	$kg/(m^2 \cdot s)$
h	Height	m
h	Specific enthalpy	J/kg
h	Surface film coefficient for heat transfer	$W/(m^2 \cdot K)$
k	Mass related permeability (mass may be moisture, air, salt …)	s
l	Length	m
l	Specific enthalpy of evaporation or melting	J/kg
m	Mass	kg
n	Ventilation rate	s^{-1}, h^{-1}
p	Partial pressure	Pa
q	Heat flow rate, heat flux	W/m^2
r	Radius	m
s	Specific entropy	$J/(kg \cdot K)$
t	Time	s
u	Specific latent energy	J/kg
v	Velocity	m/s
w	Moisture content	kg/m^3
x, y, z	Cartesian co-ordinates	m
A	Water sorption coefficient	$kg/(m^2 \cdot s^{0.5})$
A	Area	m^2
B	Water penetration coefficient	$m/s^{0.5}$
D	Diffusion coefficient	m^2/s

Symbol	Meaning	Units
D	Moisture diffusivity	m^2/s
E	Irradiation	W/m^2
F	Free energy	J
G	Free enthalpy	J
G	Mass flow (mass = vapour, water, air, salt)	kg/s
H	Enthalpy	J
I	Radiation intensity	J/rad
K	Thermal moisture diffusion coefficient	$kg/(m \cdot s \cdot K)$
K	Mass permeance	s/m
K	Force	N
L	Luminosity	W/m^2
M	Emittance	W/m^2
N	Vapour diffusion constant	s^{-1}
P	Power	W
P	Thermal permeance	$W/(m^2 \cdot K)$
P	Total pressure	Pa
Q	Heat	J
R	Thermal resistance	$m^2 \cdot K/W$
R	Gas constant	$J/(kg \cdot K)$
S	Entropy, saturation degree	J/K, –
T	Absolute temperature	K
T	Period (of a vibration or a wave)	s, days, etc.
U	Latent energy	J
U	Thermal transmittance	$W/(m^2 \cdot K)$
V	Volume	m^3
W	Air resistance	m/s
X	Moisture ratio	kg/kg
Z	Diffusion resistance	m/s
α	Thermal expansion coefficient	K^{-1}
α	Absorptivity	–
β	Surface film coefficient for diffusion	s/m
β	Volumetric thermal expansion coefficient	K^{-1}
δ	Vapour conductivity	s
η	Dynamic viscosity	$N \cdot s/m^2$
θ	Temperature	°C
λ	Thermal conductivity	$W/(m \cdot K)$

Symbol	Meaning	Units
μ	Vapour resistance factor	–
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
ρ	Reflectivity	–
σ	Surface tension	N/m
τ	Transmissivity	–
ϕ	Relative humidity	–
α, ϕ, Θ	Angle	rad
ξ	Specific moisture ratio	kg/kg per unit of moisture potential
Ψ	Porosity	–
Ψ	Volumetric moisture ratio	m^3/m^3
Φ	Heat flow	W

Table 0.2. List with suffixes and notations.

Symbol	Meaning
Indices	
A	Air
c	Capillary, convection
e	Outside, outdoors
h	Hygroscopic
i	Inside, indoors
cr	Critical
CO_2, SO_2	Chemical symbol for gasses
m	Moisture, maximal
r	Radiant, radiation
sat	Saturation
s	Surface, area, suction
rs	Resulting
v	Water vapour
w	Water
ϕ	Relative humidity
Notation	
[ ], bold	Matrix, array, value of a complex number
Dash	Vector (ex.: $\overline{a}$)

0.3 References and literature

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[0.2] ISO-BIN (1985). Standards series X02-101 – X023-113.

[0.3] Kumaran, K. (1996). *Task 3: Material Properties*. Final Report IEA EXCO ECBCS Annex 24. ACCO, Leuven, pp. 135.

1 Performances

1.1 In general

This chapter starts by providing some definitions and the performance arrays. It then gives an analysis of the interaction between a rigorous application of performance metrics and building, followed by the possible impact of performance formulation on the construction process.

1.2 Definitions and basic characteristics

The term ‘performance’ encompasses all building-related physical properties and qualities that are predictable during the design stage and controllable during and after construction. Typical for performances is their hierarchical structure with the built environment as highest level (level 0) followed by the building (level 1), the building assemblies (level 2) and finally layers and materials (level 3). Relation between the four levels is typically top-down. ‘Predictable’ demands calculation tools and physical models that allow evaluating a design, whereas ‘controllable’ presumes the existence of measuring methods available on site. In some countries, the selection of building performance requirements had legal status. That coupled with a well-balanced enforcement policy guarantees application. One could speak of must and may requirements. Must is legally required, whereas may is left to the principal.

1.3 Advantages

The main advantage of a performance-based rationale is the objectification of expected and delivered building quality. For too long a time, designers juggled with ‘the art of construction’ without defining what kind of art was involved. With a rigorous application of performance metrics, the principal knows the physical qualities he may expect. In forensic cases, performance requirements provide a correct reference, which is not the case with the art of construction. A performance approach may also stimulate system based manufacturing. And finally, performance metrics could steer the building sector in a more research based direction.

1.4 Performance arrays

The basis for a system of performance arrays are the functional demands, the needs for accessibility, safety, well-being, durability, energy efficiency and sustainability and the requirements imposed by the usage of a building. For the arrays, see Table 1.1 and 1.2.

Performance Based Building Design 1. From Below Grade Construction to Cavity Walls.
First edition. Hugo Hens.

Table 1.1. Performance array at the building level (level 1).

Field		**Performances**
Functionality		Safety when used Adapted to usage
Structural adequacy		Global stability Strength and stiffness against vertical loads Strength and stiffness against horizontal loads Dynamic response
Building physics	Heat, air, moisture	Thermal comfort in winter Thermal comfort in summer Moisture tolerance (mould, dust mites, etc.) Indoor air quality Energy efficiency
	Sound	Acoustical comfort Room acoustics Overall sound insulation (more specific: flanking transmission)
	Light	Visual comfort Day-lighting Energy efficient artificial lighting
	Fire safety[1]	Fire containment Means for active fire fighting Escape routes
Durability		Functional service life Economic service life Technical service life
Maintenance		Accessibility
Costs		Total and net present value, life cycle costs
Sustainability		Whole building life cycle assessment and evaluation

[1] In countries like The Netherlands, Germany and Austria fire safety belongs to building physics. In other countries, it doesn't.

Table 1.2. Performance array at the building assembly level (level 2).

Field		**Performances**
Structural adequacy		Strength and stiffness against vertical loads Strength and stiffness against horizontal loads Dynamic response
Building physics	Heat, air, moisture	Air-tightness • Inflow, outflow • Venting • Wind washing • Indoor air venting • Indoor air washing • Air looping
		Thermal insulation • Thermal transmittance (U) • Thermal bridging (linear and local thermal transmittance) • Thermal transmittance of doors and windows • Mean thermal transmittance of the envelope
		Transient response • Dynamic thermal resistance, temperature damping and admittance • Solar transmittance • Glass percentage in the envelope
		Moisture tolerance • Building moisture and dry-ability • Rain-tightness • Rising damp • Hygroscopic loading • Surface condensation • Interstitial condensation
		Thermal bridging • Temperature factor
		Others (i.e. the contact coefficient)
	Acoustics	Sound attenuation factor and sound insulation Sound insulation of the envelope against noise from outside Flanking sound transmission Sound absorption
	Lighting	Light transmittance of the transparent parts Glass percentage in the envelope
	Fire safety[1]	Fire reaction of the materials used Fire resistance
Durability		Resistance against physical attack (mechanical loads, moisture, temperature, frost, UV-radiation, etc.) Resistance against chemical attack Resistance against biological attack
Maintenance		Resistance against soiling Easiness of cleaning
Costs		Total and net present value
Sustainability		Life cycle analysis profiles

[1] In countries like The Netherlands, Germany and Austria fire safety belongs to building physics. In other countries, it doesn't.

1.5 Design based on performance metrics

1.5.1 The design process

‘Designing’ is multiply undefined. At the start, information is only indefinitely known. Each design activity may produce multiple answers, some better than others, which however cannot be classified as wrong. That indefiniteness demands a cyclic approach, starting with global choices based on sparse sets of known data, for buildings listed as project requirements and design intents. The choices depend on the knowledge, experience and creativity of the designer. The outcomes are one or more sketch designs, which then are evaluated based on the sets of imposed or demanded level 0 and 1 performance requirements. One of the sketch designs is finally optimized and the rest not meeting the performances are discarded. The result is a pre-design with form and spatiality fixed but the building fabric still open for adaptation.

With the pre-design, the set of agreed-on data increases. During the stages that follow, refinement alternates with calculations that have a double intent: finding ‘correct’ answers and adjusting the fabric to comply with the performance requirements imposed. That last phase ends with the final design, encompassing the specifications and the construction drawings needed to realize the building.

1.5.2 Integrating a performance analysis

Designing evolves from the whole to the parts and from vaguely to precisely known data and parameters. These are generated by the design itself, allowing performance analysis to become more refined as the design advances.

During the sketch design phase only level 1 performance requirements such as structural integrity, energy efficiency, comfort and costs receive attention. As most data are only vaguely known, only simple models facilitating global parametric analysis can be used. This isn’t unimportant as decisions taken during sketch design fix many qualities of the final design.

At the pre-design stage along with level 1, the level 2 performance requirements also have to be considered as these govern translation of form and spatiality into building construction. As more parameters and data are established, evaluation can be more refined. The load bearing system gets its final form, the enclosure is designed and the first finishing choices are made. Options are considered and adjusted from a structural, building physical, safety, durability, maintainability, cost and sustainability point of view.

Detailing starts with the final design. Designing becomes analyzing, calculating, comparing, correcting and deciding about materials, layer thicknesses, beam, column and wall dimensions, reinforcement bars and so on. The performance metrics now fully operate as a quality reference. Proposed structural solutions and details must comply with all level 2 and 3 requirements, if needed with feedback to level 1. That way, performances get translated into solutions. Performances in fact do not allow construction. For that, each design idea has to be transformed into materials, dimensions, assemblies, junctions, fits, building sequences and buildability, with risk, reliability and redundancy as important aspects.

Performance requirements also should become part of the specifications, so contractors may propose alternatives on condition they perform equally or better for the same or lower price.

1.6 Impact on the building process

For decades, the triad <principal/architect/contractor> dominated the building process. The principal formulated a demand based on a list of requirements and intents. He engaged an architectural firm, which produced the design, all construction drawings with consultant's help (structural engineers, mechanical engineers and others), and the specifications on which contractors had to bid. The lowest bidder got the contract and constructed the building under supervision of the architect.

That triad suffers from drawbacks. The architect is saddled with duties for which he or she is hardly qualified. Producing construction drawings is typically a building engineering activity. Of course, knowledge about soil mechanics, foundation techniques, structural mechanics, building physics, building materials, building technology, and building services was procured but always after the pre-design was finished, that means after all influential decisions had been made. The split between design and construction further prevented buildability from being translated into sound construction drawings, which today, still, hardly differ sometimes from the pre-design ones. Details and buildability are left to the contractor, who may lack the education, motivation and resources for that. The consequences can be imagined. No industrial activity experiences as many damage cases as the building sector.

A performance rationale allows turning the triangle into a demand/bidder model. The demand comes from the principal. He produces a document containing the project requirements and intents. That document is much broader than a list of physical performances. Site planning, functional requirements at building and room level, form, architectural expression and spatiality are all part of it. Based on that document, an integrated building team, which includes the architect, all consulting engineers and sometimes the contractor is selected based on the sketch design it proposes. The assigned team has to produce the pre- and final drawings, included structure, building services, all energy efficiency aspects and, if demanded, an evaluation according to LEED, BREEAM or any other rating systems. If the contractor is part of the team, the assigned team also has to construct and decommission the building. Otherwise, a contractor is chosen based on a price to quality evaluation.

1.7 References and literature

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