A method for human-centered appraisal of façade design for serviceability

MSc BT | Sagar Oke | 5578752

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Industry Partner
AGC INTERPANE

TU Delft

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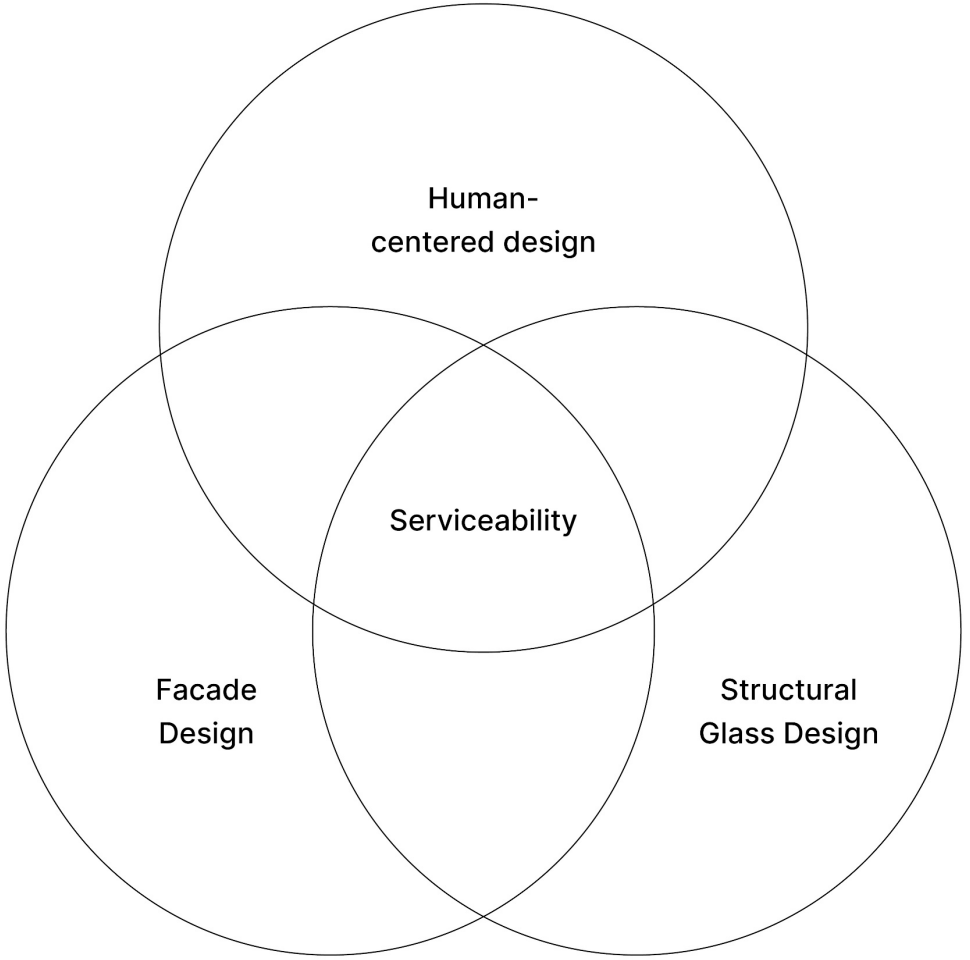
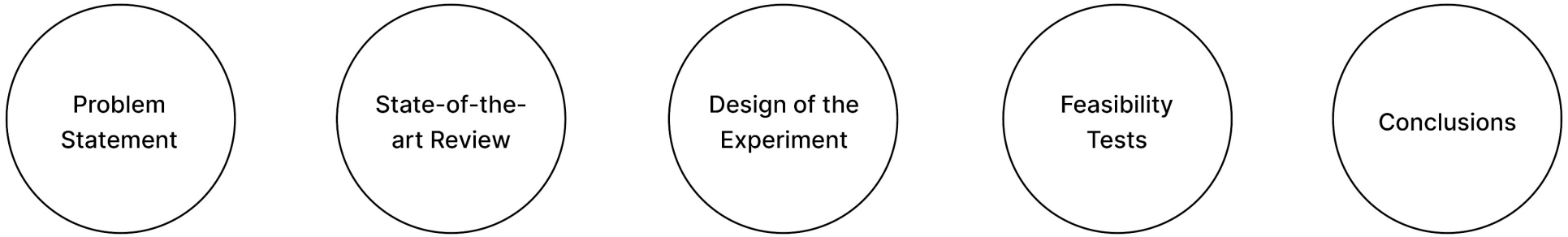
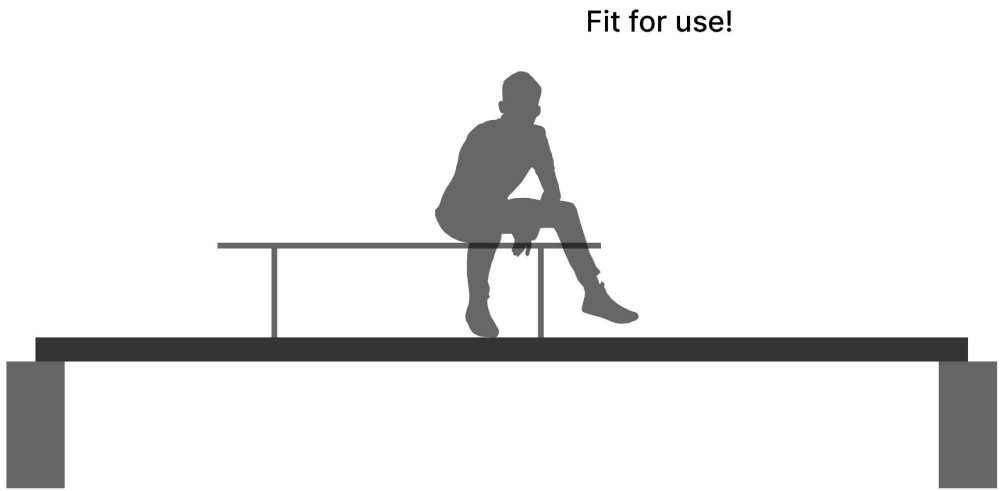



Problem Statement
State-of-the-art Review
Design of the Experiment
Feasibility Tests
Conclusions

Serviceability

Serviceability

Conditions under which a structure/ component is considered ‘fit for use’.



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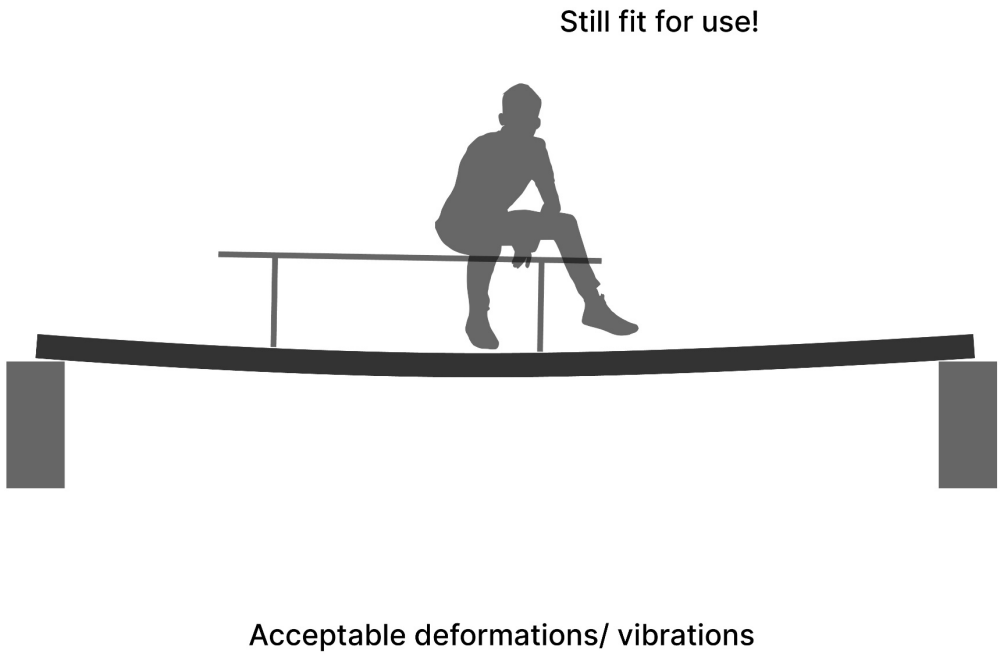


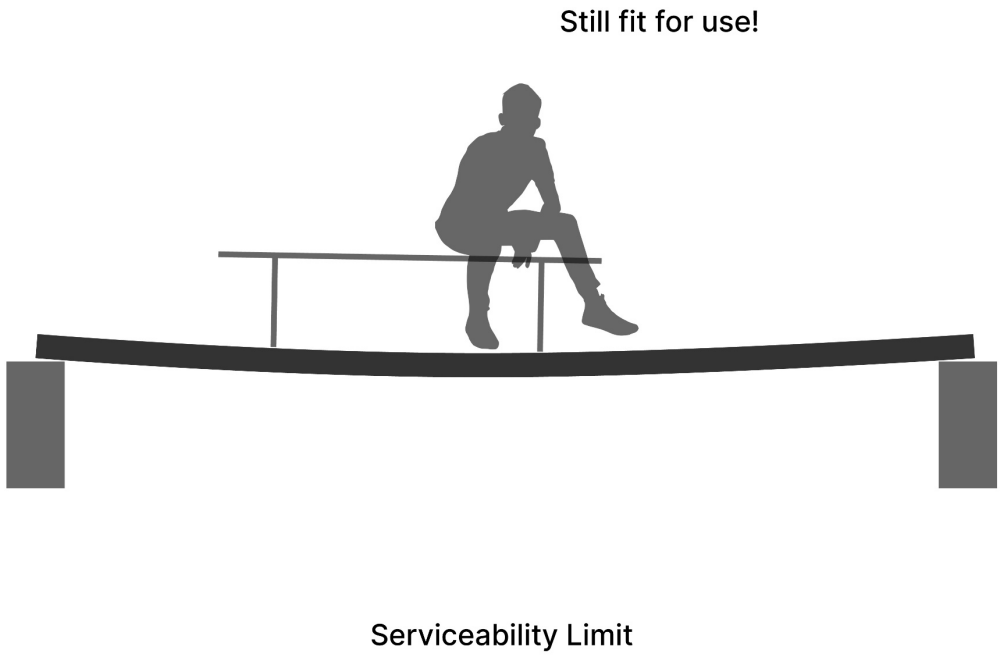
Serviceability

Serviceability

Conditions under which a structure/ component is considered ‘fit for use’.

Serviceability Limit State (SLS)

Conditions beyond which specified service requirements for a structure or structural member are no longer met.



Serviceability

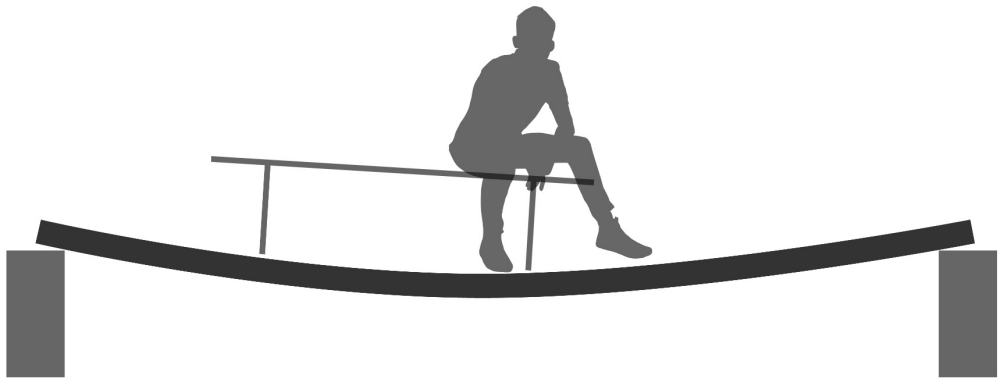
Serviceability

Conditions under which a structure/ component is considered ‘fit for use’.

Serviceability Limit State (SLS)

Conditions beyond which specified service requirements for a structure or structural member are no longer met.

Bad idea.



Serviceability Limit Crossed

=

Structurally safe, but not fit for use

Serviceability

Serviceability

Conditions under which a structure/ component is considered ‘fit for use’.

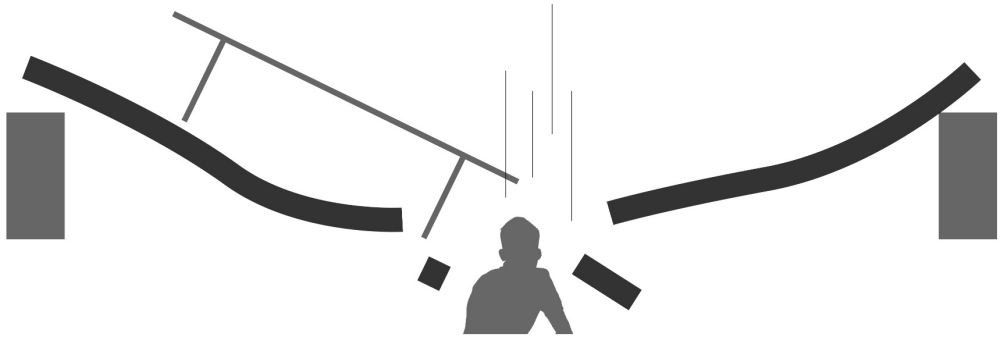
Serviceability Limit State (SLS)

Conditions beyond which specified service requirements for a structure or structural member are no longer met.

Ultimate Limit State (ULS)

Conditions at which a structure undergoes failure.

.....



Ultimate Limit

Serviceability

Serviceability

Conditions under which a structure/ component is considered ‘fit for use’.

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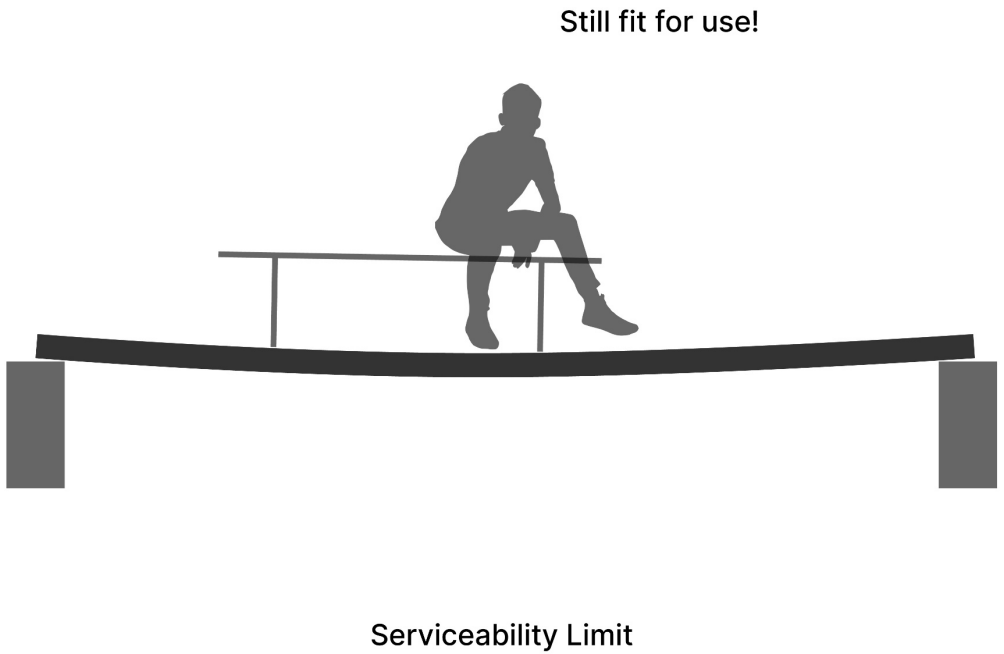
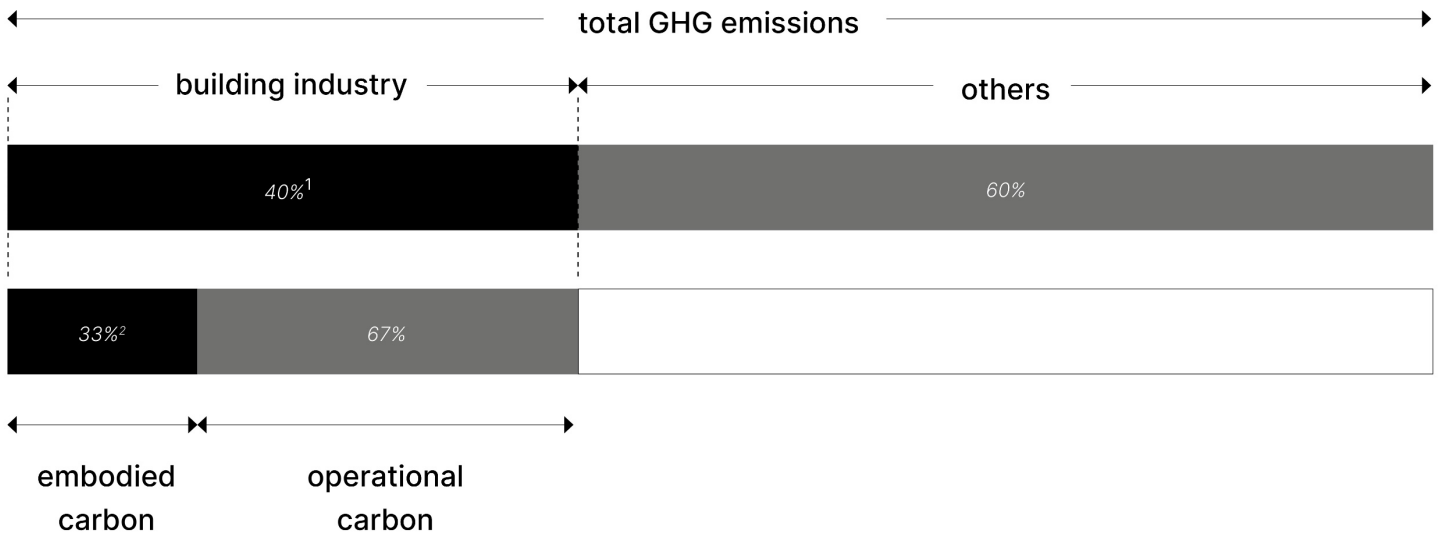
Conditions beyond which specified service requirements for a structure or structural member are no longer met.

- **Leaner structures = Reduction in embodied carbon**

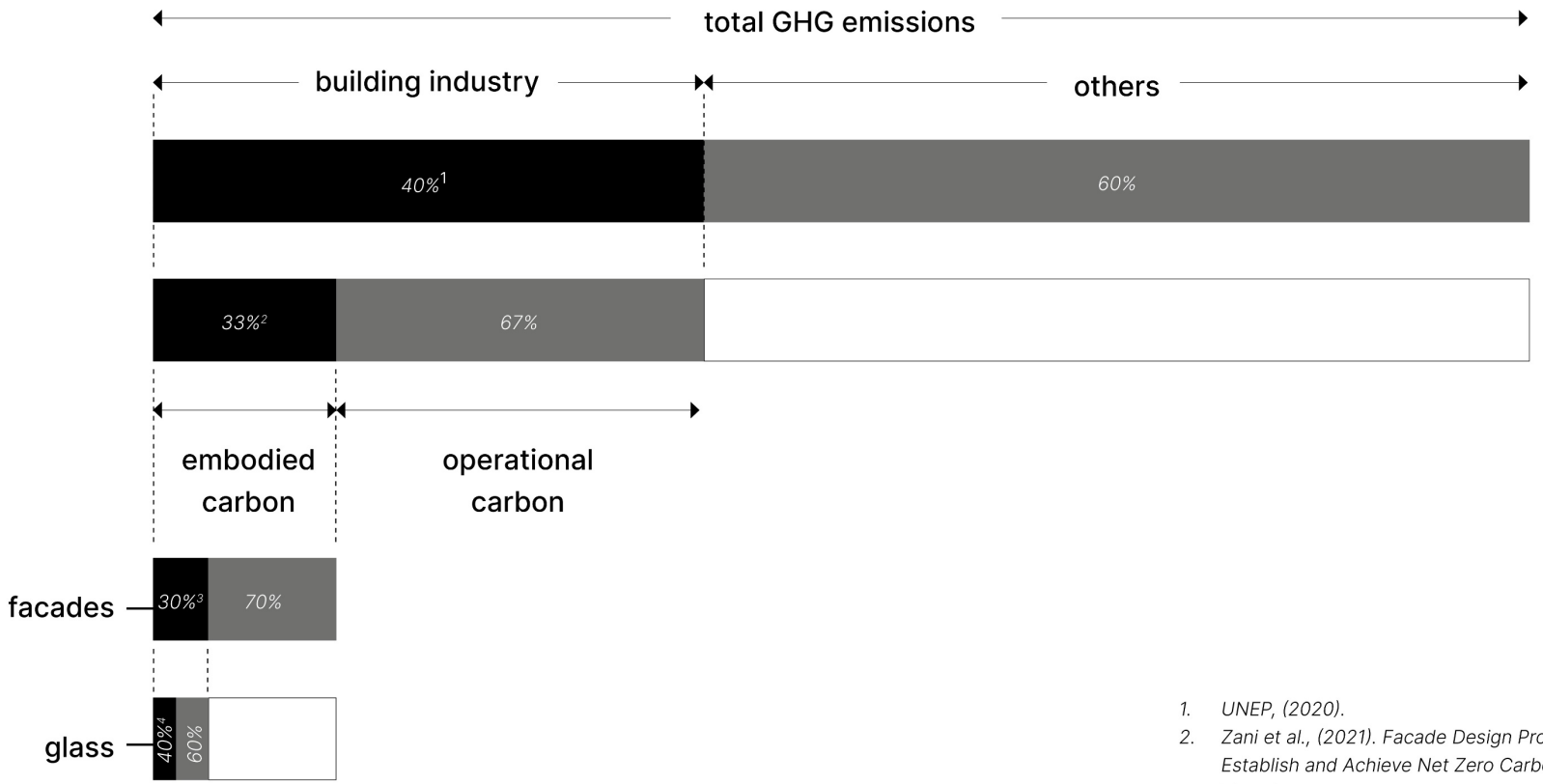


Embodied Carbon vs. Operational Carbon



1. *UNEP, (2020).*
2. *Zani et al., (2021). Facade Design Process to Establish and Achieve Net Zero Carbon Building Targets*

Contributions of facade glazing



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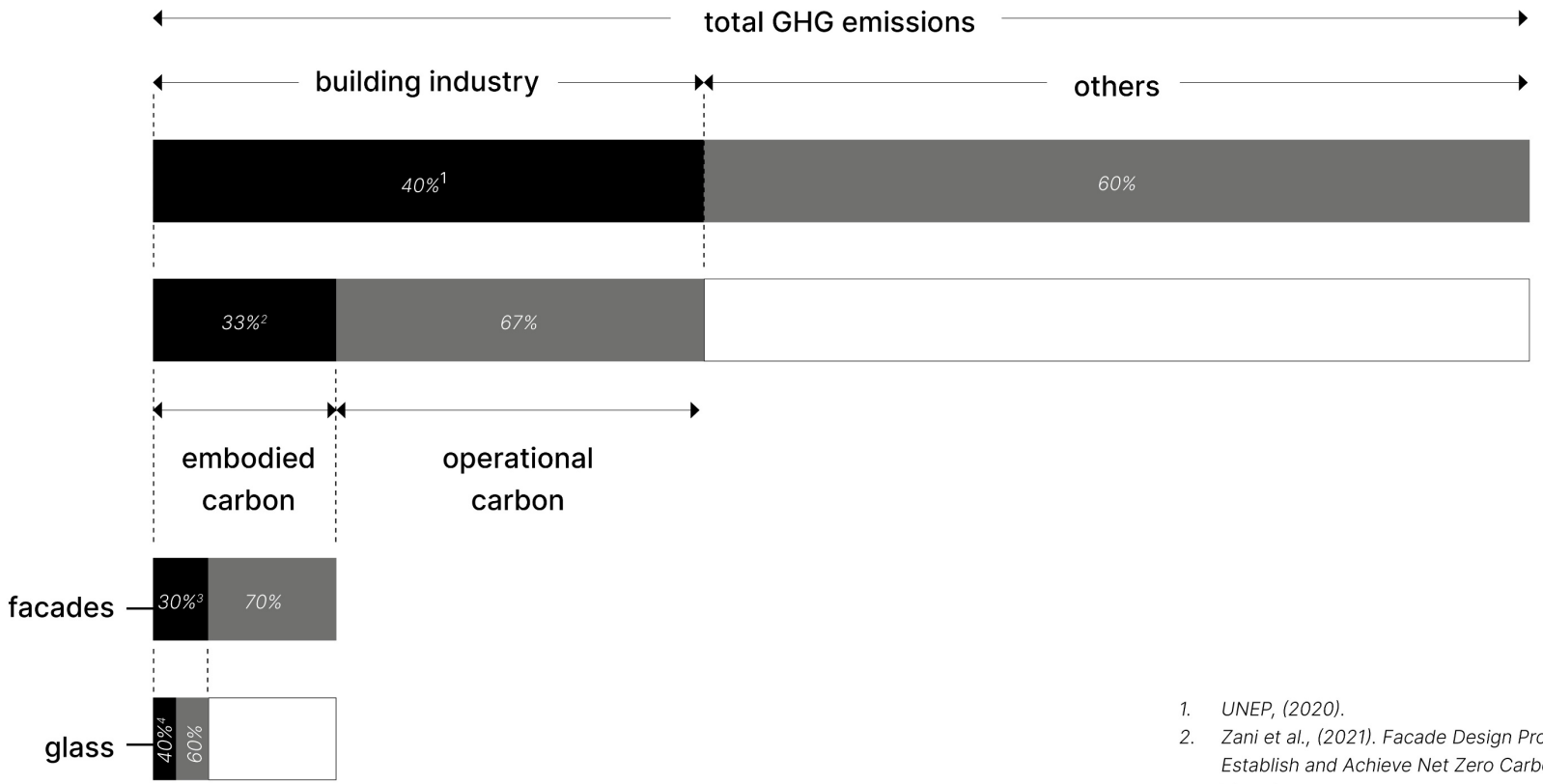
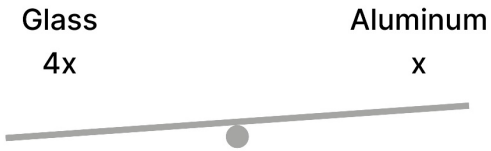


Reducing even 1mm thickness of glass can reduce up to **3 $kgCO_2e/m^2$** facade area.



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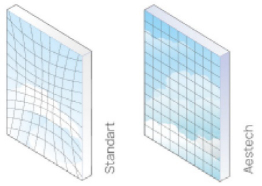
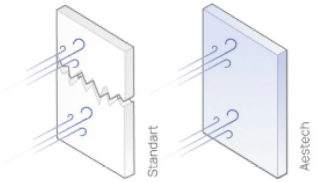
Embodied Carbon vs. Operational Carbon

Aestech — our frameless glazing technology removes old architectural constraints

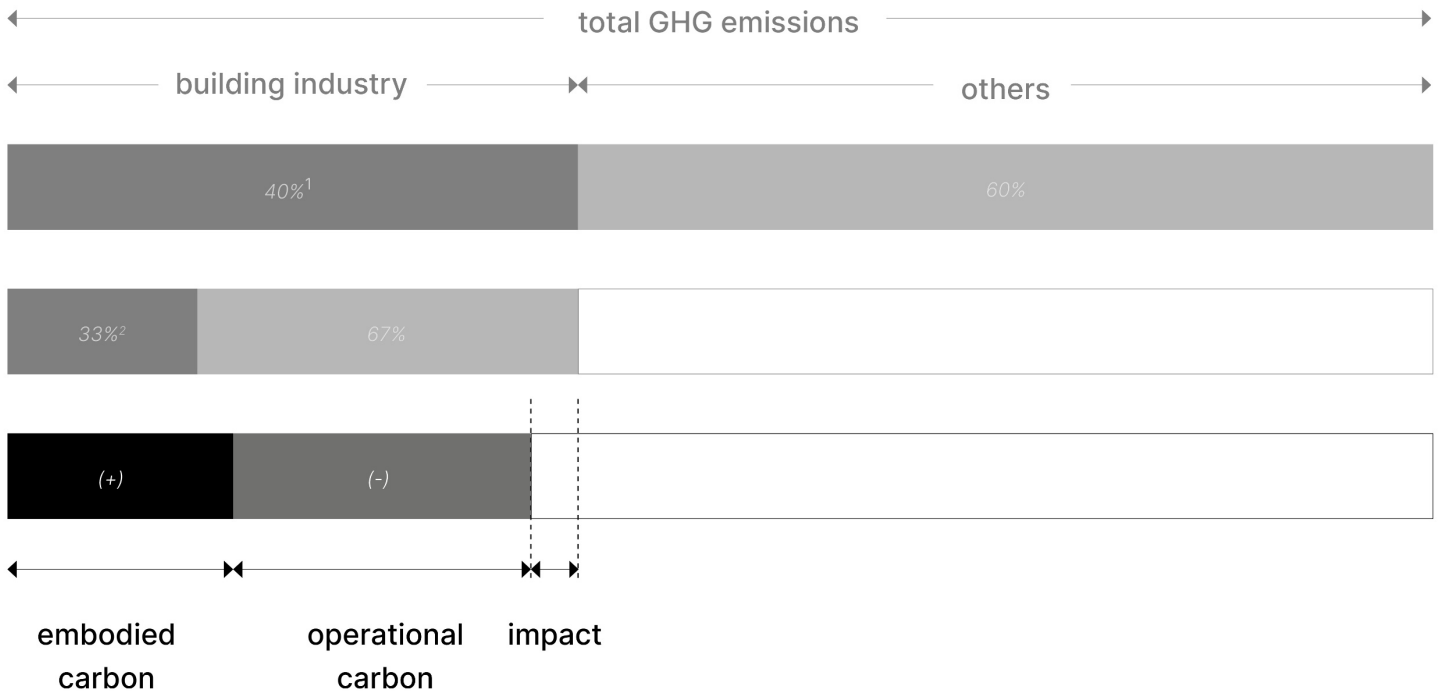
Low optical distortions



High load resistance



Source: Promotional email of Aestech: frameless glazing technology provider.



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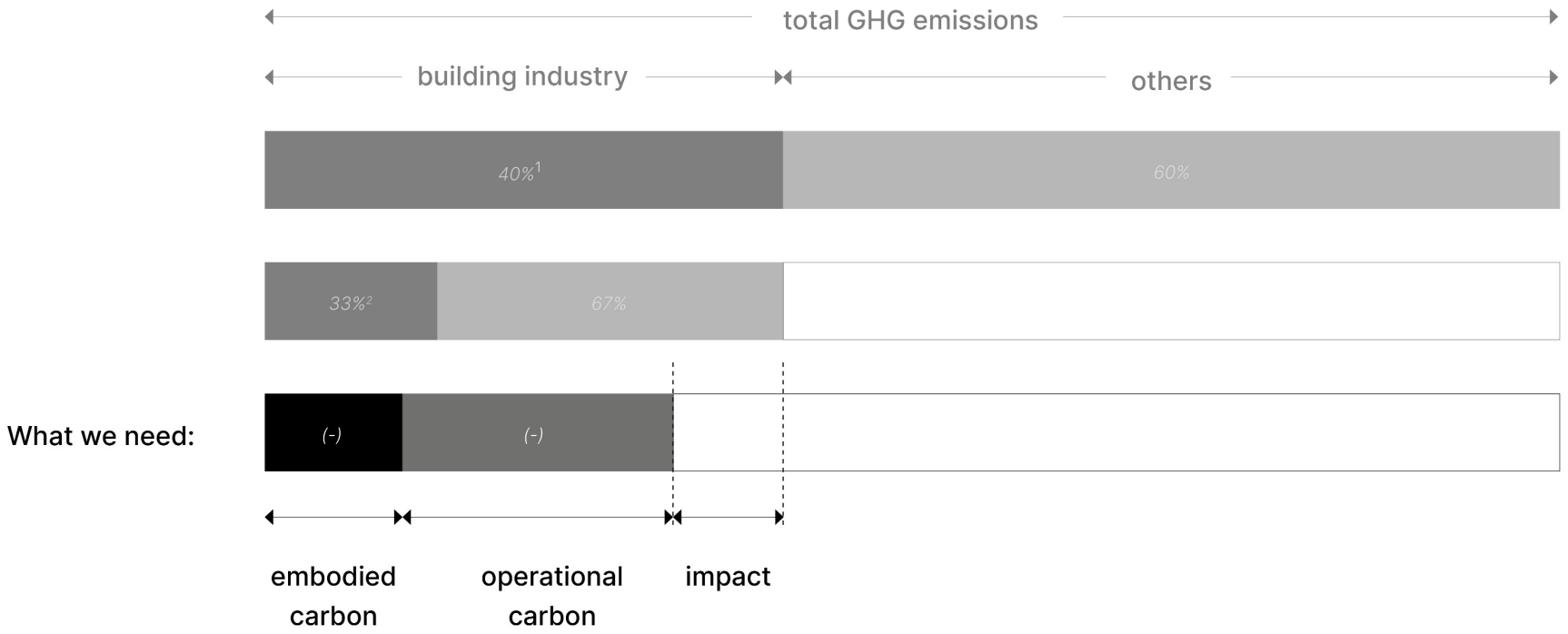

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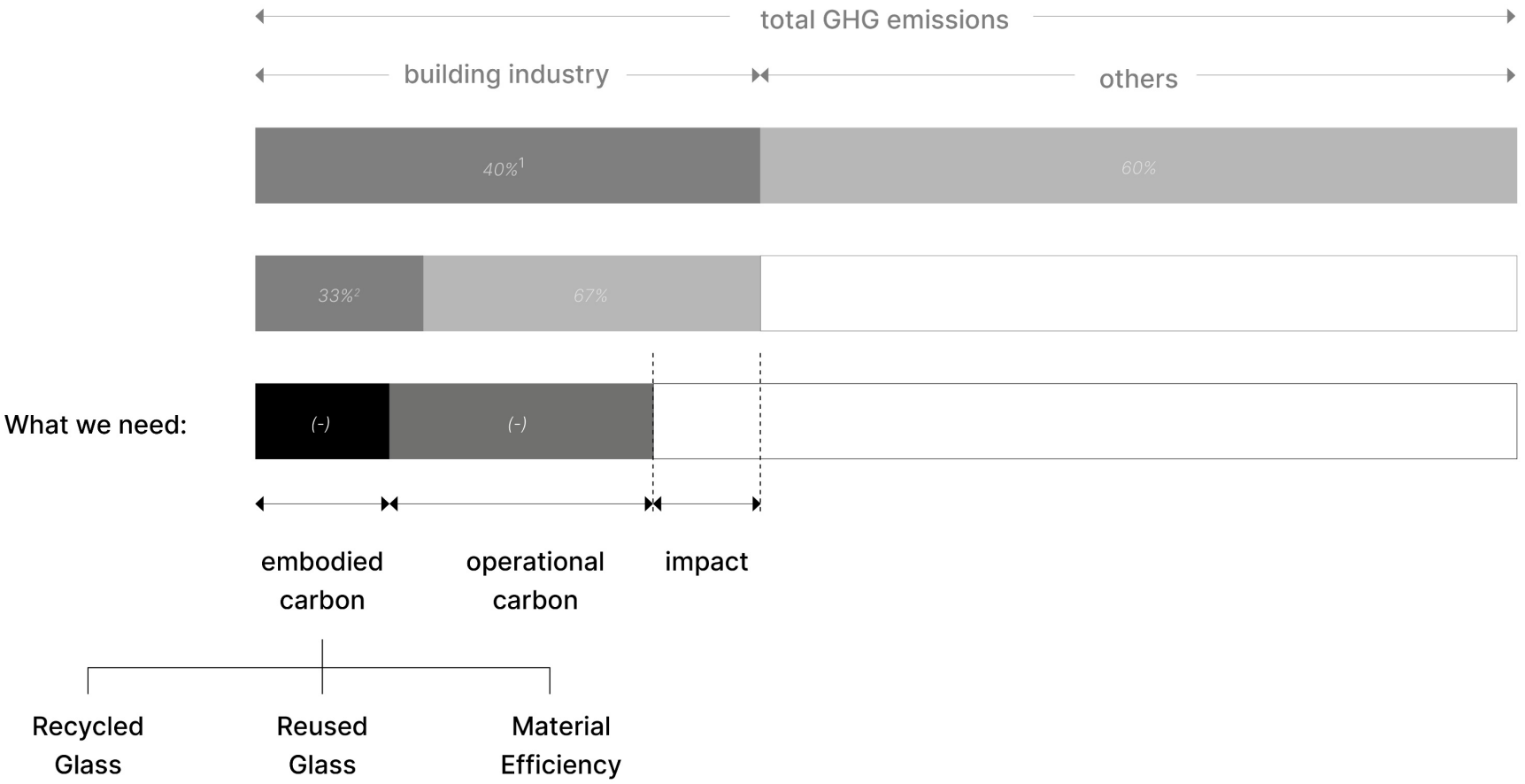

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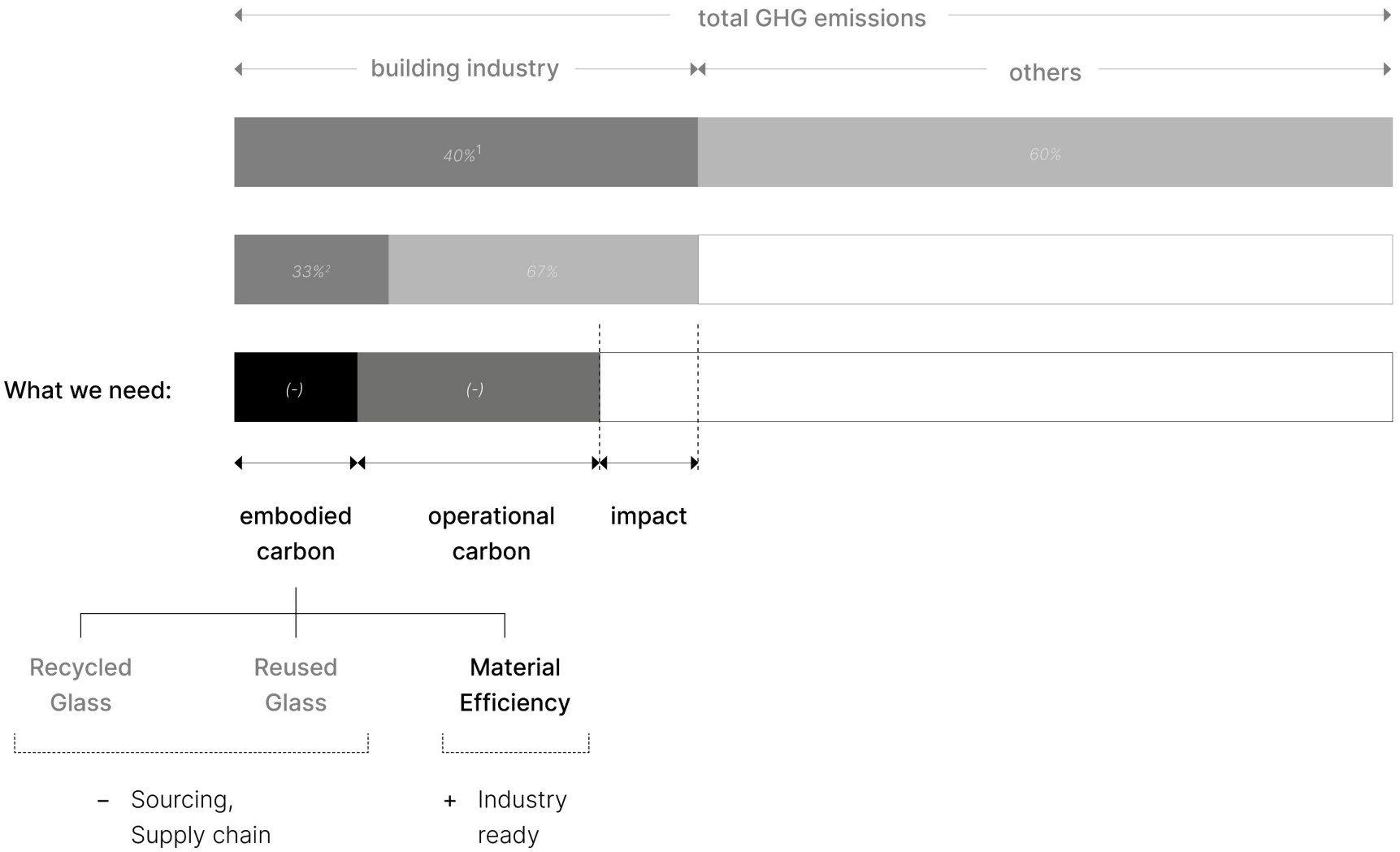
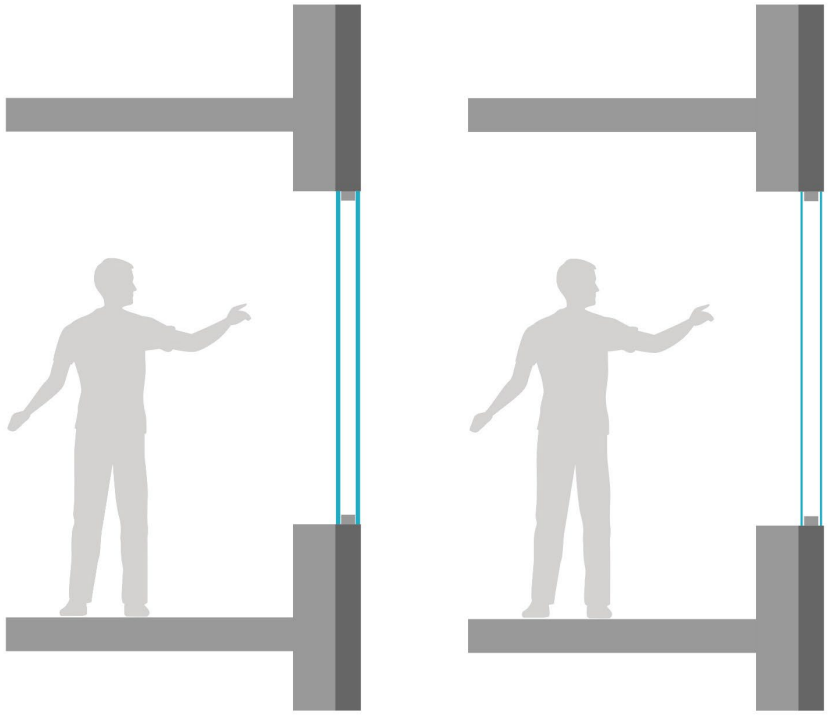


Material Efficiency

AGC Falcon (Aluminosilicate)
Thin glass : 0.5mm to 2.0 mm thickness[1]

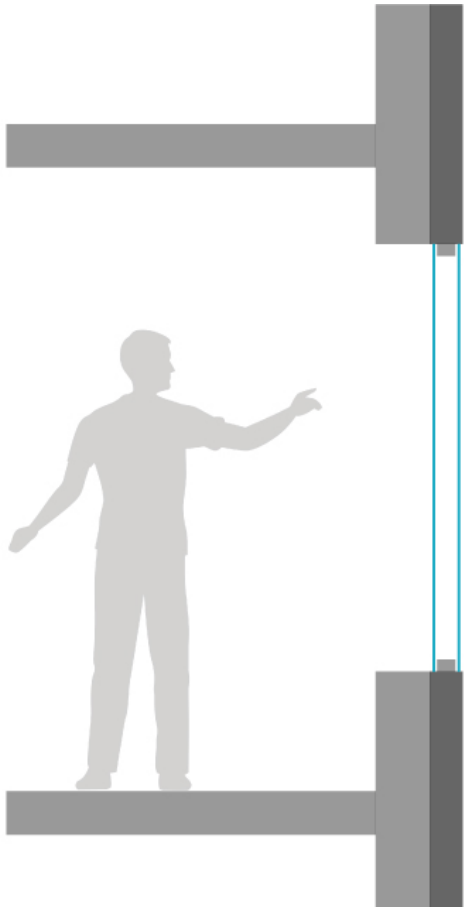
AGC Fineo
Vacuum Insulated Glazing: 4-0.1-8 mm[2]

OR

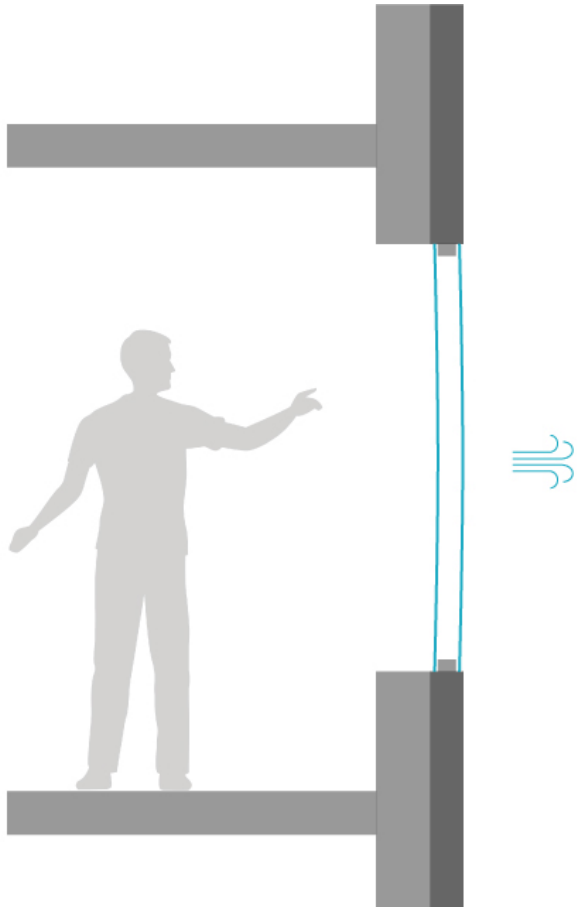


Reducing thickness of conventional facade glazing

Material Efficiency



Effect of climate loading

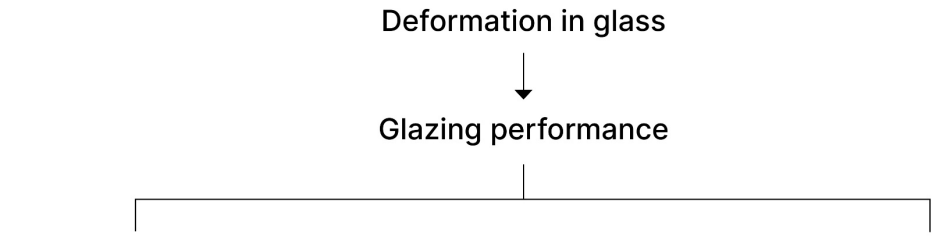


Effect of wind loading

Serviceability Limits in facade glazing → Deformation in glass

Deformations

Performance criteria



Objective criteria

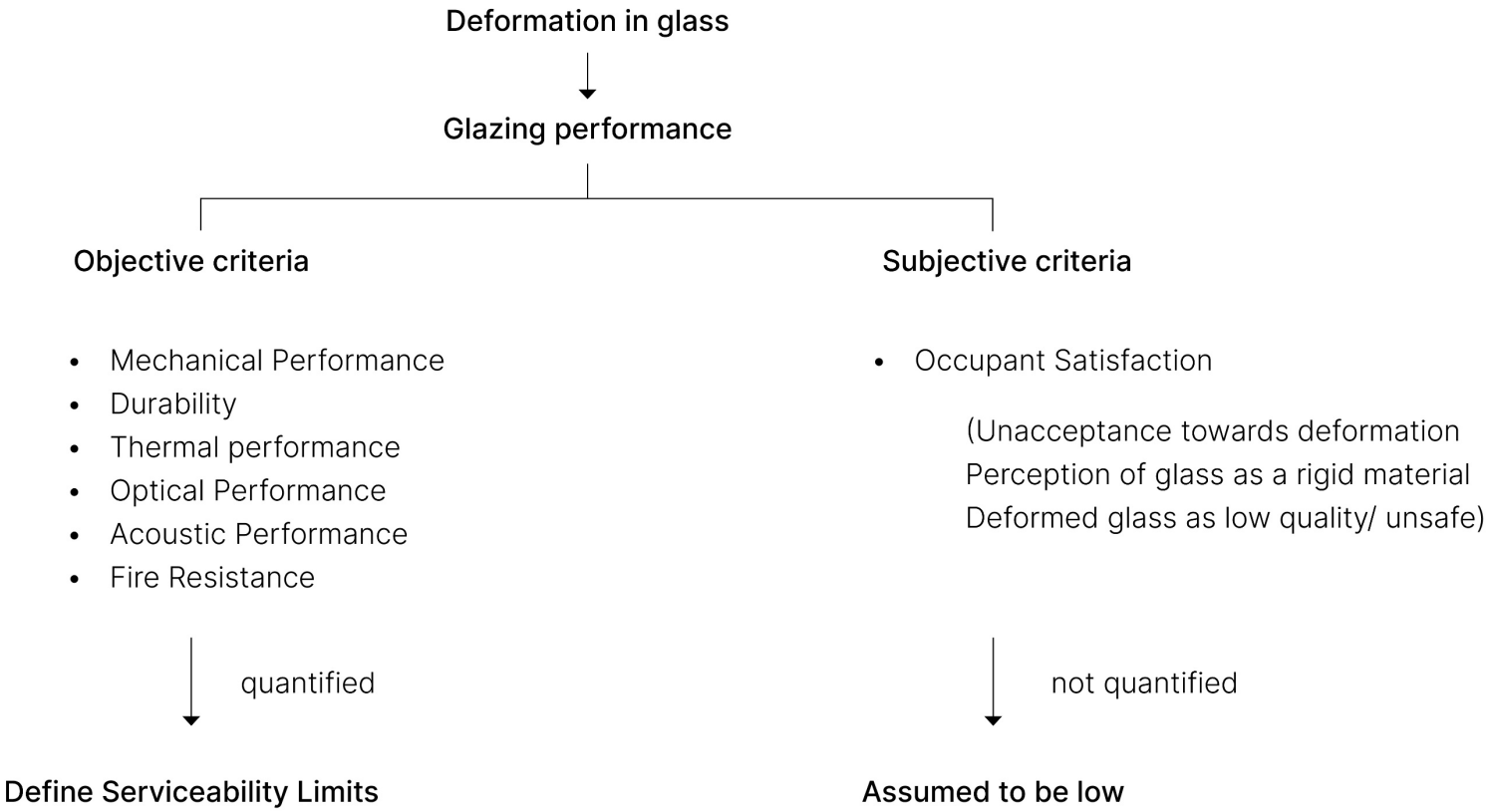
- Mechanical Performance
- Durability
- Thermal performance
- Optical Performance
- Acoustic Performance
- Fire Resistance

Subjective criteria

- Occupant Satisfaction

  (Unacceptance towards deformation
  Perception of glass as a rigid material
  Deformed glass as low quality/ unsafe)

Performance criteria



Performance criteria

Deformation in glass

↓

Glazing performance

Objective criteria

- Mechanical Performance
- Durability
- Thermal performance
- Optical Performance
- Acoustic Performance
- Fire Resistance

↓ quantified

Define Serviceability Limits

Subjective criteria

- Occupant Satisfaction

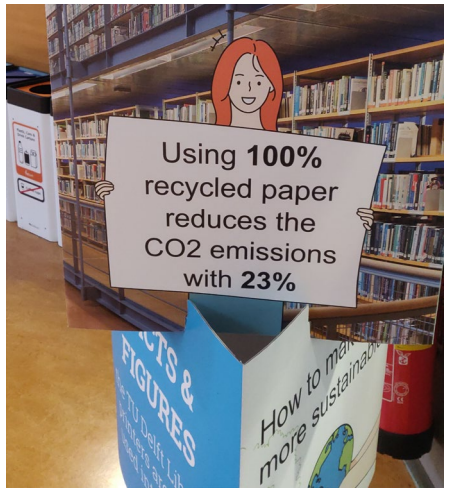
  (Unacceptance towards deformation
  Perception of glass as a rigid material
  Deformed glass as low quality/ unsafe)

↓ not quantified

Assumed to be low

+ Require fulfilment of objective criteria
+ Thresholds can be increased to accommodate imperfections
+ Important for comprehensive definition of serviceability limits

Performance criteria



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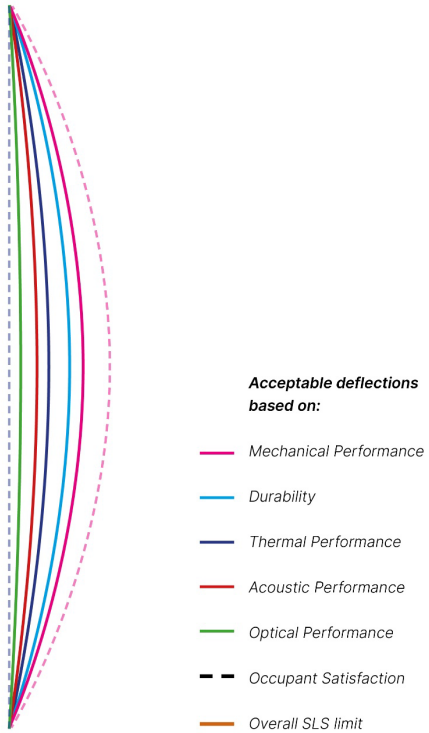
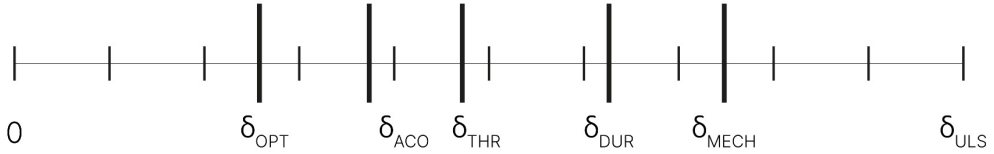
Serviceability limits based on criteria



Acceptable deflections based on:

- *Mechanical Performance*
- *Durability*
- *Thermal Performance*
- *Acoustic Performance*
- *Optical Performance*
- *Occupant Satisfaction*
- *Overall SLS limit*



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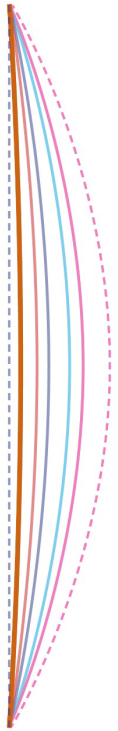

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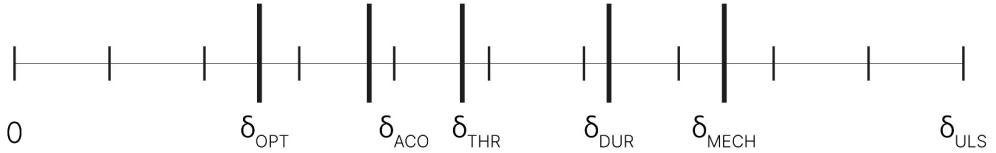

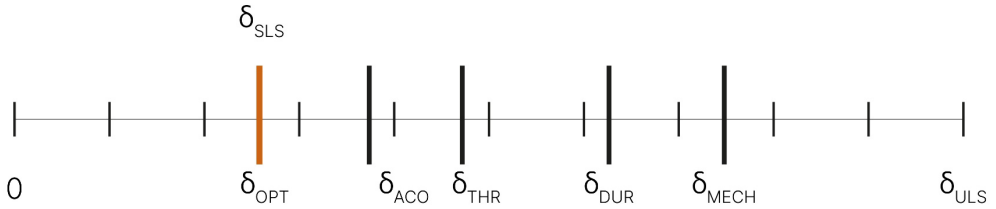

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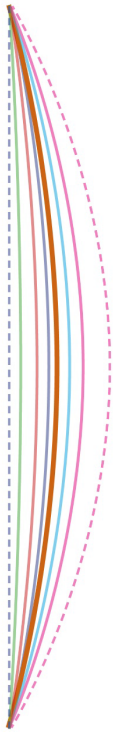

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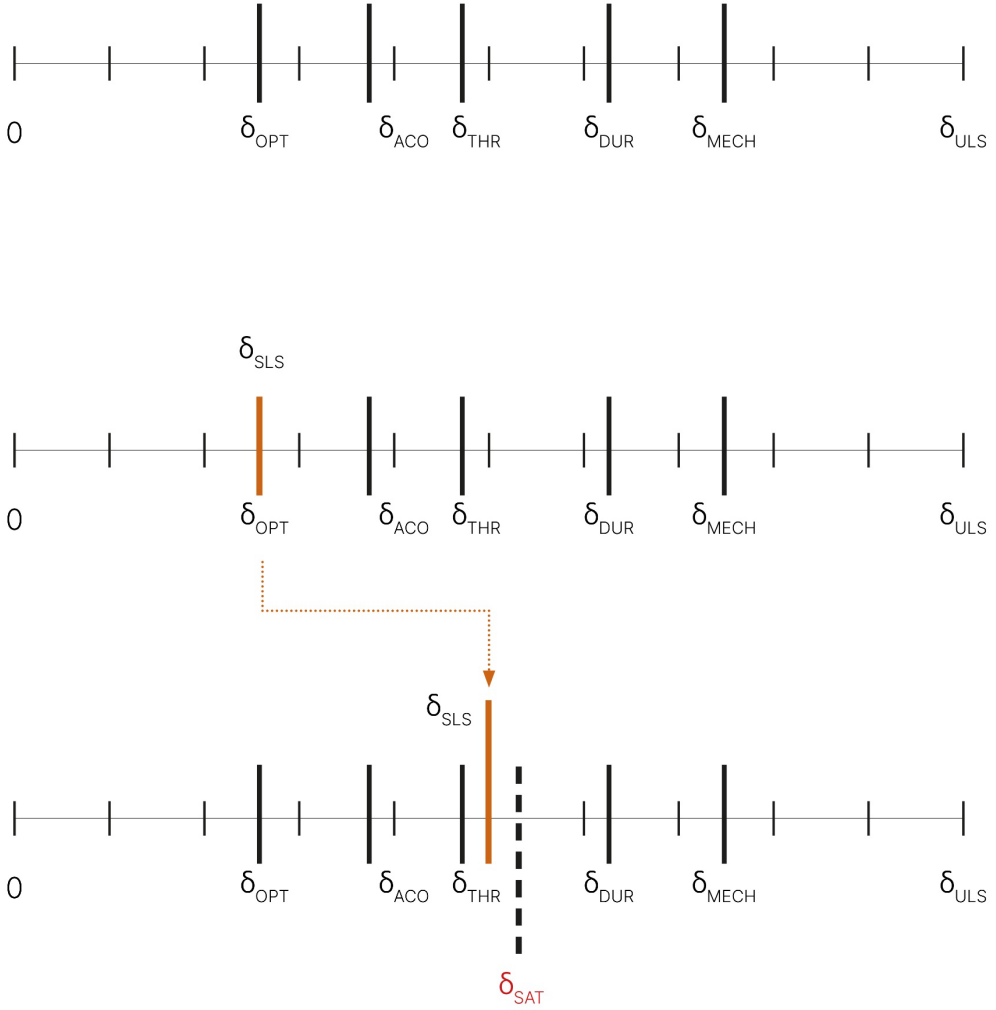


Hypothesis

Conventional perception of glass as a rigid material influences the acceptance threshold of deformation.

Increasing the threshold of acceptance could pave way for transition towards use of thinner glass in facades.

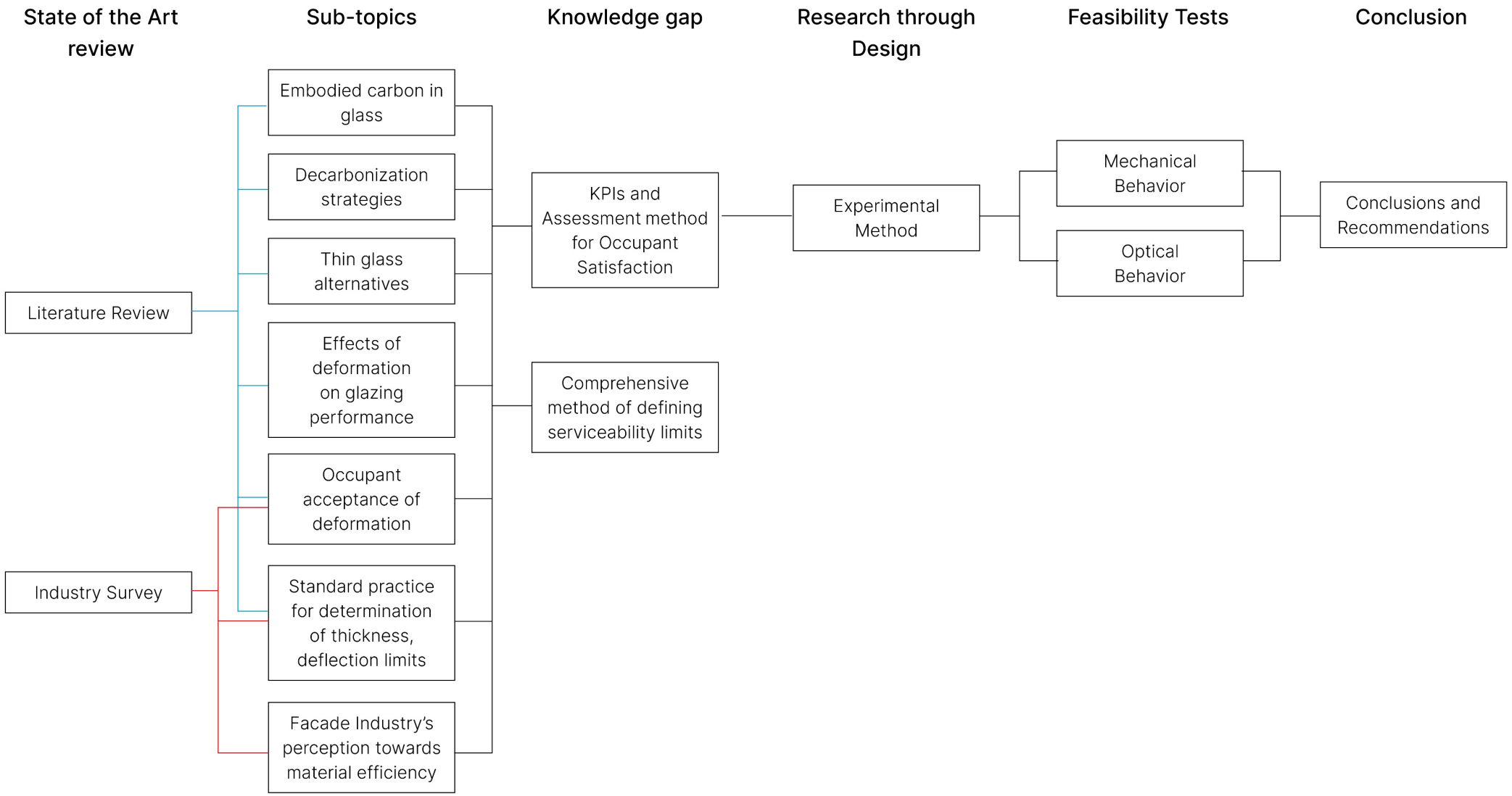
Research Question

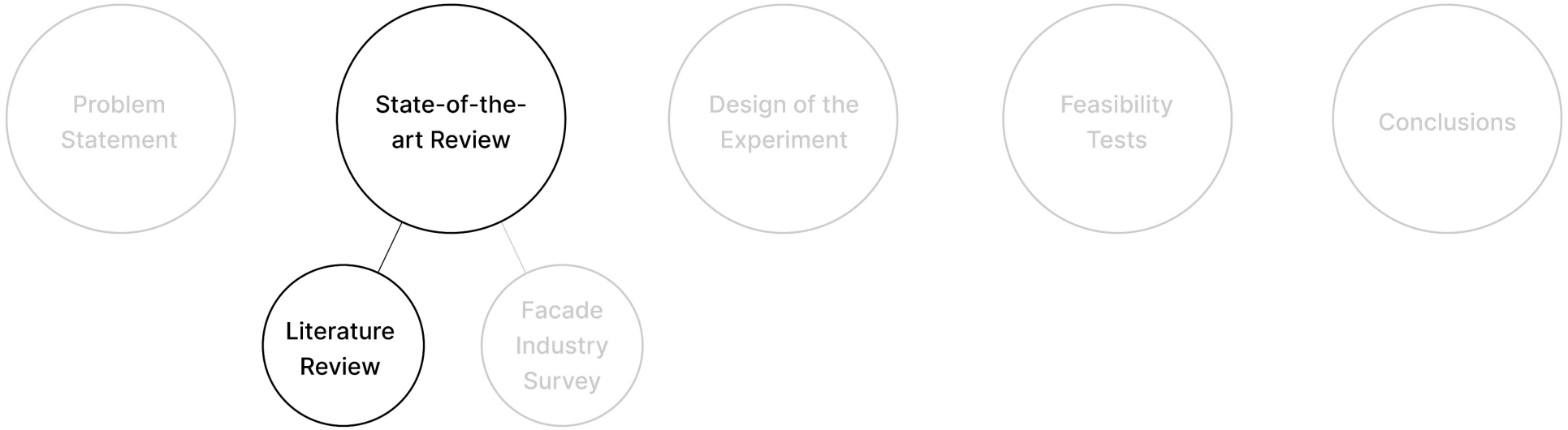
How can we empirically determine the relationship between occupant satisfaction and level of deformation in façade glazing?

Research Methods

Research Question	Sub Questions	Methods
How can we empirically determine the relationship between occupant satisfaction and level of deformation in façade glazing?	What are the factors influencing amount of deformation in façade glazing?	Literature Review
	What are the effects of deformation of façade glazing on its performance?	Literature Review
	What are all the serviceability criteria that govern the limits on façade deformation?	Façade Industry Survey and Literature Review
	Which criteria and industry standards are followed in practice to determine the glass thickness and deflection limits?	Façade Industry Survey and Literature Review
Design Question	What is a feasible method to empirically determine the relationship between occupant satisfaction and level of deformation in façade glazing?'	Research Through Design
	What is the level of occupant acceptance towards façade deformation under wind or climatic loads?	Experiment

Process


State of the Art review
Sub-topics
Knowledge gap
Research through Design
Feasibility Tests
Conclusion
Literature Review
Industry Survey
Embodied carbon in glass
Decarbonization strategies
Thin glass alternatives
Effects of deformation on glazing performance
Occupant acceptance of deformation
Standard practice for determination of thickness, deflection limits
Facade Industry's perception towards material efficiency
KPIs and Assessment method for Occupant Satisfaction
Comprehensive method of defining serviceability limits
Experimental Method
Mechanical Behavior
Optical Behavior
Conclusions and Recommendations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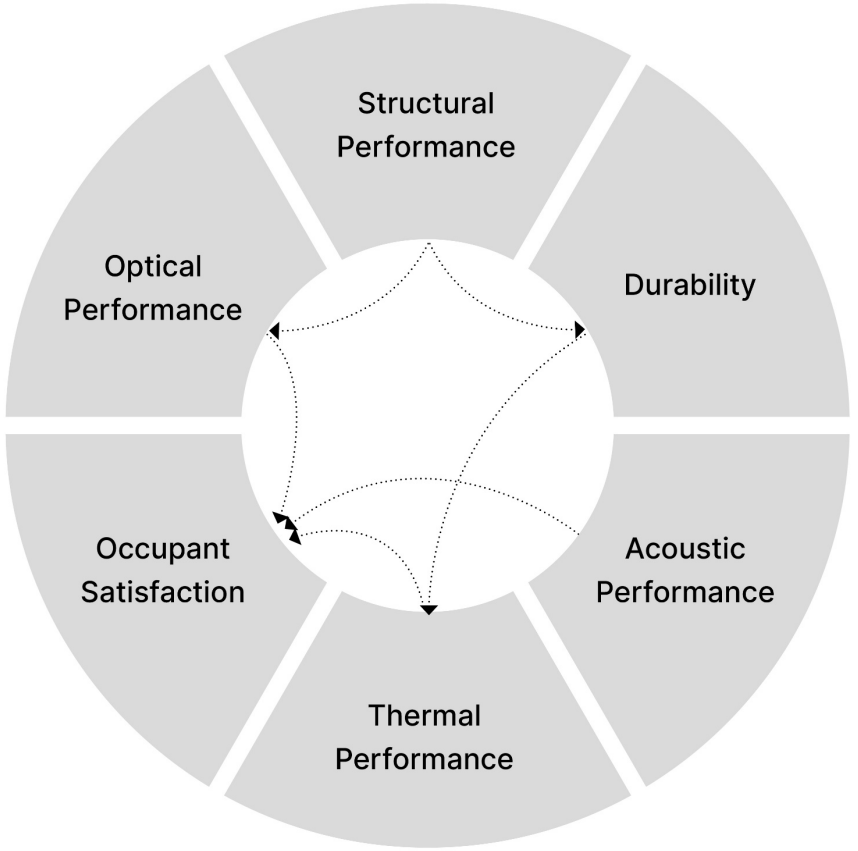
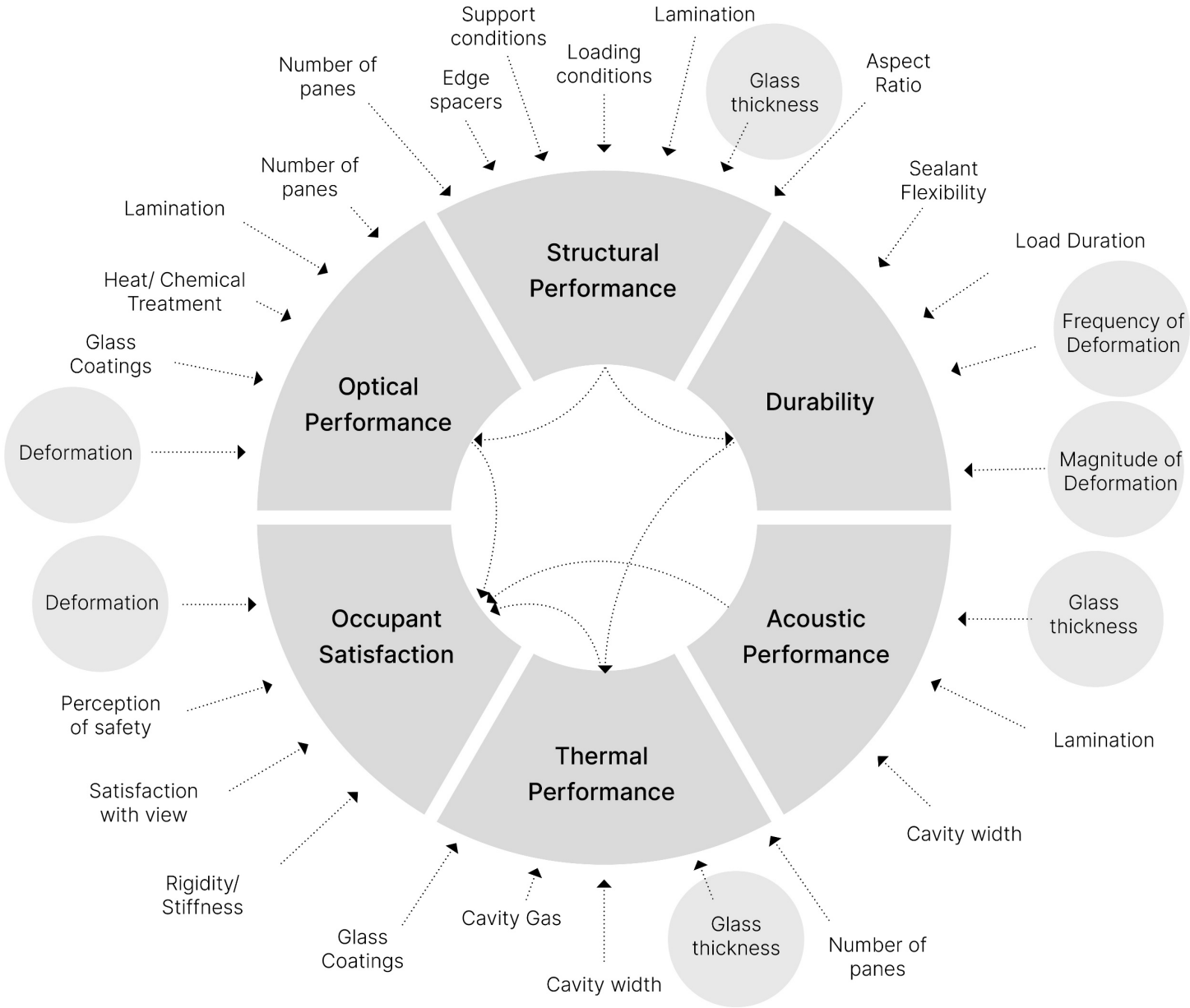
Interdependency of performance indicators

- Performance criteria are interdependent.
- Occupant satisfaction depends on optical, thermal and acoustical performance.



Interdependency of performance indicators

- Performance criteria are interdependent.
- Occupant satisfaction depends on optical, thermal and acoustical performance.
- Glass thickness/ deformation alone does not affect any performance criteria.



Effects of deformation on glazing performance

- Performance criteria are interdependent.
- Occupant satisfaction depends on optical, thermal and acoustical performance.
- Glass thickness/ deformation alone does not affect any performance criteria.
- Performance indicators and assessment methods for occupant satisfaction were not found.

Glazing properties affected by deformation	Primary Effects of deformation	Performance Indicators	Assessment methods as per literature review	Alternative assessment methods
Structural Performance	Unfavourable stress concentrations; effect of load sharing; buckling performance	Stress and strain states	Numerical and analytical methods; lab testing	Not required
Durability	Excessive and repetitive straining of sealants resulting in leakage of air cavity	Edge strain in glass	Numerical and analytical methods; lab testing	Not required
Thermal Performance	Climate loads cause change in gap-width of IGU, affecting its thermal performance	U-value of glazing	Numerical and analytical methods; field measurement	Not required
Optical Performance	Distortions in reflected image and view through glazing	Optical distortion	Zebra-board testing (not sufficient)	Field testing, high precision optical simulations
Acoustic Performance	Change of gap width causing change in acoustic performance.	R-value	Not found	Field testing, Lab testing
Occupant Satisfaction	Feeling of alarm or disturbance due to movement in glass	**Not defined**	**Not found**	**Empirical assessment through experiment**

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Standards governing glass thickness and deflection limits

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- Comprehensive assessment of serviceability is not done.
- Limits in different criteria are different and the basis for the limits was not clear.

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1990:2002+A1

December 2005

ICS 91.010.30

Supersedes ENV 1991-1:1994
Incorporating corrigenda December 2008 and April 2010

English version

Eurocode - Basis of structural design

Eurocodes structuraux - Eurocodes: Bases de calcul des structures

Eurocode: Grundlagen der Tragwerksplanung

This European Standard was approved by CEN on 29 November 2001.

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Management Centre: rue de Stassart, 36 B-1050 Brussels

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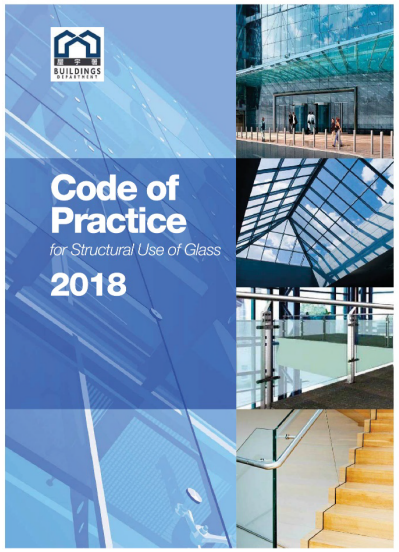
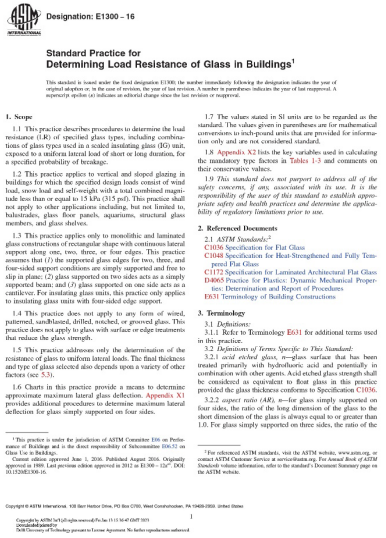
Ref. No. EN 1990:2002

EN 1990:2002 - Eurocode: Basis of structural design



Code of Practice for Structural Use of Glass, 2018, Buildings Department of Hong Kong



Designation: E1300 – 16

Standard Practice for Determining Load Resistance of Glass in Buildings[1]

This standard is issued under the fixed designation E1300; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes procedures to determine the load resistance (LR) of specified glass types, including combinations of glass types used in a sealed insulating glass (IG) unit, exposed to a uniform lateral load of short or long duration, for a specified probability of breakage.

1.2 This practice applies to vertical and sloped glazing in buildings for which the specified design loads consist of wind load, snow load and self-weight with a total combined magnitude less than or equal to 15 kPa (315 psf). This practice shall not apply to other applications including, but not limited to, balustrades, glass floor panels, aquariums, structural glass members, and glass shelves.

1.3 This practice applies only to monolithic and laminated glass constructions of rectangular shape with continuous lateral support along one, two, three, or four edges. This practice assumes that (1) the supported glass edges for two, three, and four-sided support conditions are simply supported and free to slip in plane; (2) glass supported on two sides acts as a simply supported beam; and (3) glass supported on one side acts as a cantilever. For insulating glass units, this practice only applies to insulating glass units with four-sided edge support.

1.4 This practice does not apply to any form of wired, patterned, sandblasted, drilled, notched, or grooved glass. This practice does not apply to glass with surface or edge treatments that reduce the glass strength.

1.5 This practice addresses only the determination of the resistance of glass to uniform lateral loads. The final thickness and type of glass selected also depends upon a variety of other factors (see 5.3).

1.6 Charts in this practice provide a means to determine approximate maximum lateral glass deflection. Appendix X1 provides additional procedures to determine maximum lateral deflection for glass simply supported on four sides.

1.7 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for mathematical conversions to inch-pound units that are provided for information only and are not considered standard.

1.8 Appendix X2 lists the key variables used in calculating the mandatory type factors in Tables 1-3 and comments on their conservative values.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
C1036 Specification for Flat Glass
C1048 Specification for Heat-Strengthened and Fully Tempered Flat Glass
C1172 Specification for Laminated Architectural Flat Glass
D4065 Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures
E631 Terminology of Building Constructions

3. Terminology

3.1 *Definitions:*
3.1.1 Refer to Terminology E631 for additional terms used in this practice.
3.2 *Definitions of Terms Specific to This Standard:*
3.2.1 *acid etched glass, n*—glass surface that has been treated primarily with hydrofluoric acid and potentially in combination with other agents. Acid etched glass strength shall be considered as equivalent to float glass in this practice provided the glass thickness conforms to Specification C1036.
3.2.2 *aspect ratio (AR), n*—for glass simply supported on four sides, the ratio of the long dimension of the glass to the short dimension of the glass is always equal to or greater than 1.0. For glass simply supported on three sides, the ratio of the

[1] This practice is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.52 on Glass Use in Buildings.
Current edition approved June 1, 2016. Published August 2016. Originally approved in 1988. Last previous edition approved in 2012 as E1300 – 12a[ε]. DOI: 10.1520/E1300-16.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

ASTM E1300-16 - Determining load resistance of Glass in Buildings

TECHNICAL SPECIFICATION
SPÉCIFICATION TECHNIQUE
TECHNISCHE SPEZIFIKATION

FINAL DRAFT
FprCEN/TS 19100-1

April 2021

ICS 91.080.99

English Version

Design of glass structures - Part 1: Basis of design and materials

Conception et calcul des structures en verre - Partie 1 : Bases de conception et matériaux

Bemessung und Konstruktion von Tragwerken aus Glas - Teil 1: Grundlagen der Bemessung und Materialien

This draft Technical Specification is submitted to CEN members for Vote. It has been drawn up by the Technical Committee CEN/TC 250.

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Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

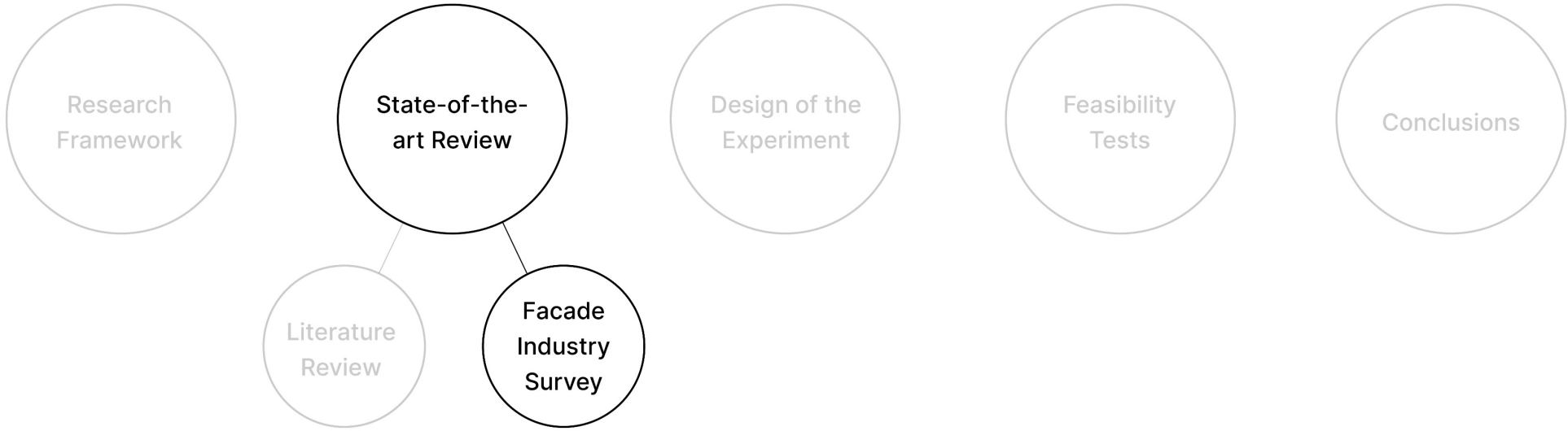
Warning : This document is not a Technical Specification. It is distributed for review and comments. It is subject to change without notice and shall not be referred to as a Technical Specification.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

Ref. No. FprCEN/TS 19100-1:2021 E

FprCEN/TS 19100 - Final Draft: Design of glass structures (Parts 1, 2 and 3)

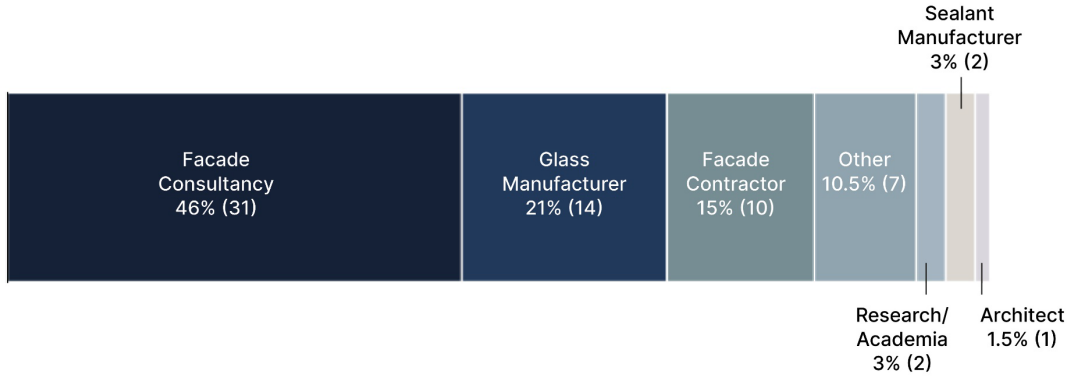

Research Framework
State-of-the-art Review
Literature Review
Facade Industry Survey
Design of the Experiment
Feasibility Tests
Conclusions

Respondents

- Sent to 200+ professionals from the facade industry
- 67 responses were found fit for analysis
- Mainly Consultants/ Engineers from Facade Consultancy. Glass Manufacturing company or Facade Contractors

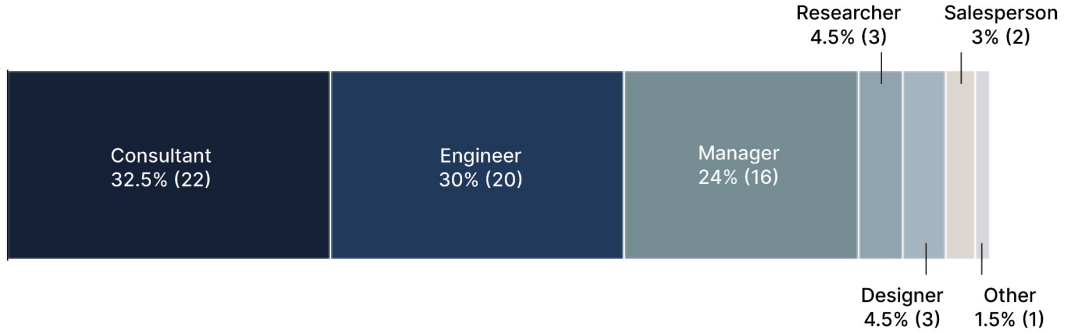
Organization type

Q2.1 Which of the following best describes your organization?



Role in the company

Q2.2 How would you best describe your role in the organization?

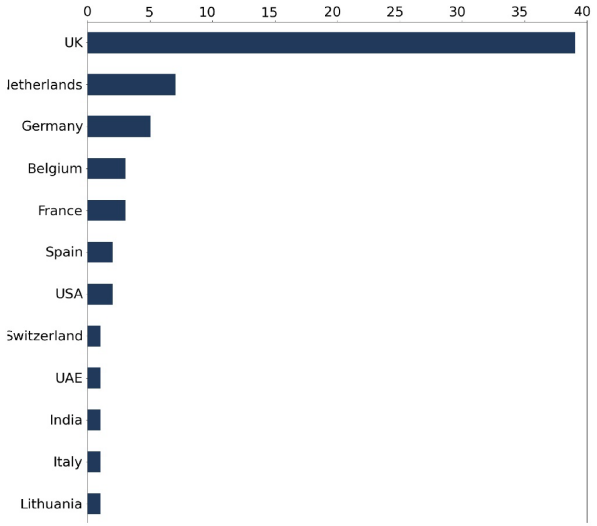


Respondents

- Sent to 200+ professionals from the facade industry
- 67 responses were found fit for analysis
- Mainly Consultants/ Engineers from Facade Consultancy. Glass Manufacturing company or Facade Contractors
- Maximum respondents based out of the UK
- Moderate to High level of knowledge on SLS

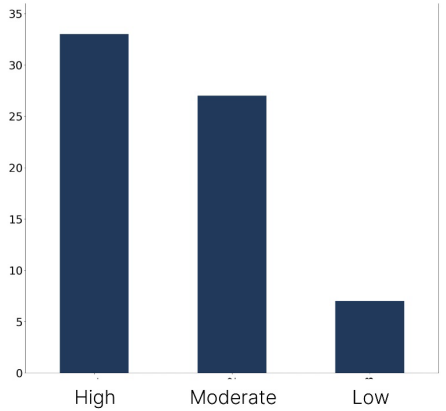
Respondents' Location

Q2.5 Which country are you currently based out of?



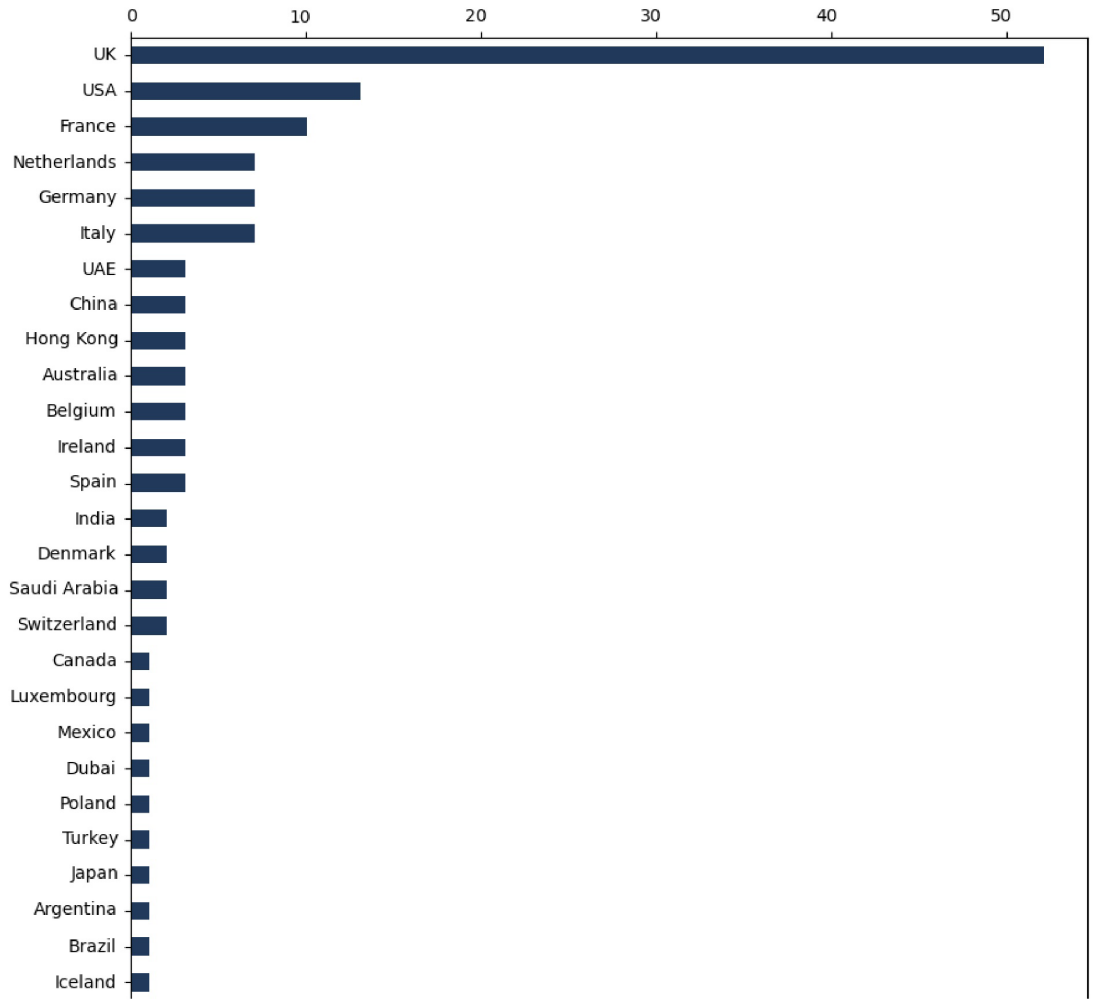
SLS knowledge

Q4.1 How would you rate your knowledge on serviceability limits of glass in facades?



Project Location

Q3.2 In which countries are some of the major projects you are working on located?



Types of responses and analysis

- Sent to 200+ professionals from the facade industry
- 67 responses were found fit for analysis
- Mainly Consultants/ Engineers from Facade Consultancy. Glass Manufacturing company or Facade Contractors
- Maximum respondents based out of the UK
- Moderate to High level of knowledge on SLS
- Quantitative and Qualitative analysis was conducted

Numerical

Responses indicated on a scale of 1-5

e.g. Perceived effects of deformation, reduced glass thickness, etc.

Text

Responses in the form of free text

Checklist

e.g. Optical defects, guidelines followed, etc.

Descriptive

e.g. Information required to help specify thinner glass, likeliness to recommend thinner glass, etc.

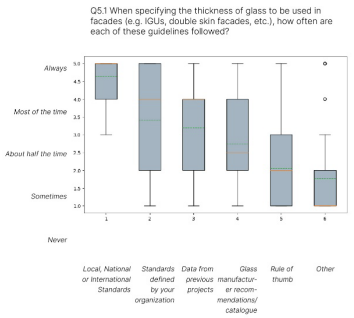
Quantitative Analysis

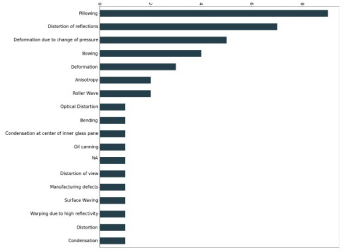
Box Plots, Bar Charts

Qualitative Analysis

Code-based Inductive Analysis

ATLAS.ti QUALITATIVE DATA ANALYSIS

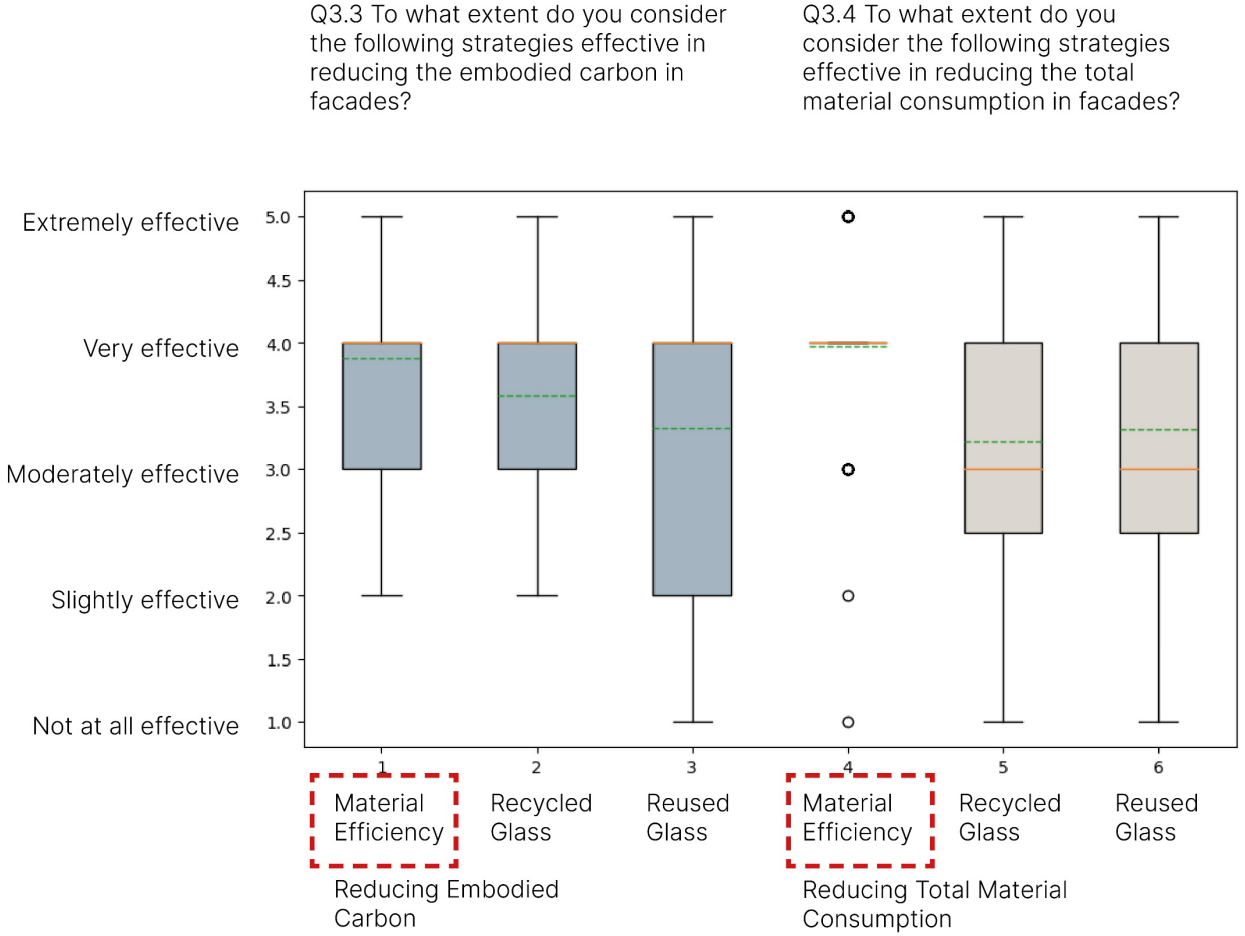




	ORG:1_GlassMan	ORG:2_SealMan	ORG:3_FacCons	ORG:4_FacCont	ORG:6_Architect	ORG:7_Other	Totals
NEED: Change in aesthetic goals			2				2
NEED: Changes to conventional design approach		1					1
NEED: Distinction between performance and deflections						1	1
NEED: Partial factors clearly defined			1				1
NEED: Scale of production	1	1					2
NEED: To educate stakeholders	1		3	1		1	6
NEED: To lower acoustical requirements	1		1				2
NEED: To lower safety factors			1				1
NEED: To update standards			2	4			6
NEED: Updated calculation tools			1	2		1	4
NEED: What to include in standards	3		3	2		1	9
NEED: Wind tunnel calculations				2			2
Totals	6	2	14	11	0	4	37

Perceived effect of sustainable strategies

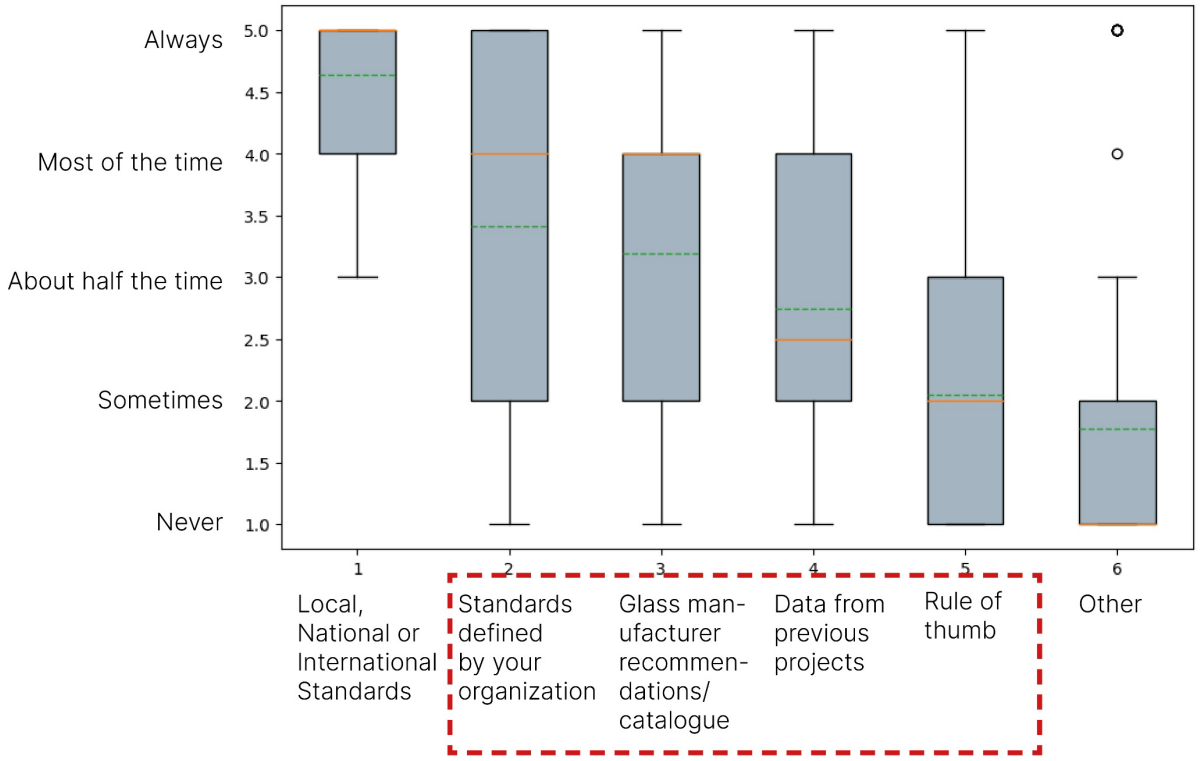
- Material Efficiency is perceived as a more effective strategy compared to using reused or recycled glass



Guidelines followed in practice

- Material Efficiency is perceived as a more effective strategy compared to using reused or recycled glass
- In addition to standards, other guidelines also followed.

Q5.1 When specifying the thickness of glass to be used in facades (e.g. IGUs, double skin facades, etc.), how often are each of these guidelines followed?



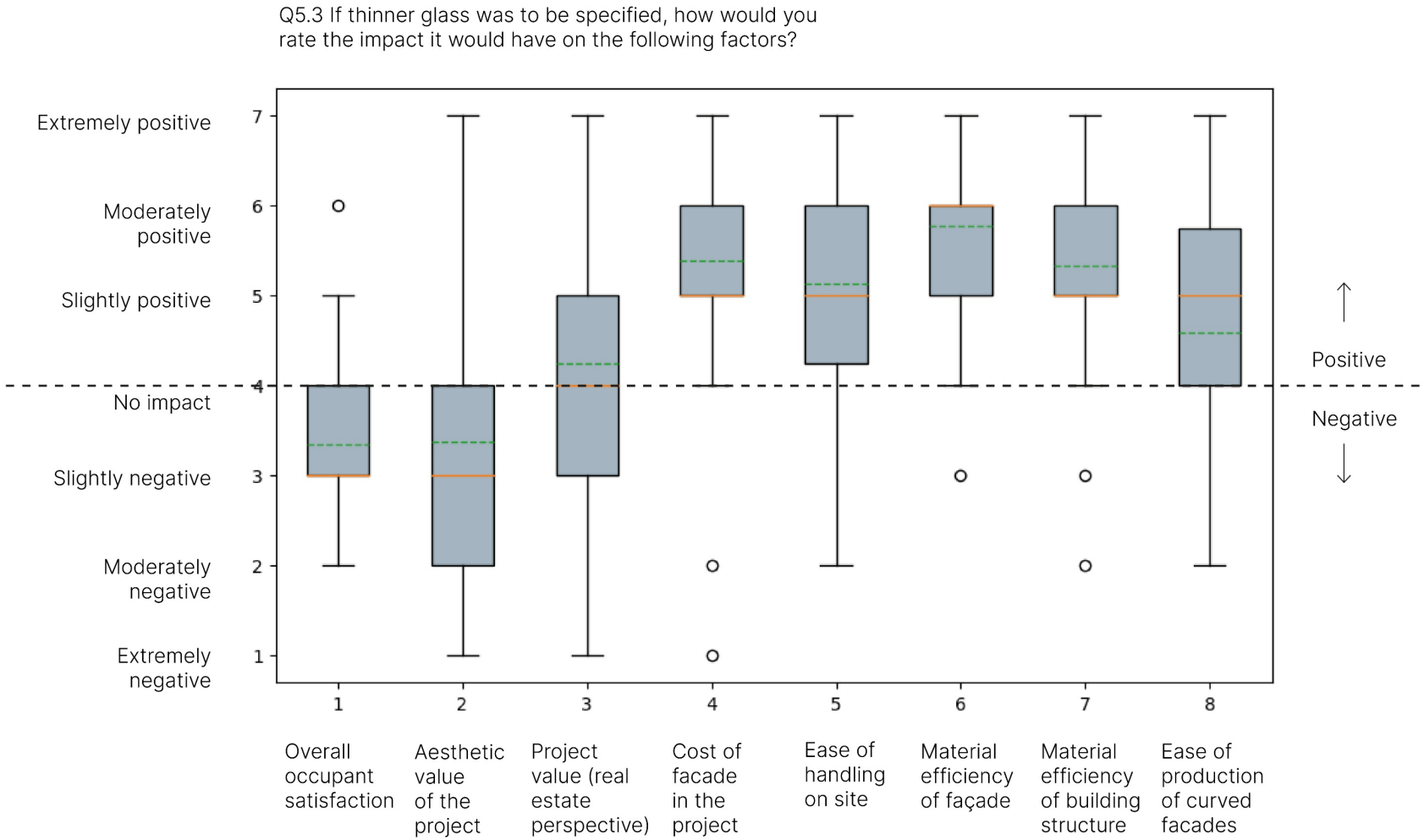
Criteria to determine glass thickness

- Material Efficiency is perceived as a more effective strategy compared to using reused or recycled glass
- In addition to standards, other guidelines also followed.
- Criteria for glass thickness in order of importance - Mechanical, Durability and Optical

Acoustic	Acoustic Performance		Glass stress Limits
Durability	Adhesive/ Cohesive failure of edge seals and weather seals		Intrusion Resistance
	Condensation resistance		Mode of breakage
	Durability		Post breakage behavior
	Weathering Conditions		Resonance
Feasibility	Client Needs		Safety
	Availability as per standard stock		Soft body impact
	Production feasibility		Stability
	Technical feasibility		Vibration frequency
Fire	Fire Resistance		VIV and other wind instabilities
Maintenance	Cleaning and Maintenance		Altitude difference
Mechanical	Breakage by climatic loads, thermal stress or impact	**Optical**	Optical defects - reflection distortion
	Deflection		Optical defects - roller wave distortion
	Deflection for occupant comfort		Optical performance
	Deflection under barrier loads		Solar factor
	Deflection under climatic loads		Visual replacement
	Deflection under mechanical loads	**Sustainability**	Carbon Footprint
	Edge Deflection		Conflict Materials
	Edge Stability		Life Cycle
	Eigen Frequency		Recycled content
	Glass strength	**Thermal**	Thermal Performance

Impact on value

- Material Efficiency is perceived as a more effective strategy compared to using reused or recycled glass
- In addition to standards, other guidelines also followed.
- Criteria for glass thickness in order of importance - Mechanical, Durability and Optical
- Negative impact on Aesthetics, occupant satisfaction
- Positive impact on costs, operations, curved facades and overall material efficiency



Barriers

- Material Efficiency is perceived as a more effective strategy compared to using reused or recycled glass
- In addition to standards, other guidelines also followed.
- Criteria for glass thickness in order of importance - Mechanical, Durability and Optical
- Negative impact on Aesthetics, occupant satisfaction
- Positive impact on costs, operations, curved facades and overall material efficiency
- Main barriers: Lack of data, high level of requirements, perception towards glass and conservative standards.

Conservative design approach	Consultants being conservative Not learning from other countries/ peers
Lack of data	On engineering properties of thinner glass On occupant/ user acceptance levels of deformation
Changes required	To glazing systems In warranties and liabilities
Perceived challenges	Manufacturing Effect on glazing performance Handling and transportation Structural calculations
High level of requirements	Architectural/ aesthetic quality Robustness Optical performance Acoustic
Manufacturing challenges	Lines not being well equipped Cost and scale required to implement change
Perception	Of deformation as inferior quality Of deformation as unsafe Of glass as a rigid material
Standards	Being conservative Being non uniform across countries Not being up to date

Conclusions

- Willingness to implement material efficiency
- Barriers: Conventional perception, design methods and standards
- Needs: Scientific research on impact of deformation on objective performance and occupant satisfaction
- Not answered: Who are the main actors to bring about change - architects/ owners/ consultants?

Problem Statement

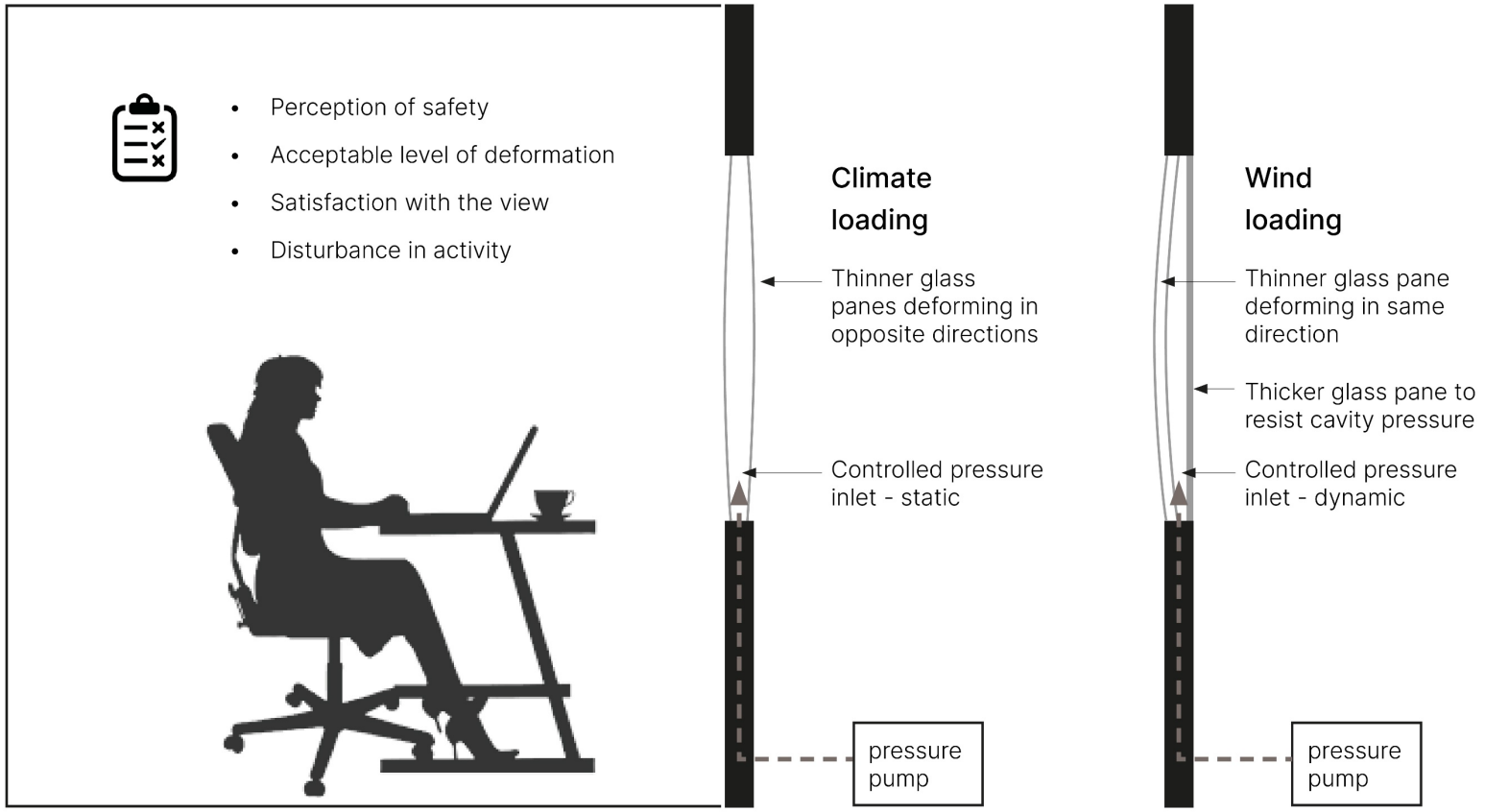
State-of-the-art Review

Design of the Experiment

Feasibility Tests

Conclusions

Concept


Perception of safety
Acceptable level of deformation
Satisfaction with the view
Disturbance in activity
Climate loading
Thinner glass panes deforming in opposite directions
Controlled pressure inlet - static
pressure pump
Wind loading
Thinner glass pane deforming in same direction
Thicker glass pane to resist cavity pressure
Controlled pressure inlet - dynamic
pressure pump

Concept

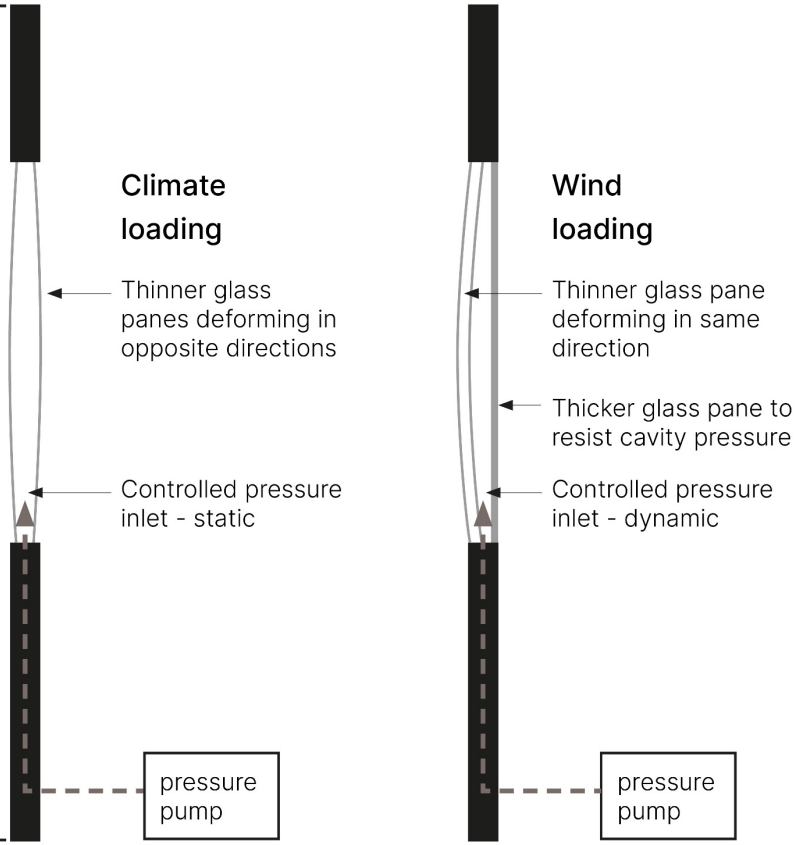
Method

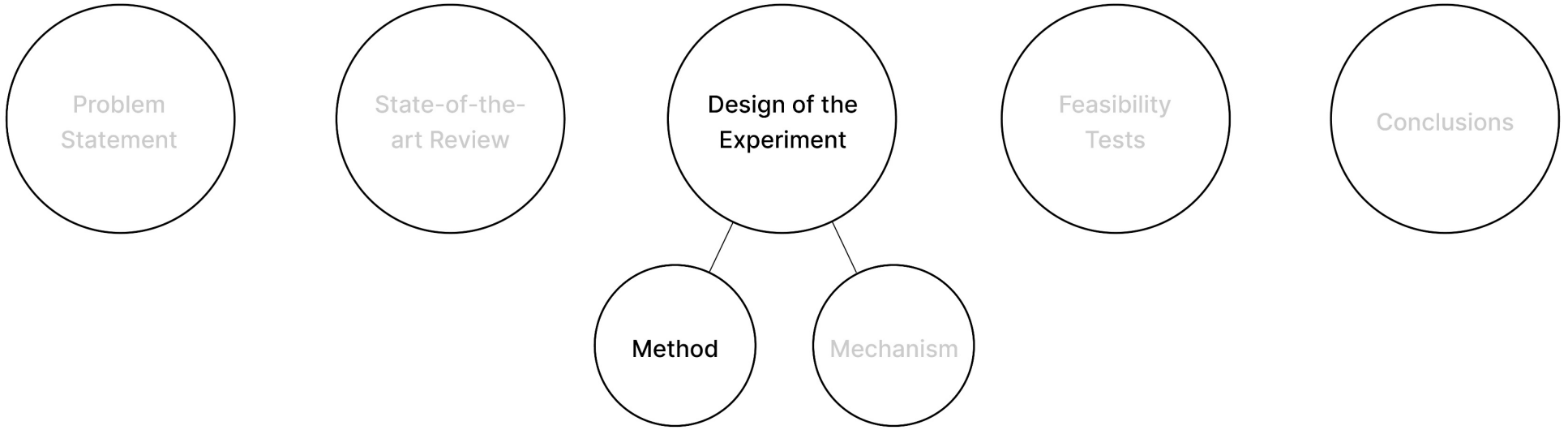
to gather statistically significant data

- Perception of safety
- Acceptable level of deformation
- Satisfaction with the view
- Disturbance in activity

Mechanism

to achieve controlled deformation of glass




Problem Statement
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Method
Mechanism

Experiment - Variables

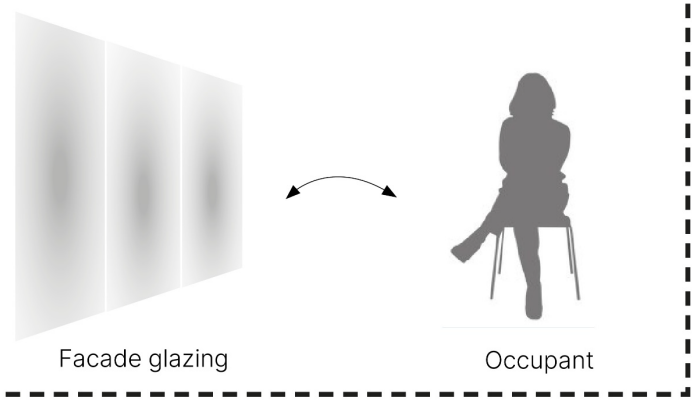
Experiment - Variables

Manipulated

Independent Variables

Nature of motion

- Centre of glass deflection
- Frequency of deformation
- Duration of deformation



Dependent Variables

Recorded

Occupant Satisfaction

- Perception of Safety
- Acceptance of Deformation
- Satisfaction with respect to view
- Disturbance in activity

Fixed/ Balanced

Confounding Variables

Recorded

Controlled (per group)

External Factors

- Acoustic Cues
- Visual Cues
- View
- Time of the day
- Weather
- Type of façade
- Indoor Environment Quality (temperature, humidity, air quality etc.)

Relationship between occupant and facade

- Distance in between body and facade
- Body's orientation
- Body's motion
- Activity performed/ engagement with façade

Individual traits

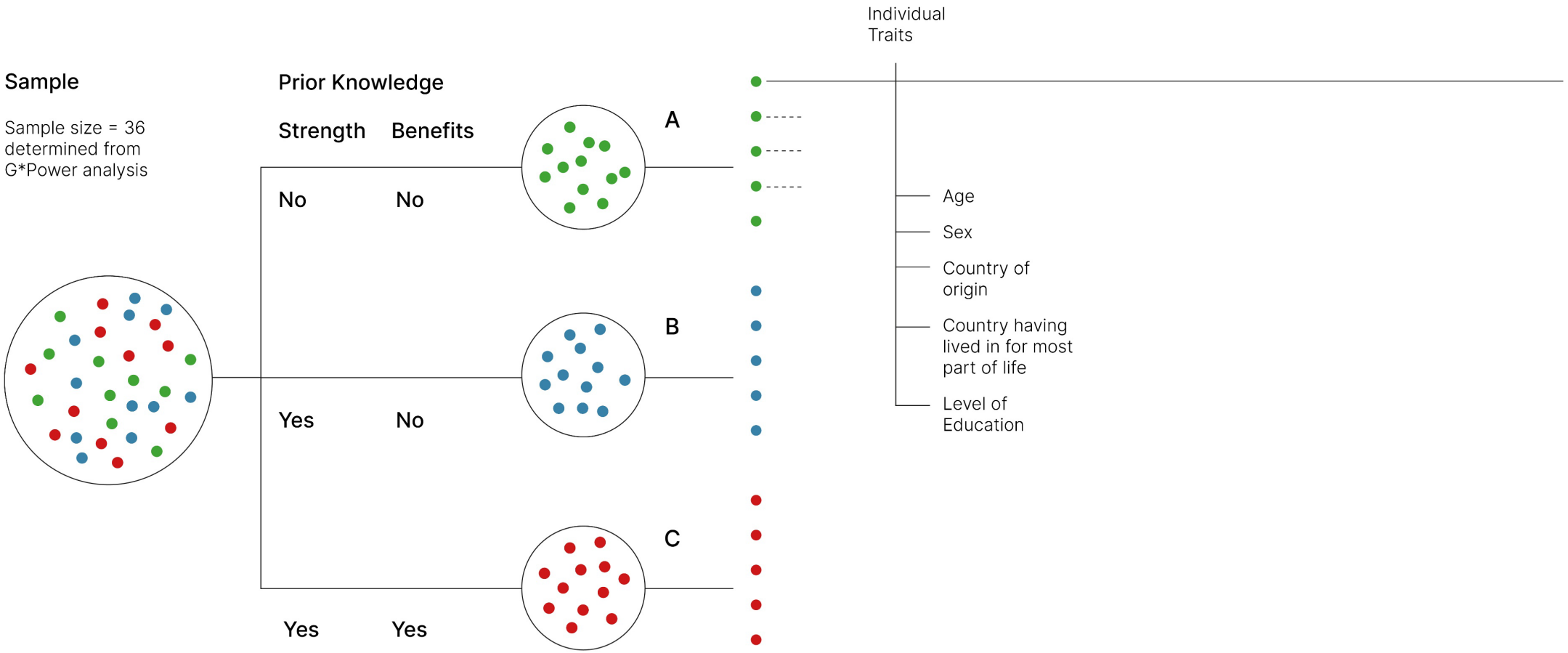
- Age
- Sex
- Country of origin
- Country having lived in for most part of life
- Level of Education

Prior Knowledge

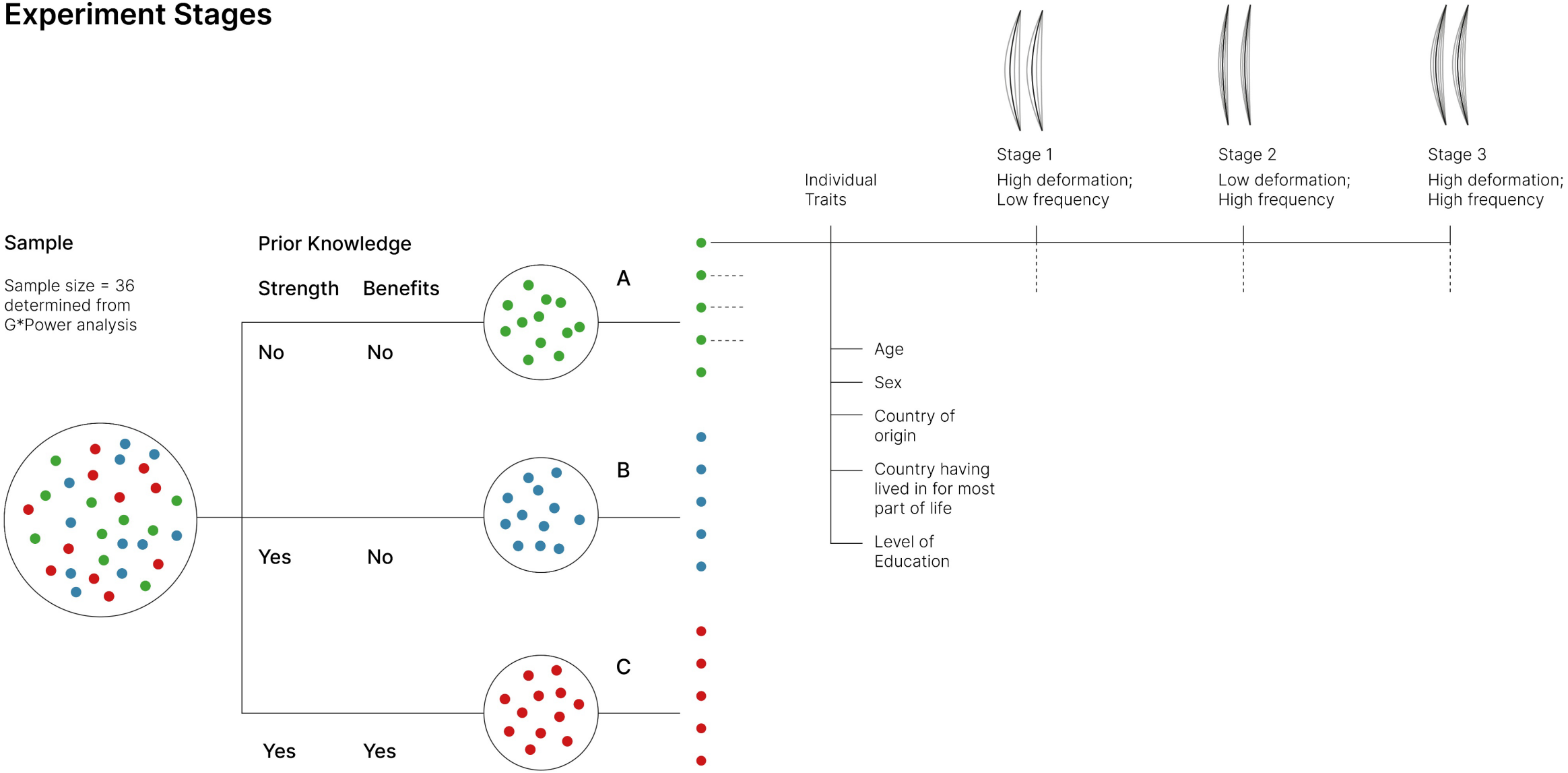
- Expectancy of motion
- Knowledge about material's capacity
- Knowledge about benefits of using thinner glass

Experiment Stages

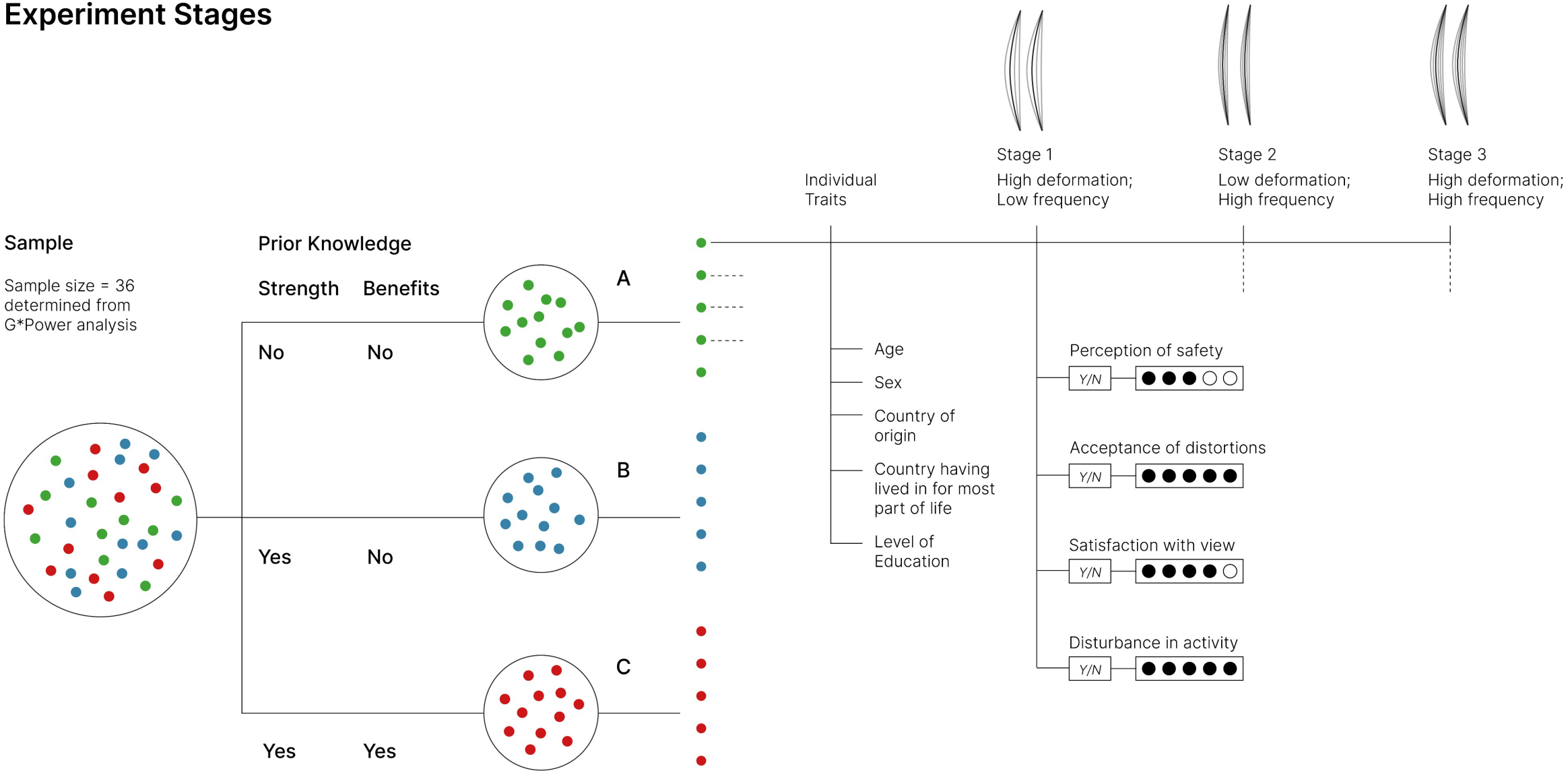
Experiment Stages



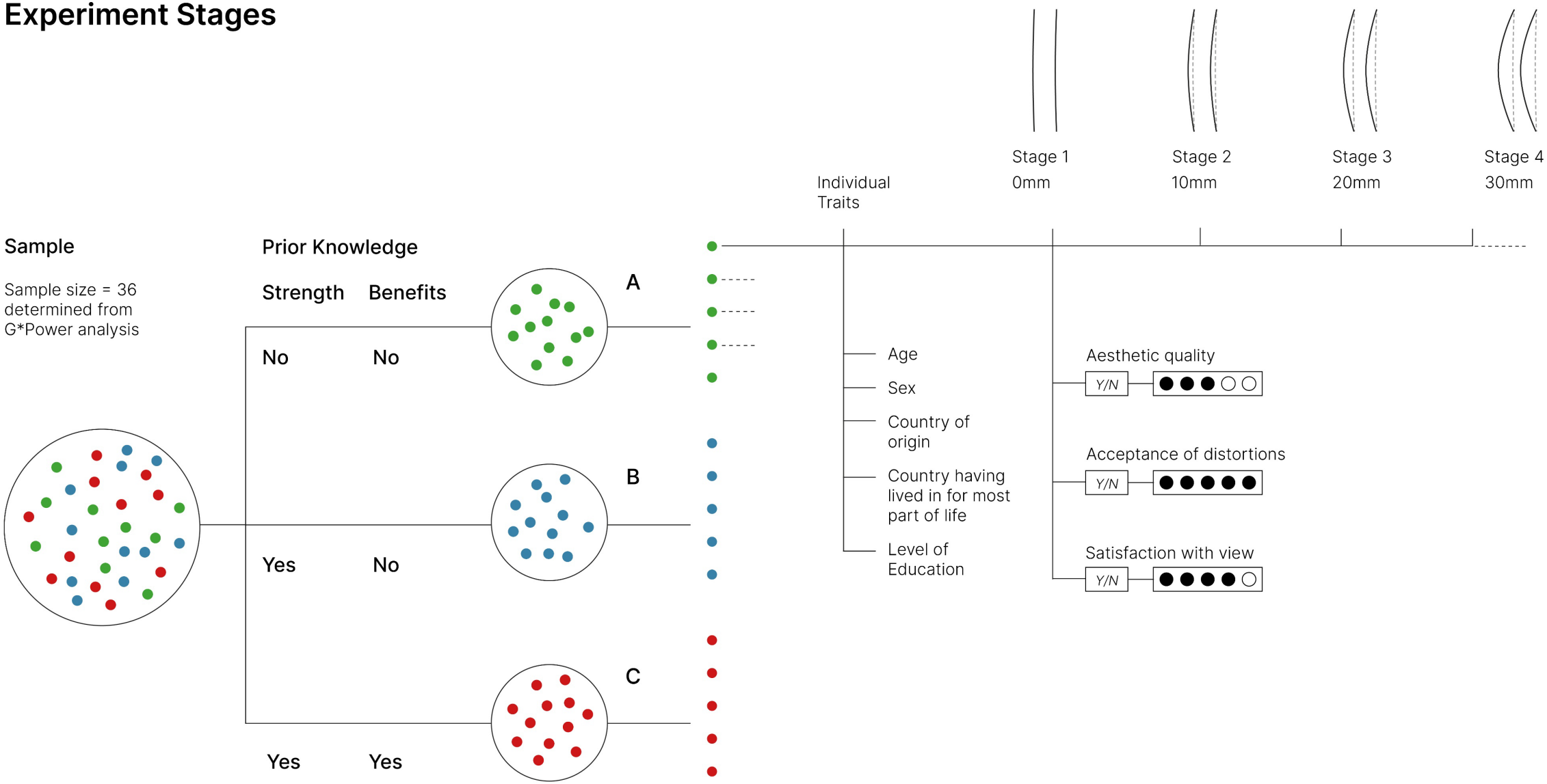
Experiment Stages



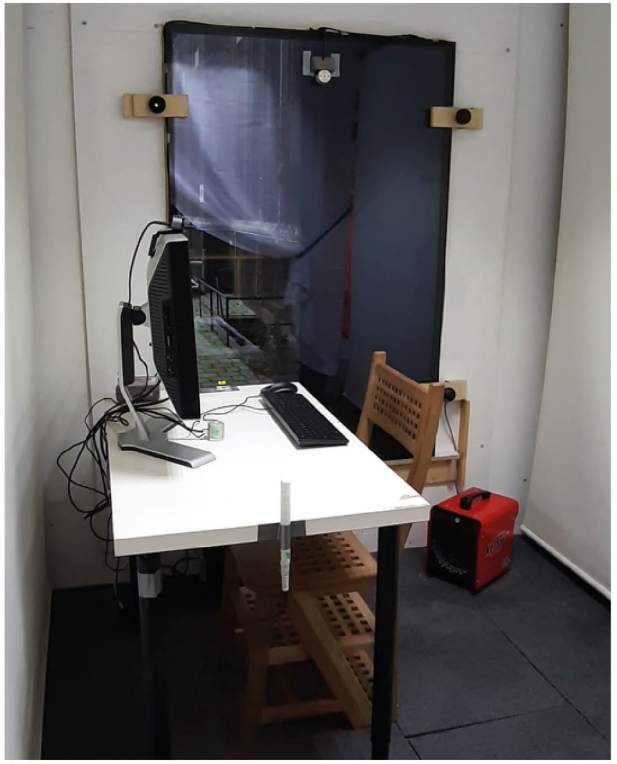
Experiment Stages

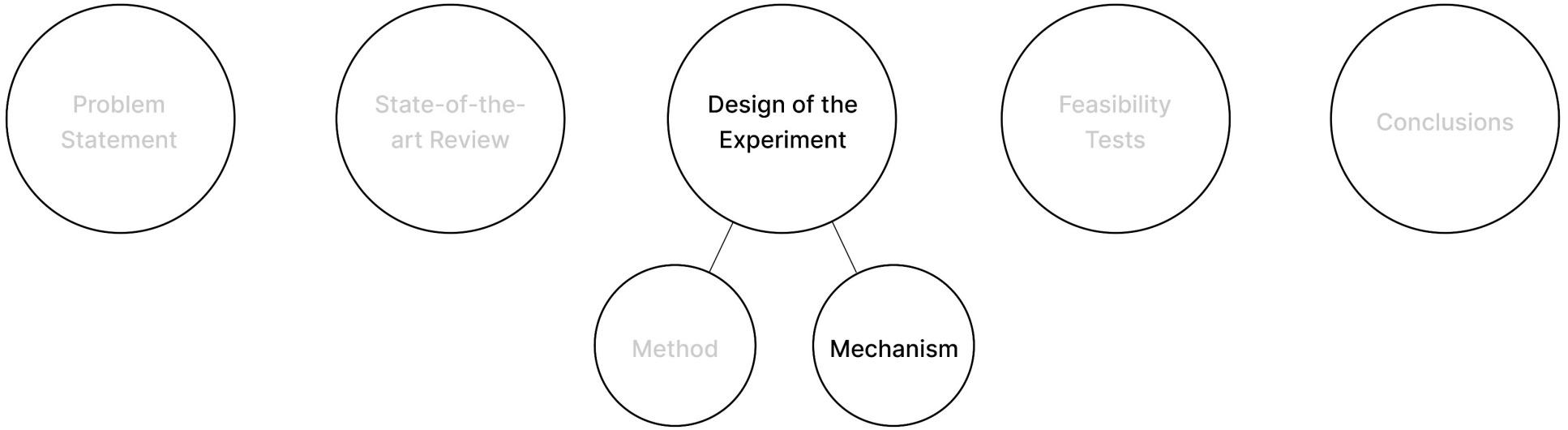


Experiment Stages



Light Van - mobile lab




Problem Statement
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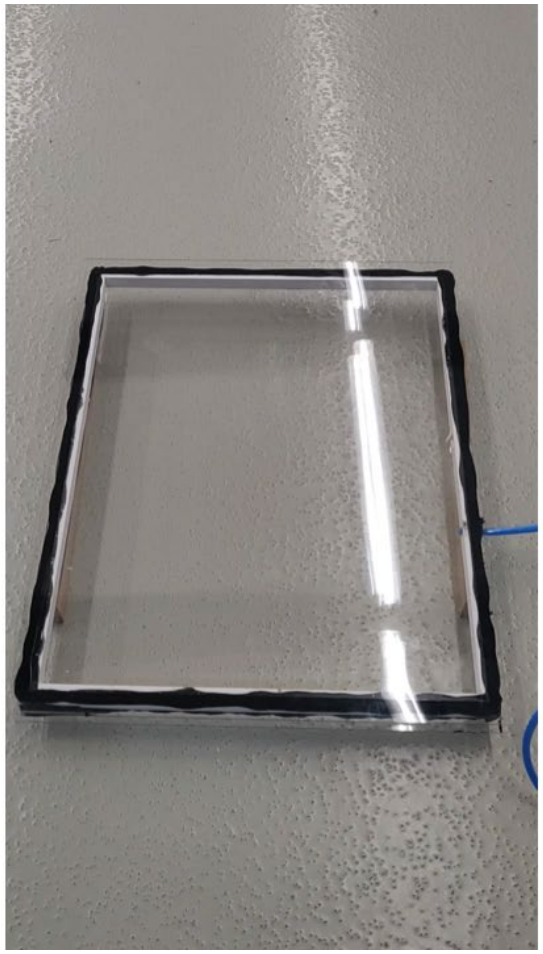
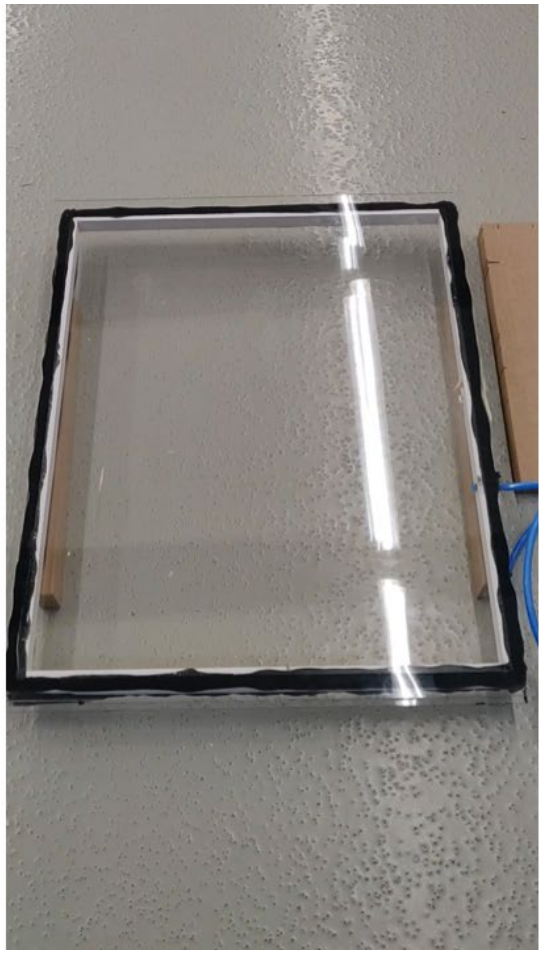
Concept

Variation in cavity air pressure

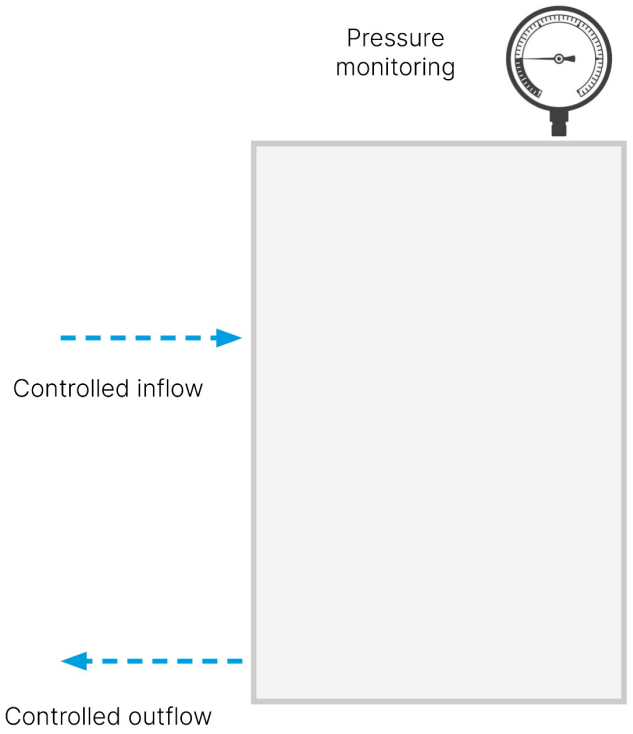
↓

Deformation and vibration in glass

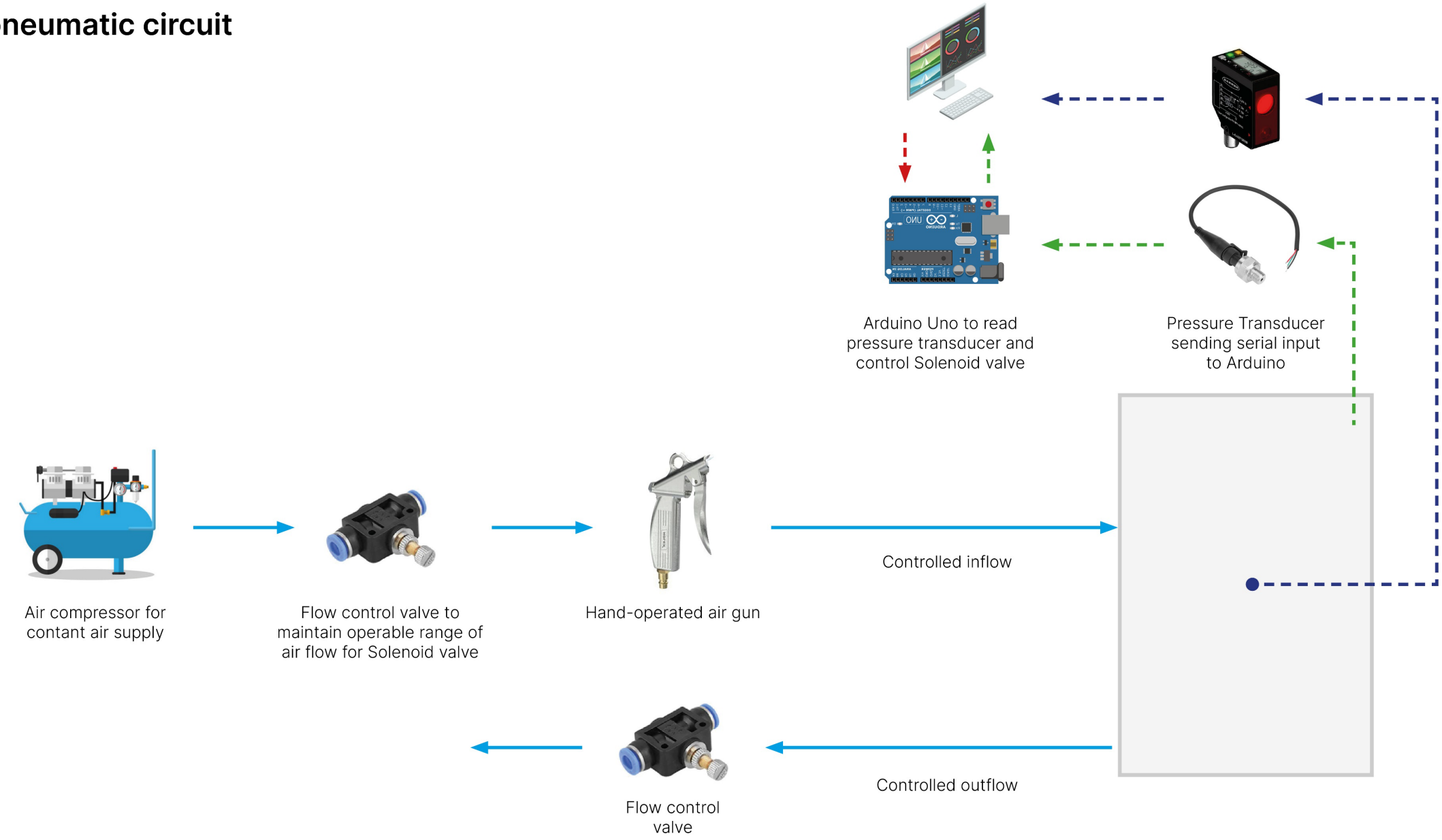




Concept


Pressure
monitoring
Controlled inflow
Controlled outflow

Electropneumatic circuit

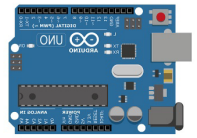


Electropneumatic circuit

Adjustable power supply for constant voltage

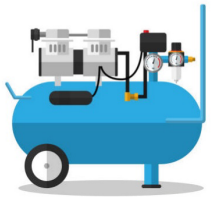
Voltage regulator also acting as a fuse

Mosfet module acting as relay switch between Arduino and valve



Arduino Uno to read pressure transducer and control Solenoid valve

Pressure Transducer sending serial input to Arduino



Air compressor for contant air supply

Flow control valve to maintain operable range of air flow for Solenoid valve

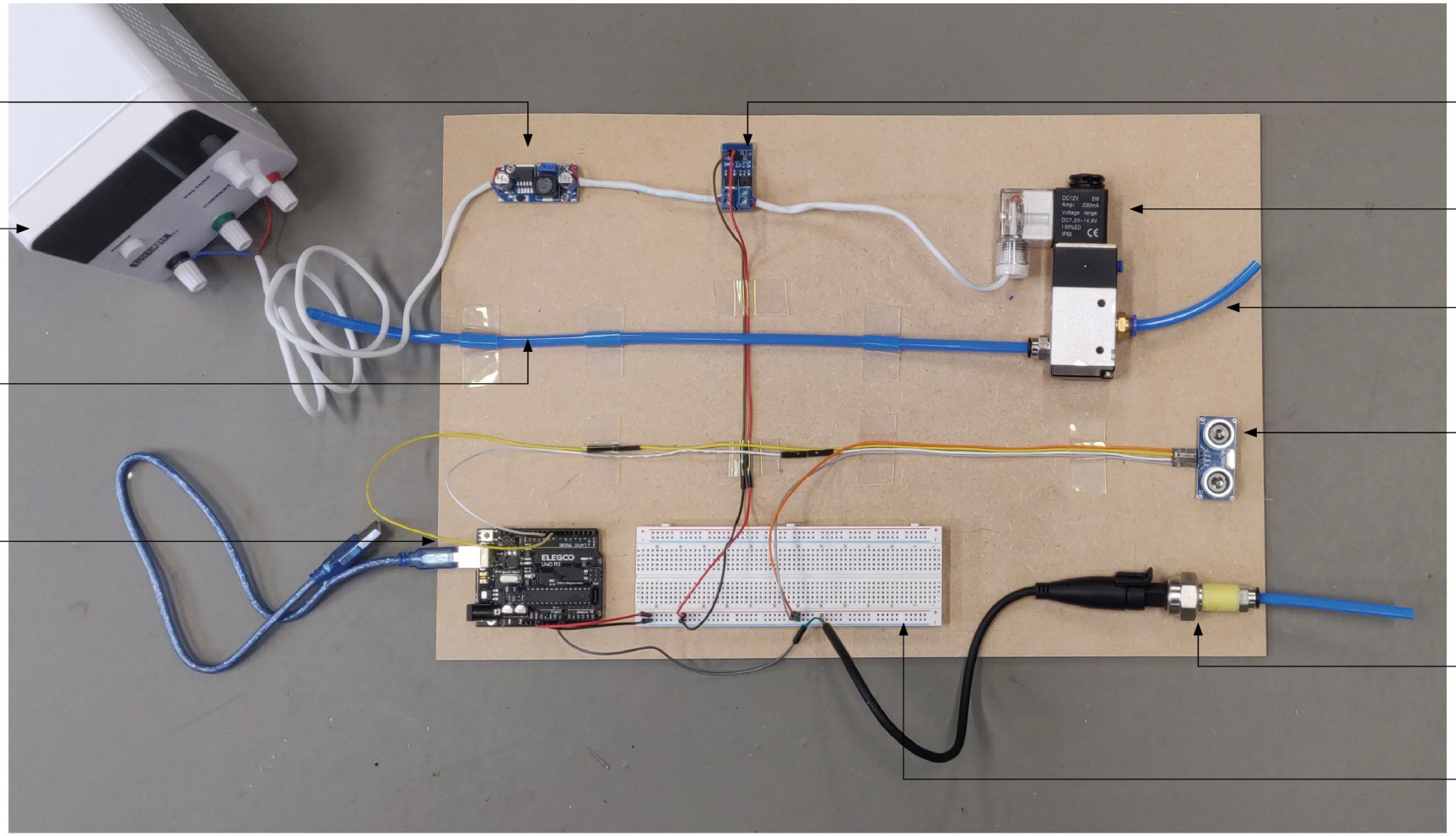
3 way 2 Solenoid valve to start and stop airflow based on Arduino's input

Controlled inflow

Flow control valve

Controlled outflow

Electropneumatic circuit



Prototype making

Applying PIB tape

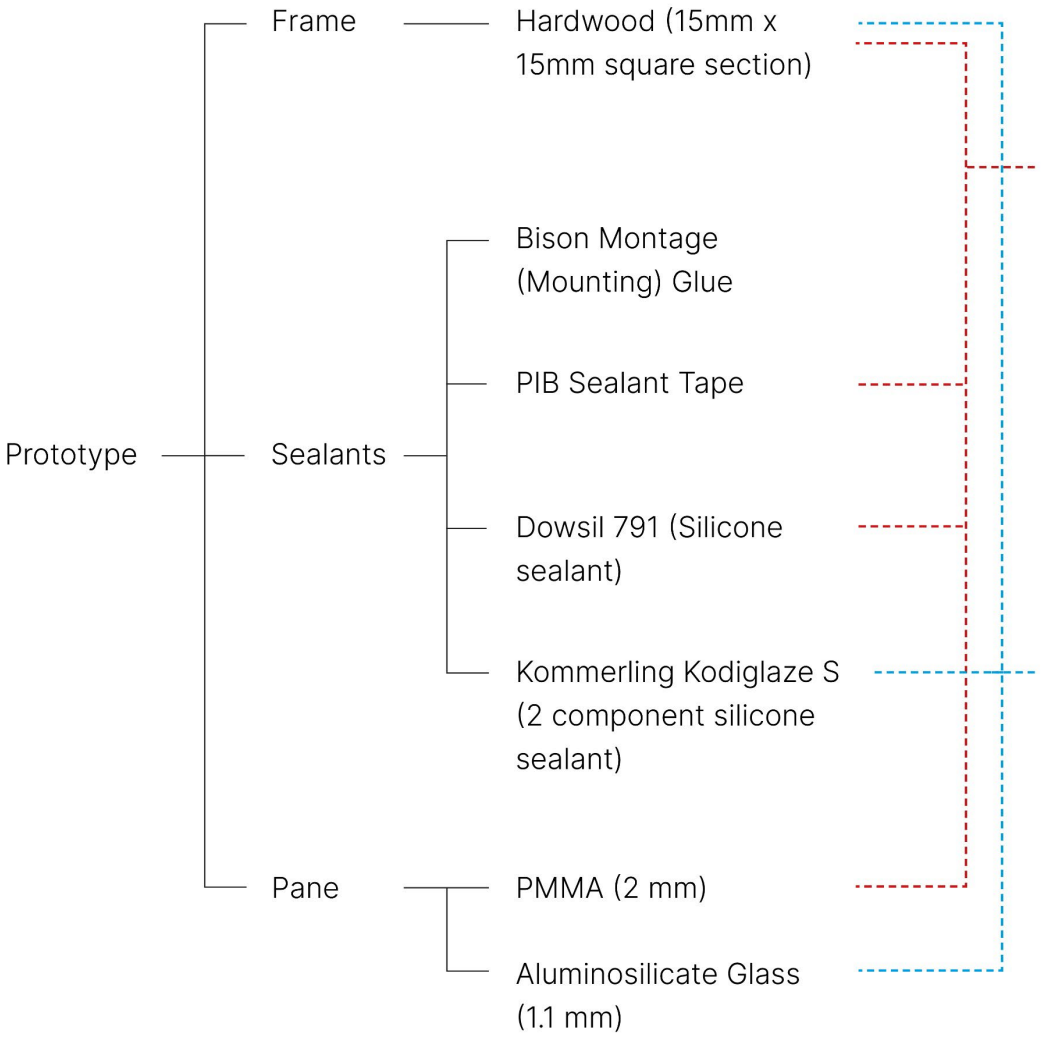
2 component glue

Applying glue using a pneumatic gun

Placing glass

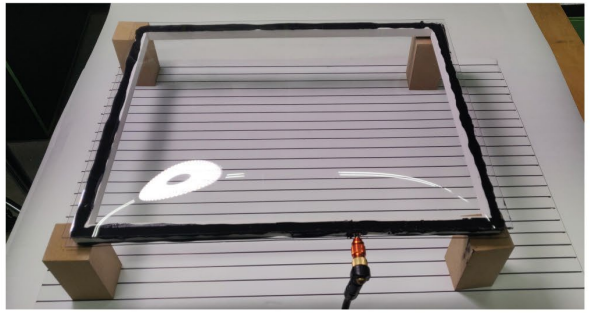
Final product

Prototype making



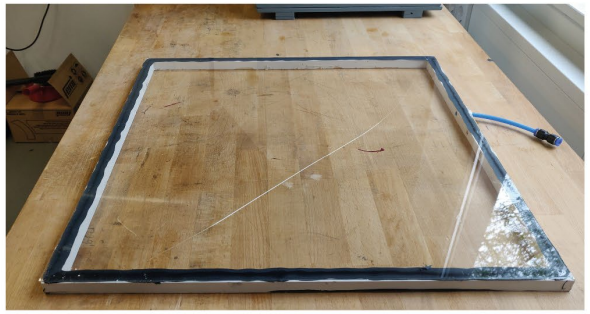
PMMA Prototype

Testing air pressure system for constant and dynamic pressure conditions

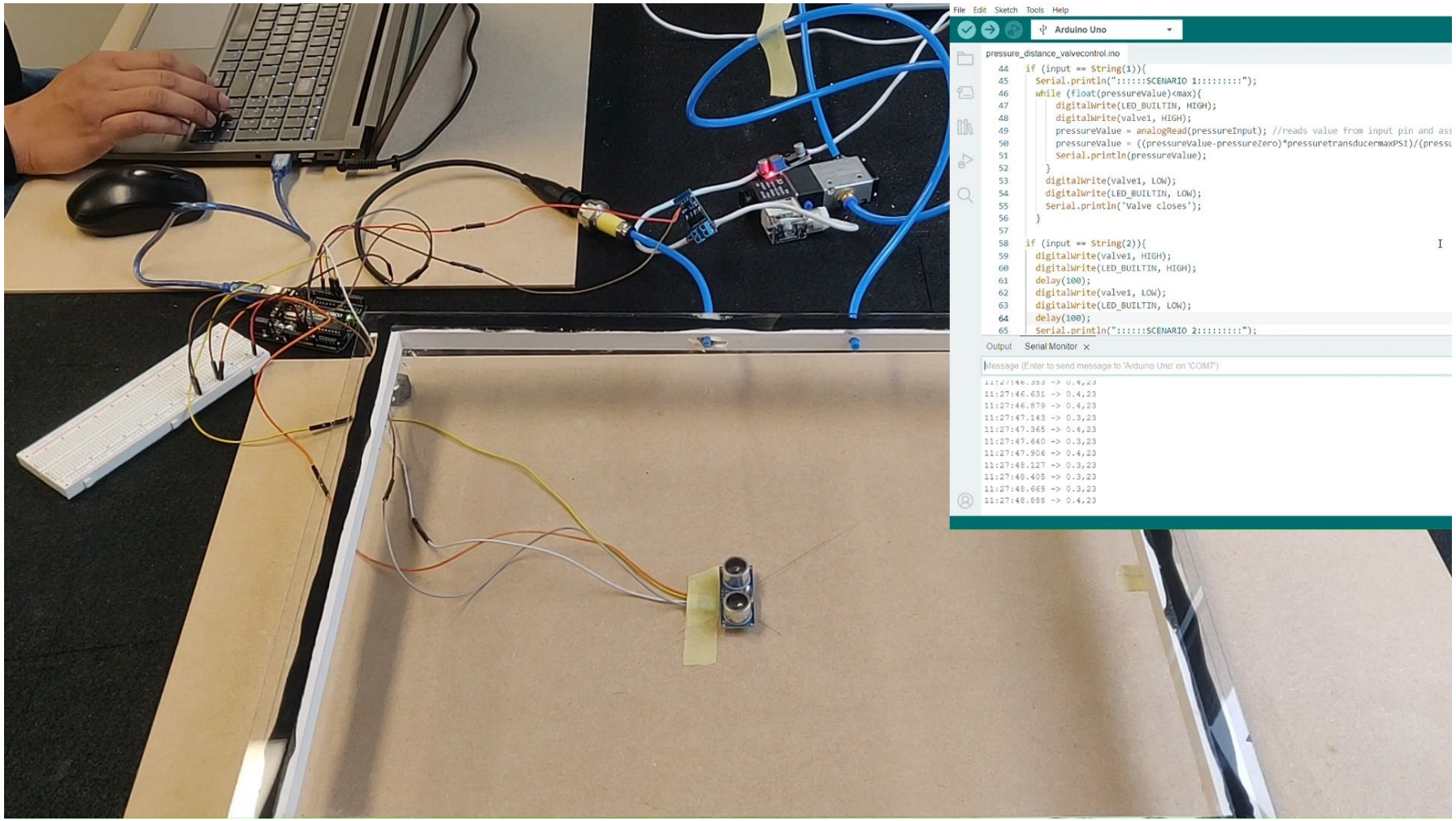


Glass Prototype

Testing self-adhesive film for optical distortions and breaking test



Testing the mechanism



Safety film testing

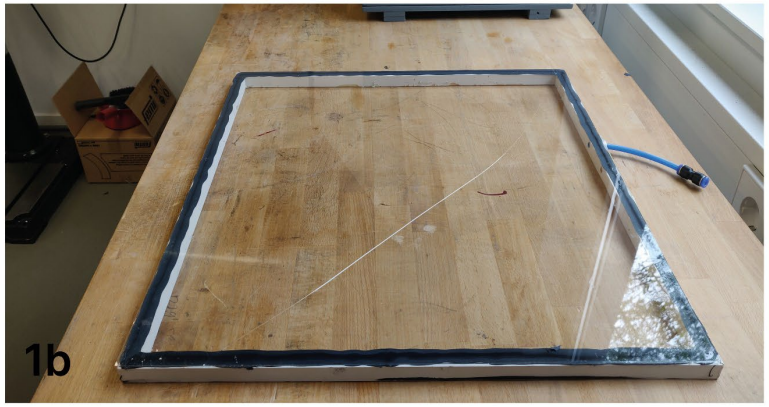
Strain energy as equating factor

Strain energy in prototype at point of failure of full size panel
= 264.23 MPa

Failure stress of CT-ASG (glass prototype) **= 325.00 MPa**

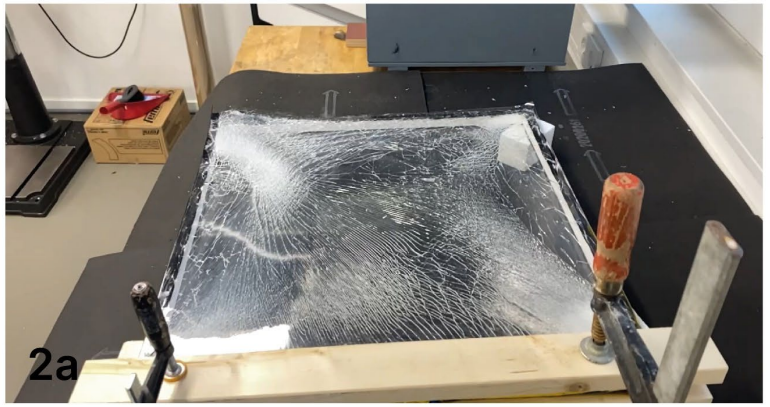
Film on one side

Shards from pane without film spread in all directions

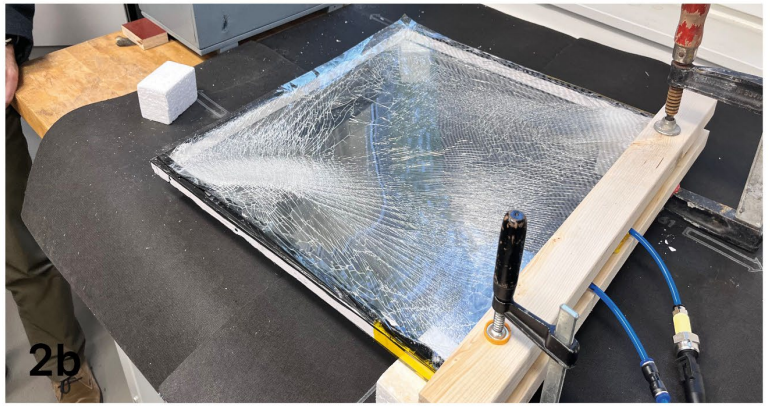


Crack in pane with film did not propagate

Film on both sides



Shards from pane with film were held in place



Clamping of weak edge was required to avoid bending during experiment

Testing the safety film

Problem Statement

State-of-the-art Review

Design of the Experiment

Feasibility Tests

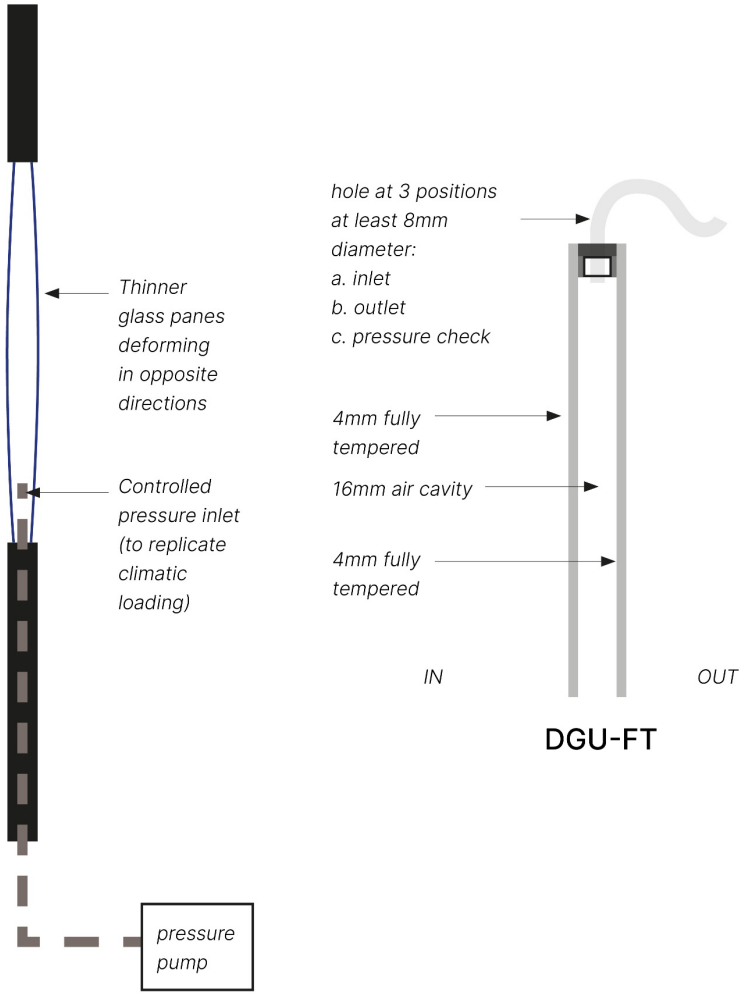
Conclusions

Glass build-up

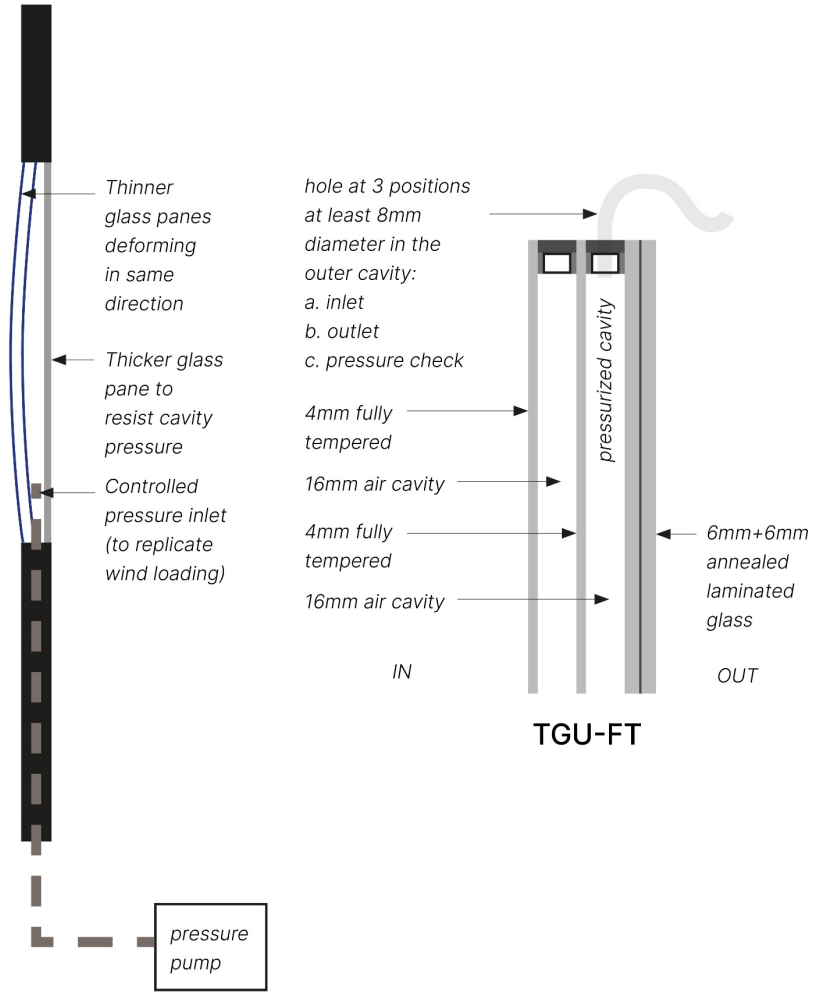
As per numerical calculations:

Glass size:	1467mm x 972mm
Glass thk:	4mm
Pressure:	2000 Pa
Support:	simply supported
Max deflection:	**34.44 mm**
Max prin. stress:	**60.32 MPa**
SLS limit:	23.00 mm
Failure stress FT	80.00 MPa

DGU-FT (2 units)

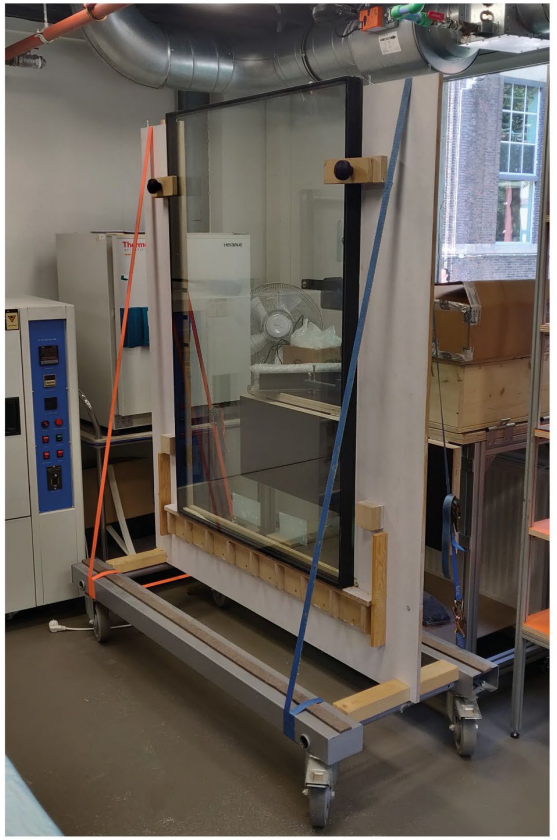


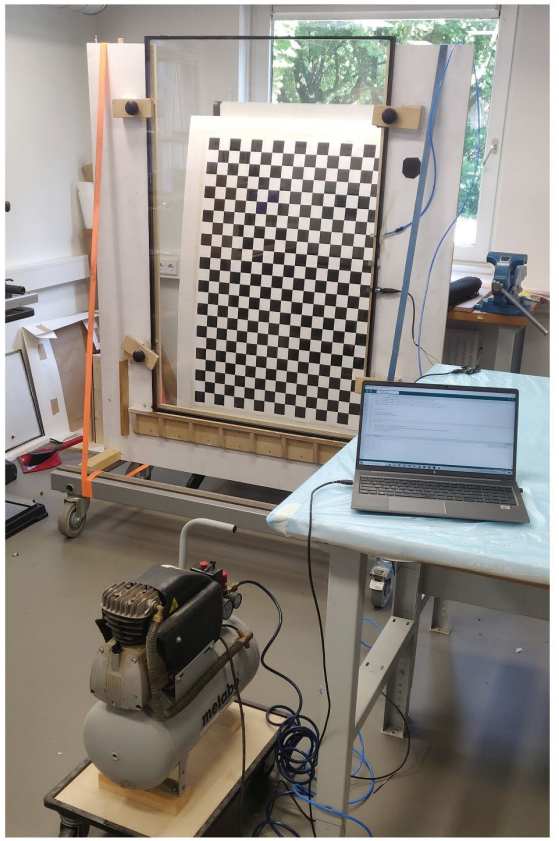
TGU-FT (2 units)



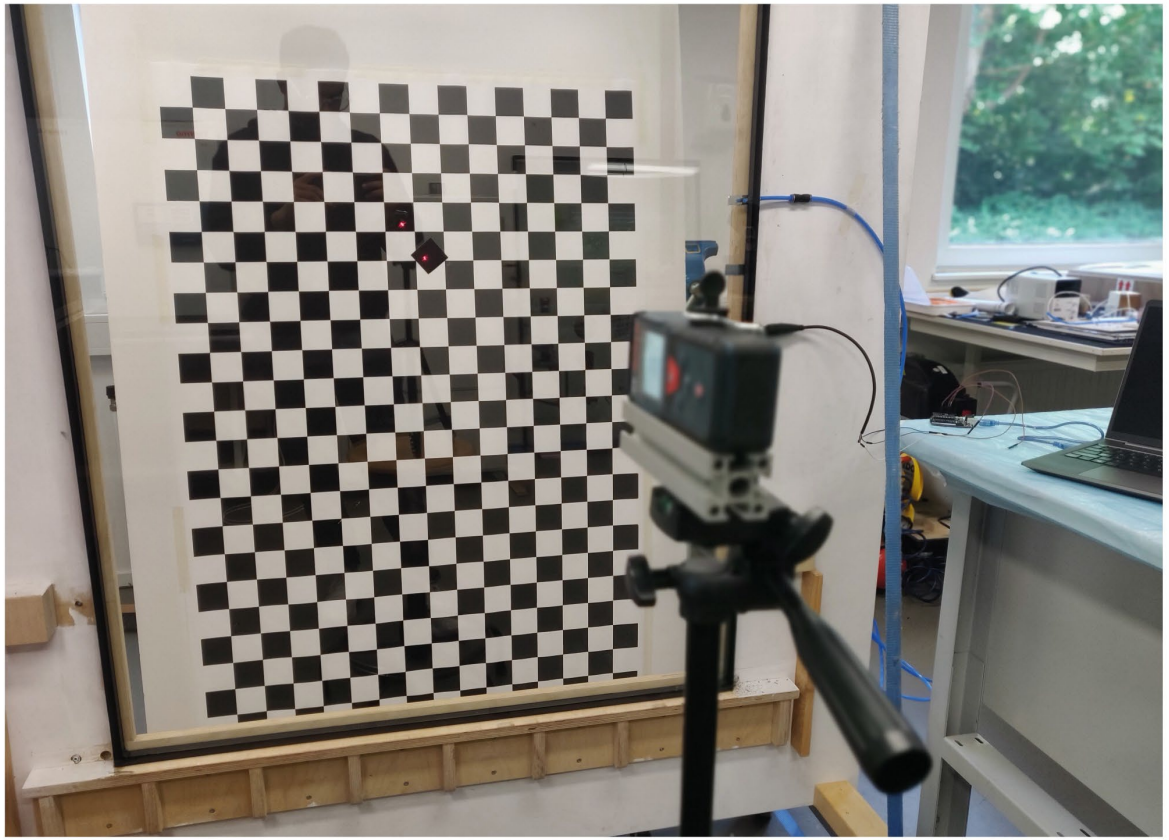
Facade Panels from AGC Interpane

Installation for testing





Pressure vs. Deflection measurements

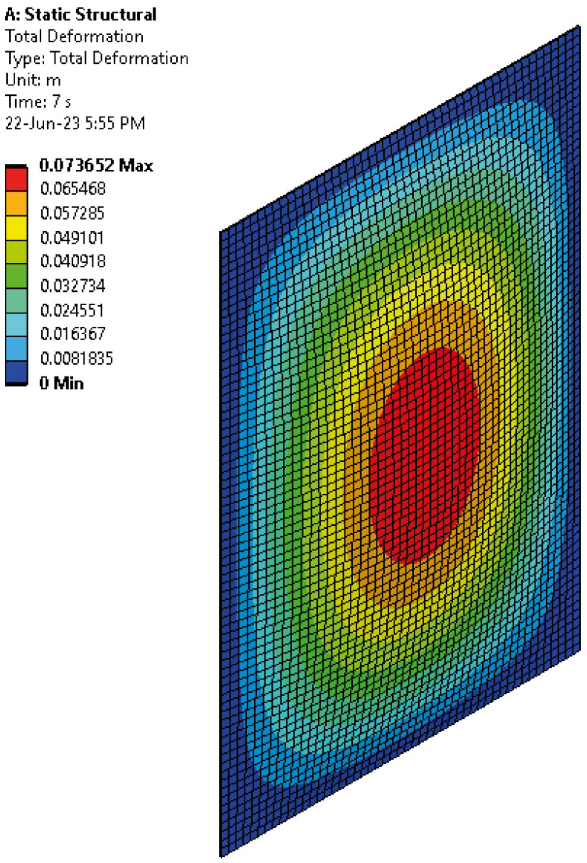


Pressure vs. Deflection measurements

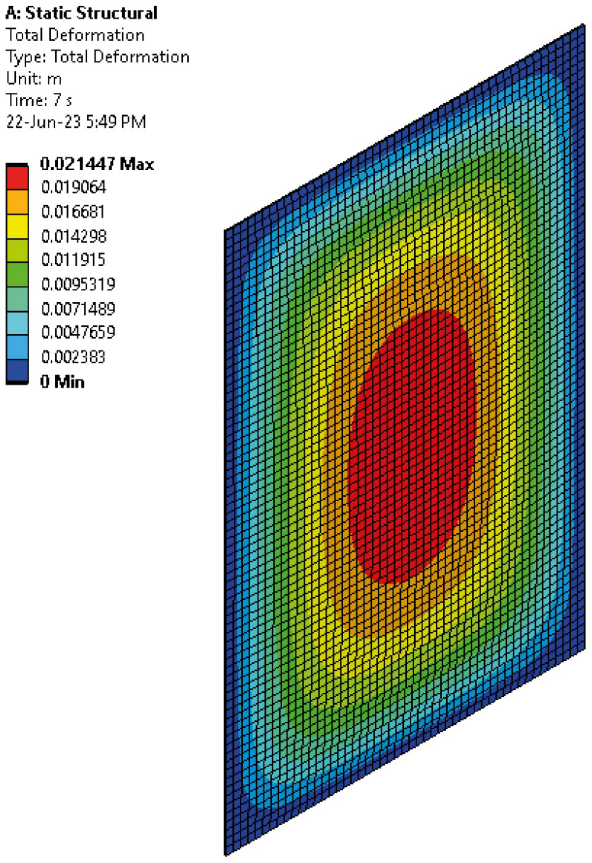
Pressure Measured (PSI)	0.0	0.1	0.2	0.3	0.4	0.5	0.6
Pressure Measured (Pa)	0.0	689.5	1379.0	2068.5	2758.0	3447.5	4137.0
TGU-1	0	5	10	13	13	13	13
TGU-2	0	5	9	11	11	13	13
TGU-3	0	3	8	10	11	12	12
DGU-1	0	8	15	18	21	23	#N/A
DGU-2	0	6	11	14	21	28	#N/A
DGU-3	0	10	15	20	24	26	#N/A

Linear vs. nonlinear deflection analysis

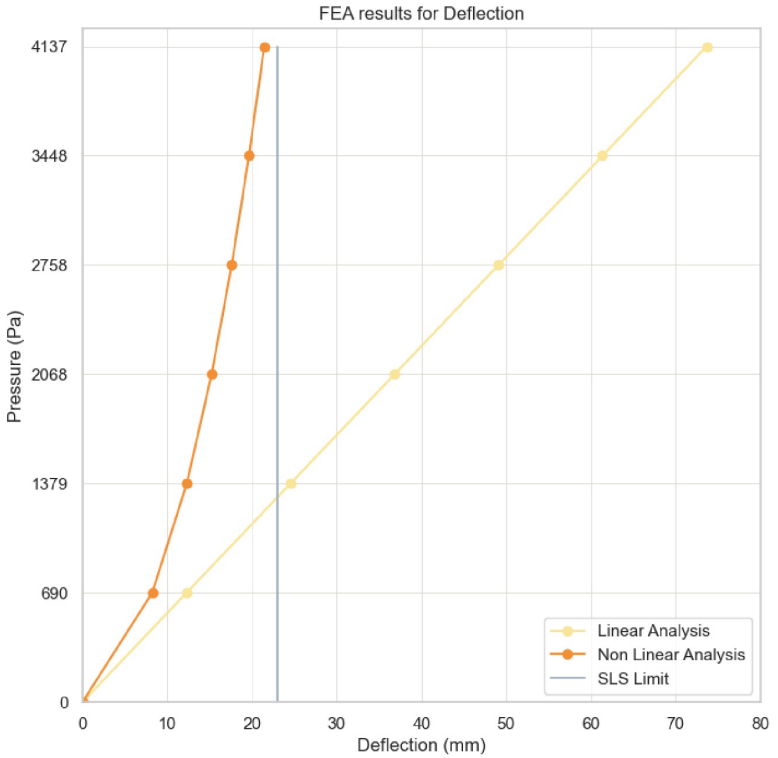
Linear analysis



Geomertically nonlinear analysis

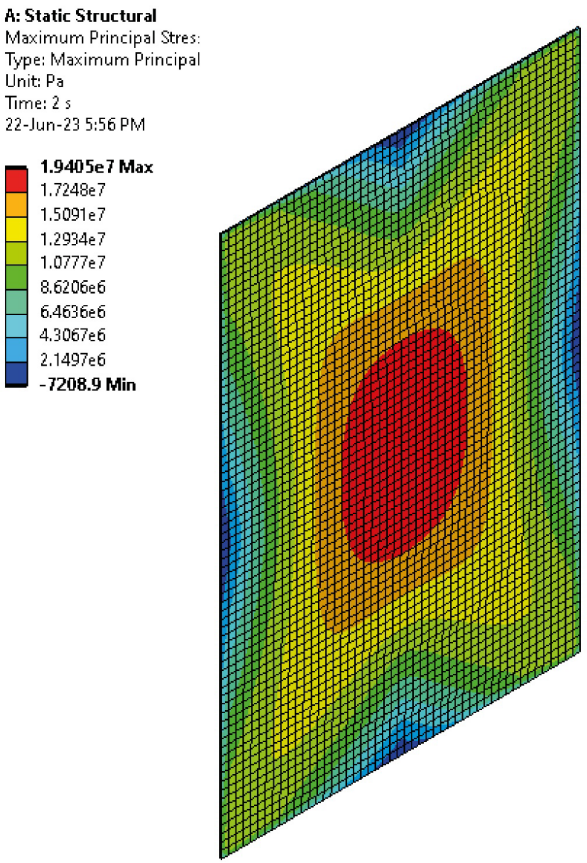


Deflection predictions

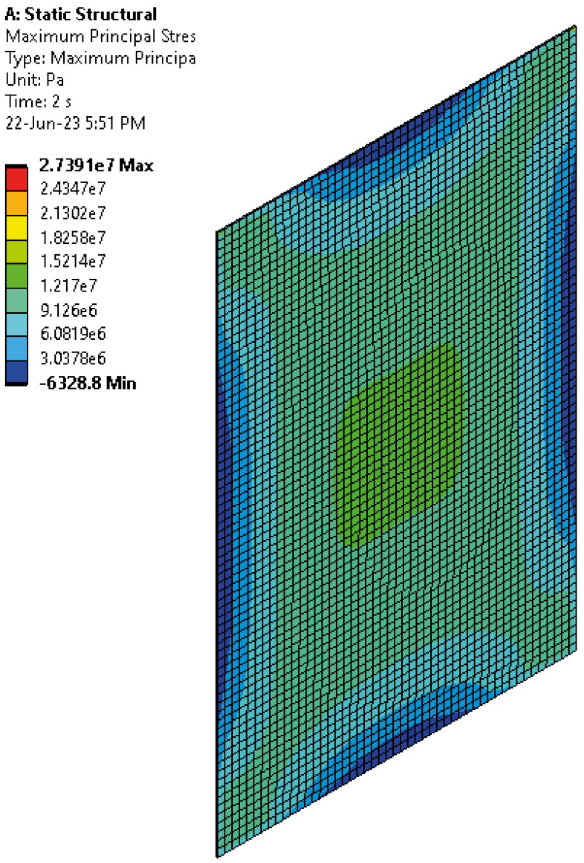


Linear vs. nonlinear stress analysis

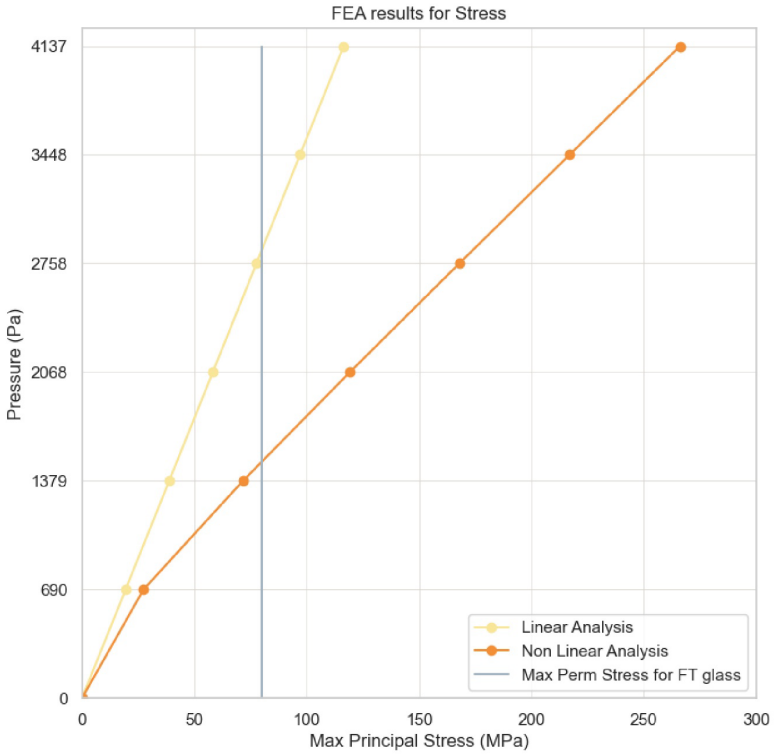
Linear analysis



Geomertically nonlinear analysis

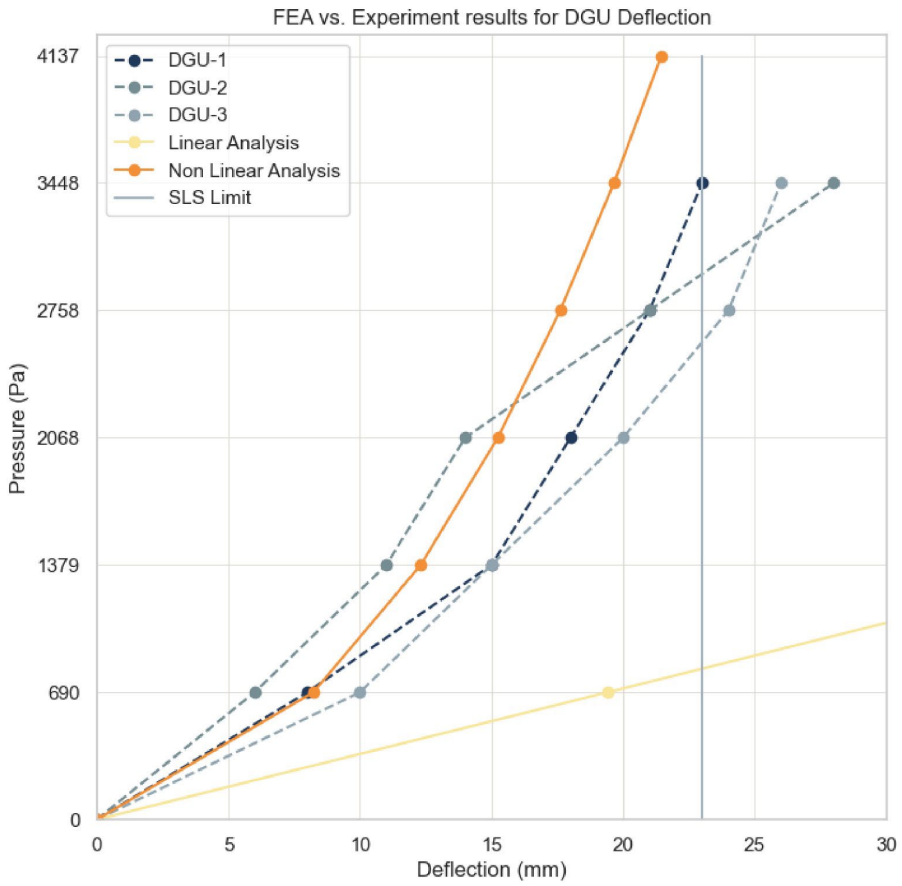


Stress predictions

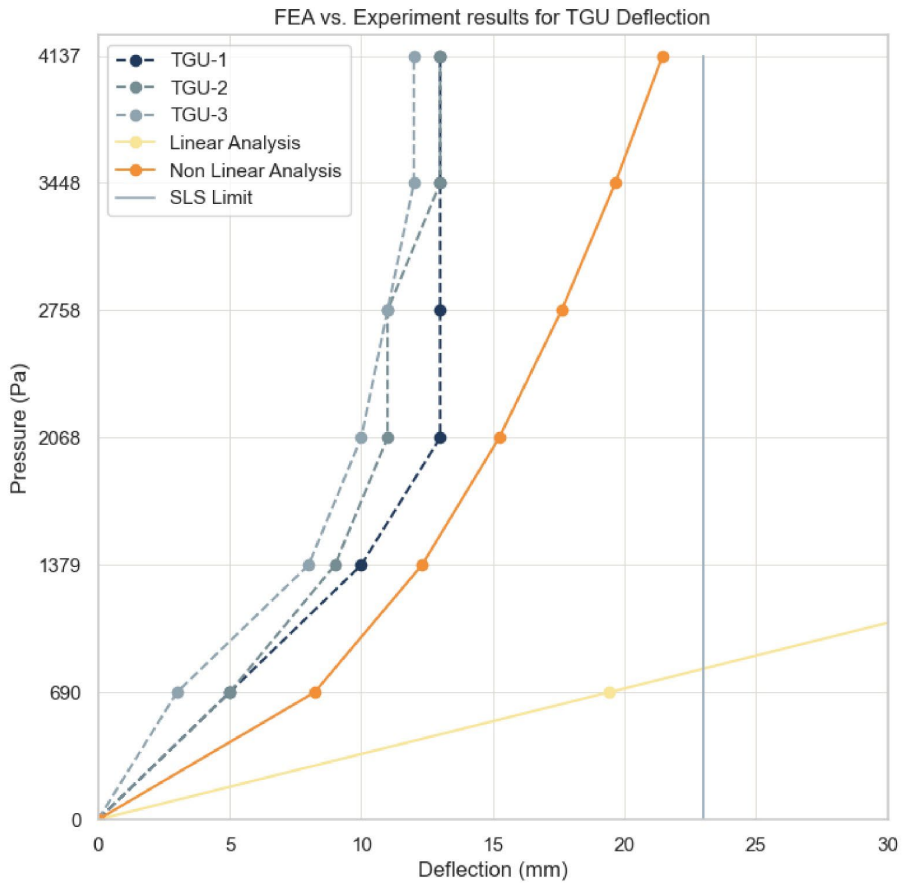


Nonlinear FEA Results vs. Experiment Readings

Double Glazing Unit

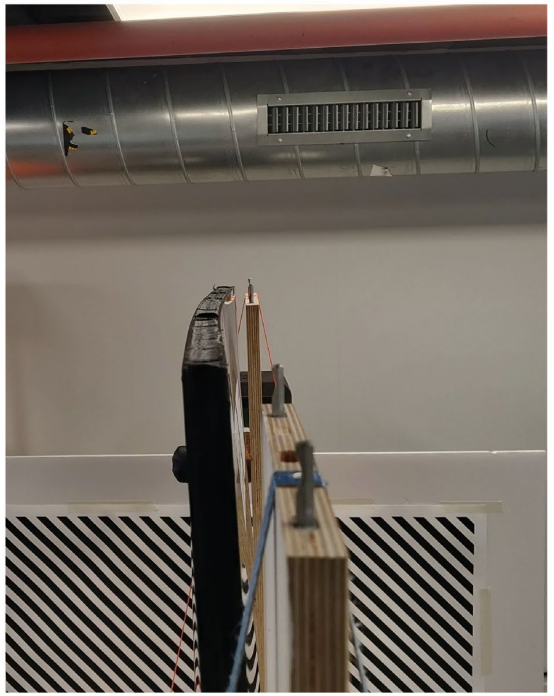


Triple Glazing Unit



Recommendations

- Air leaks and clamping erros must be rectified before experimentation
- Safety film installation may lead to unwanted optical defects



Top edge of glass pane deformed; since it was not clamped

Safety film application errros made it unfit for testing

Setup for optical tests

DSLR for HDR images

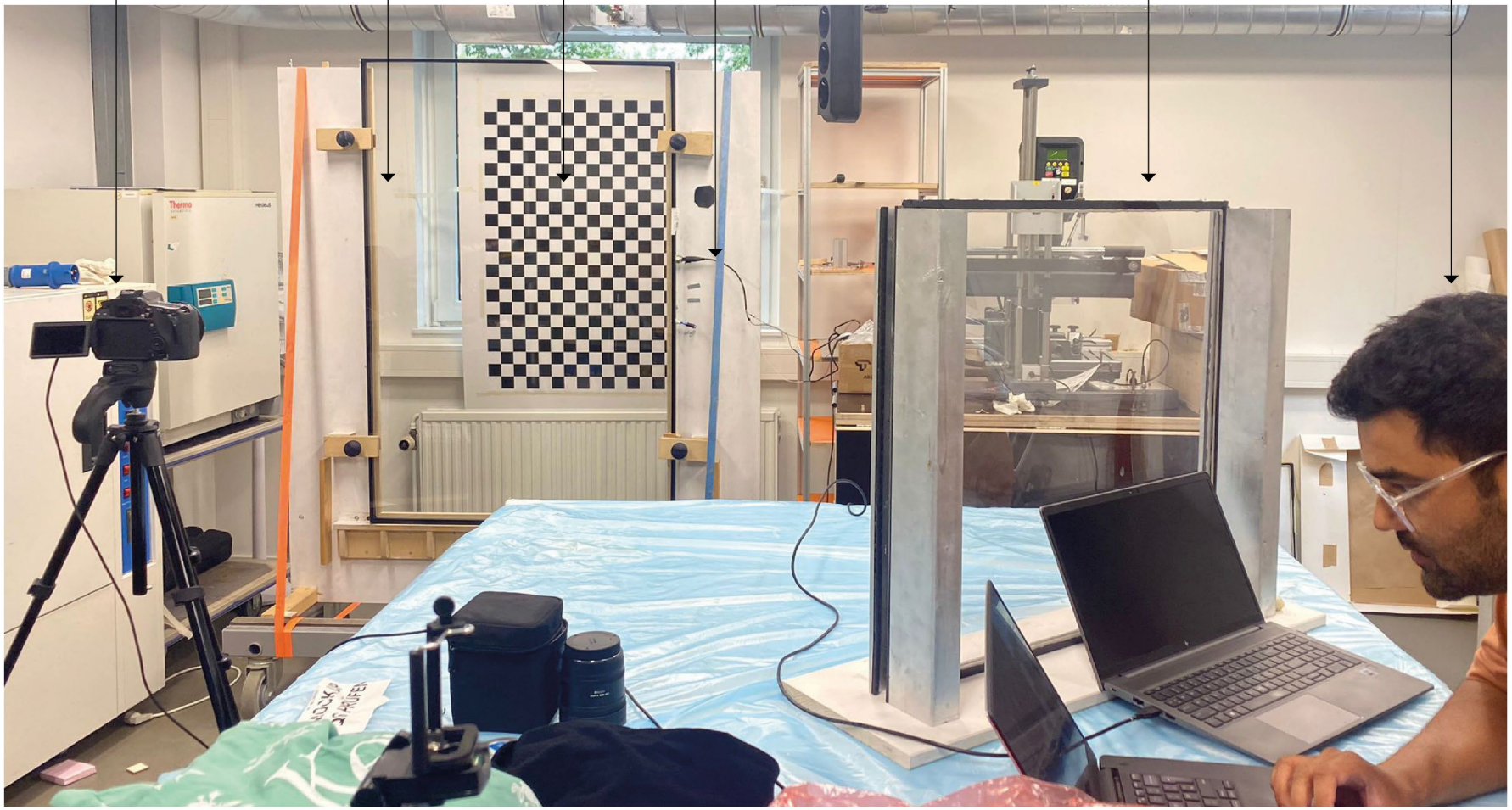
Facade panel with controlled air flow

Fixed target

Pressure sensor and air supply

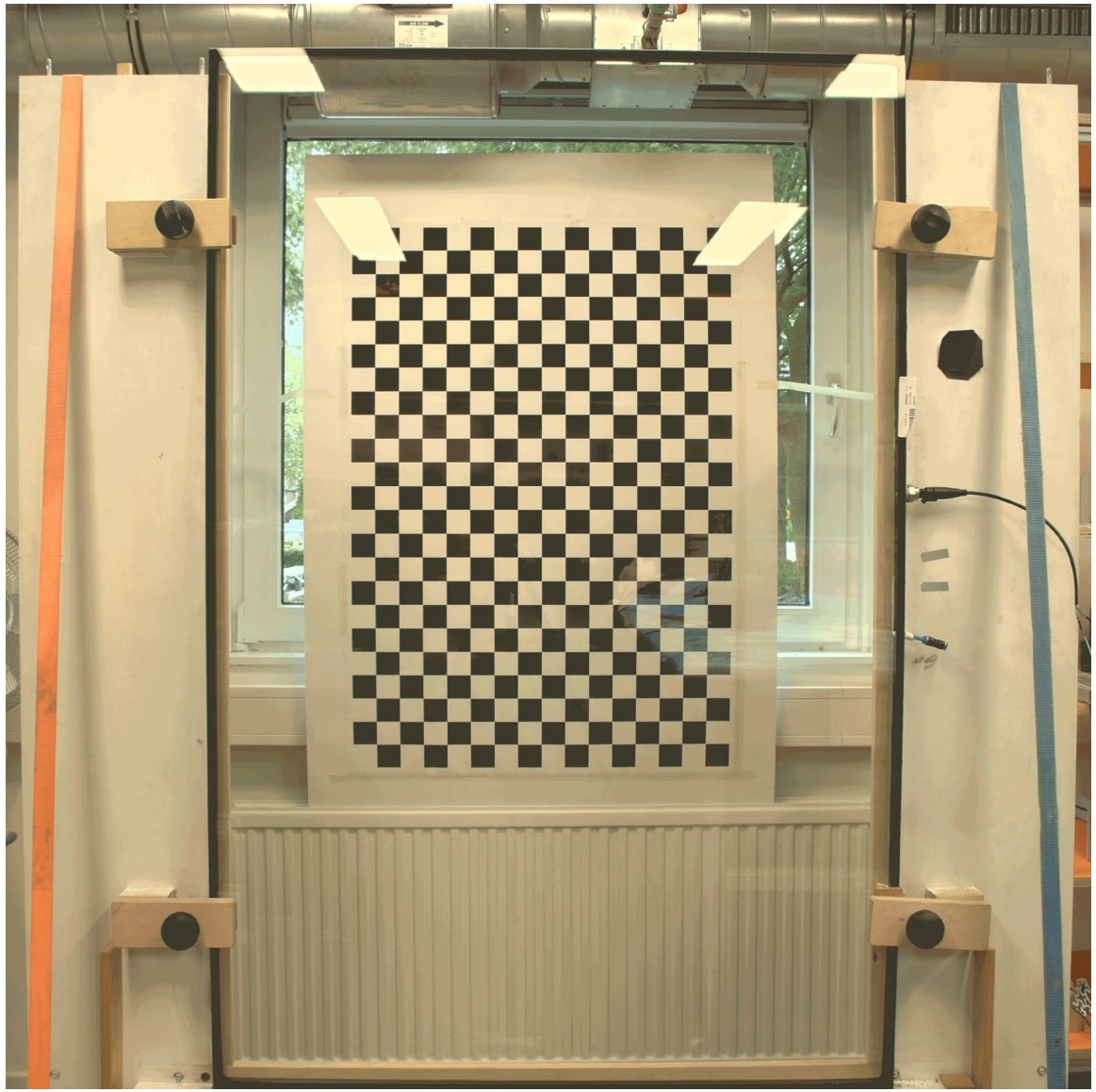
Safety barrier

Researcher at a safe distance

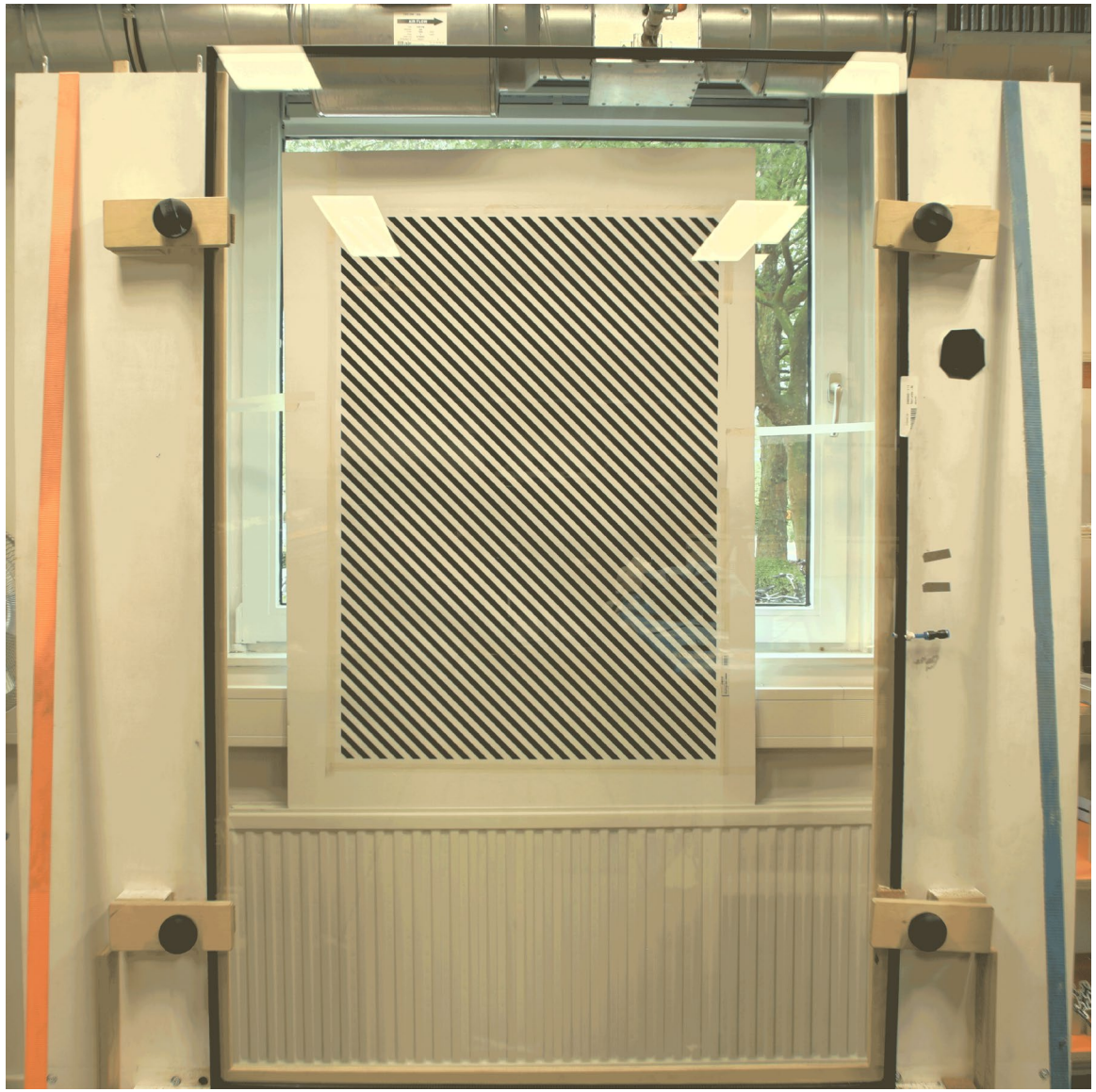


Optical test results view of the outside

Optical test results checkerboard

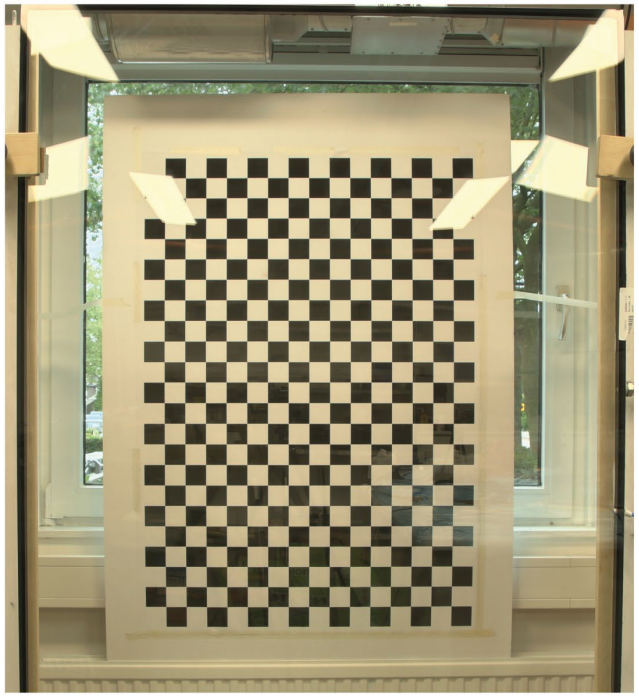


Optical test results zebra-board

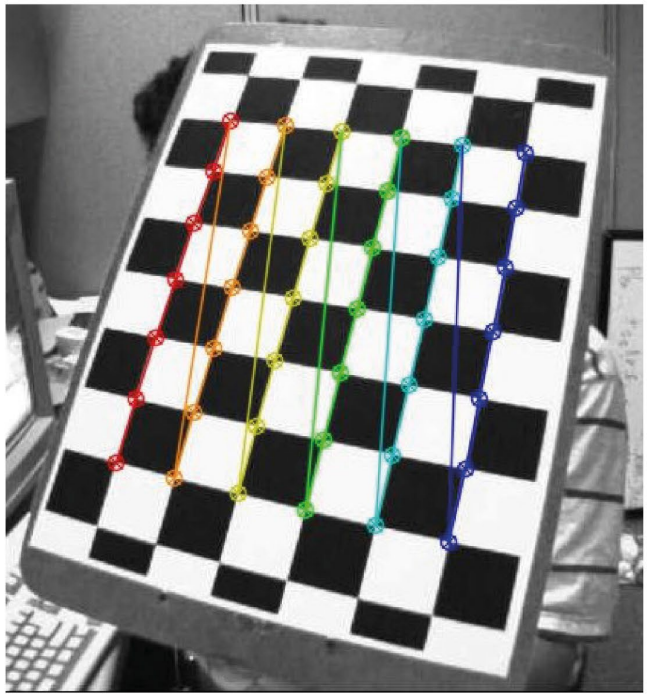


Recommendations

- Air leaks and clamping erros must be rectified before experimentation
- Safety film installation may lead to unwanted optical defects
- Subjective tests must inquire into human perception of distortions with respect to reflections.
- Objective evaluation of image similarity using suitable similarity indices.
- Wireless control using Wemos as an additional step for safety



View through the glass not affected
Distortions are perceived through reflections



Objective evaluation :
Reference from OpenCV

Problem Statement

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Conclusions

Conclusion

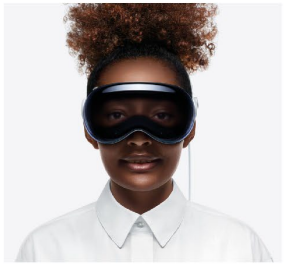
- Proof of concept for the mechanism has been provided; however experiment with volunteers needs to be tested and improved
- Setup is versatile and can be applied for testing multiple objectives

Application

- Subjective tests

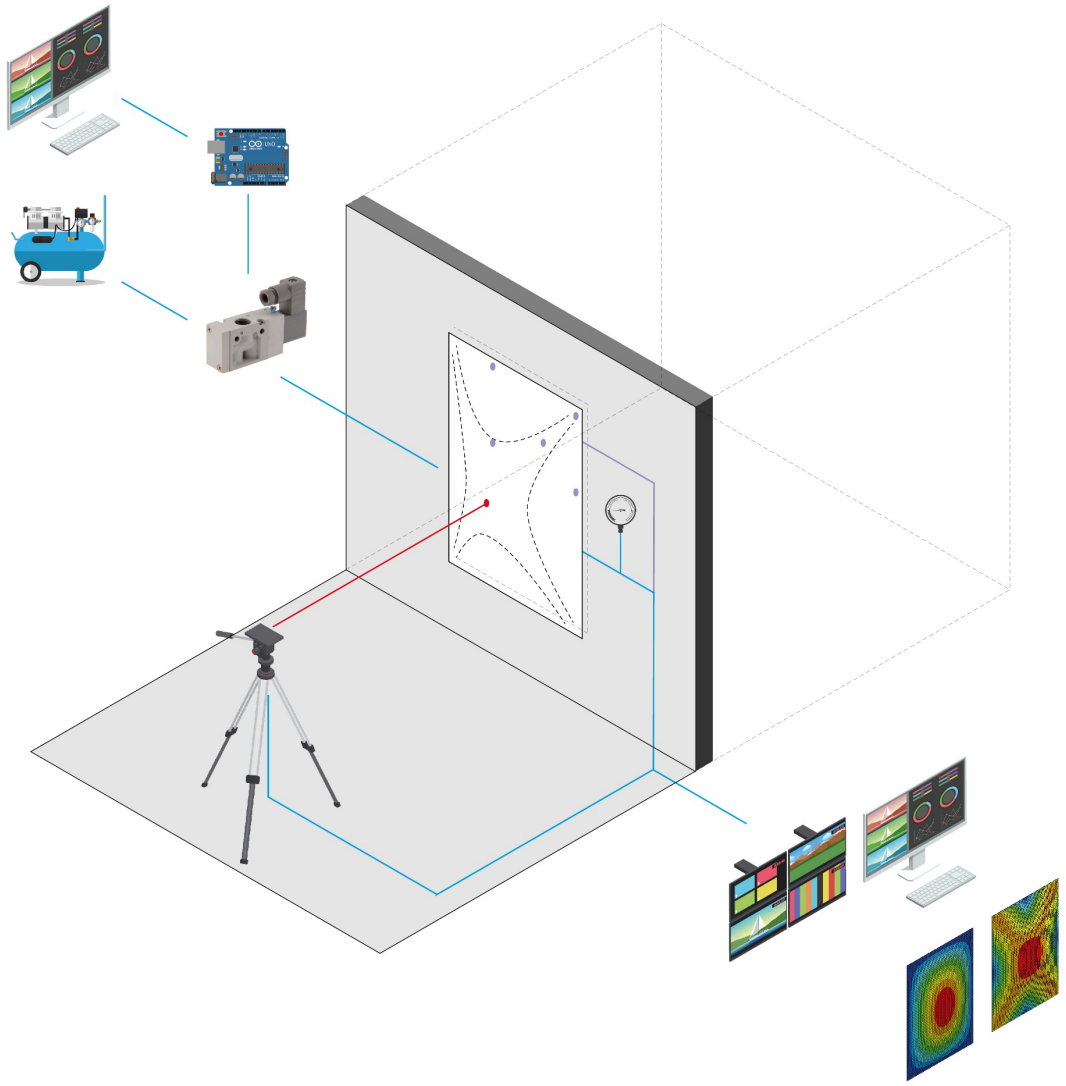
Application

- Subjective tests
- Include multiple persons
- Include VR setup



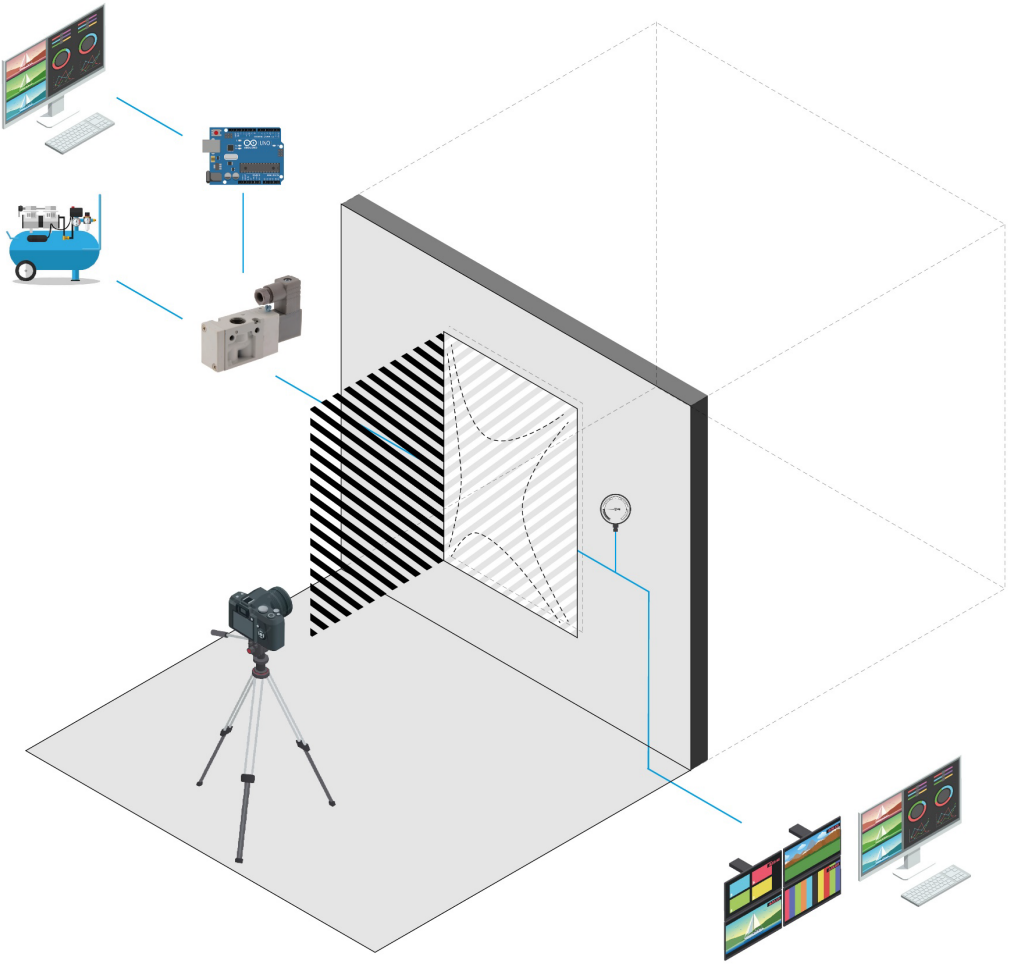
Application

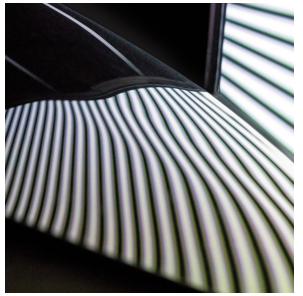
- Subjective tests
- Include multiple persons
- Include VR setup
- Mechanical behavior using strain gauges, laser serial input generator



Application

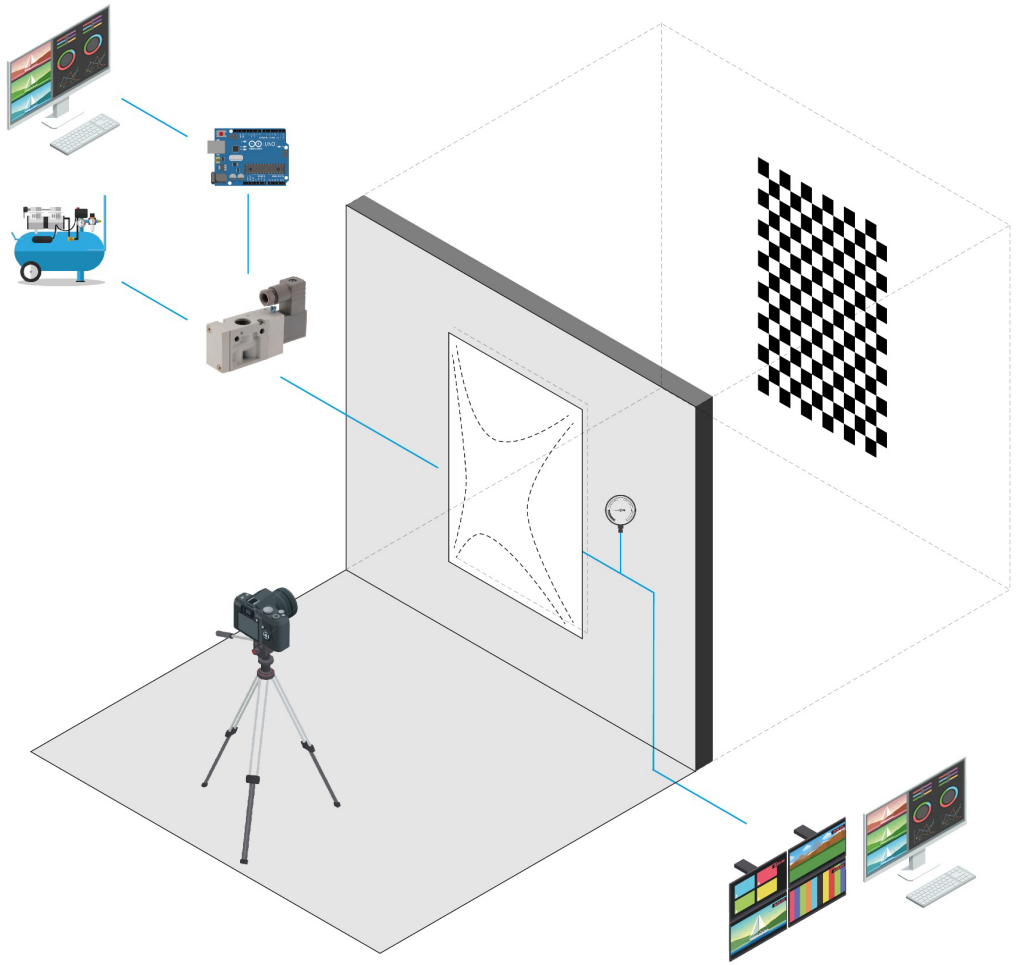
- Subjective tests
- Include multiple persons
- Include VR setup
- Mechanical behavior using strain gauges, laser serial input generator
- Optical tests for reflections





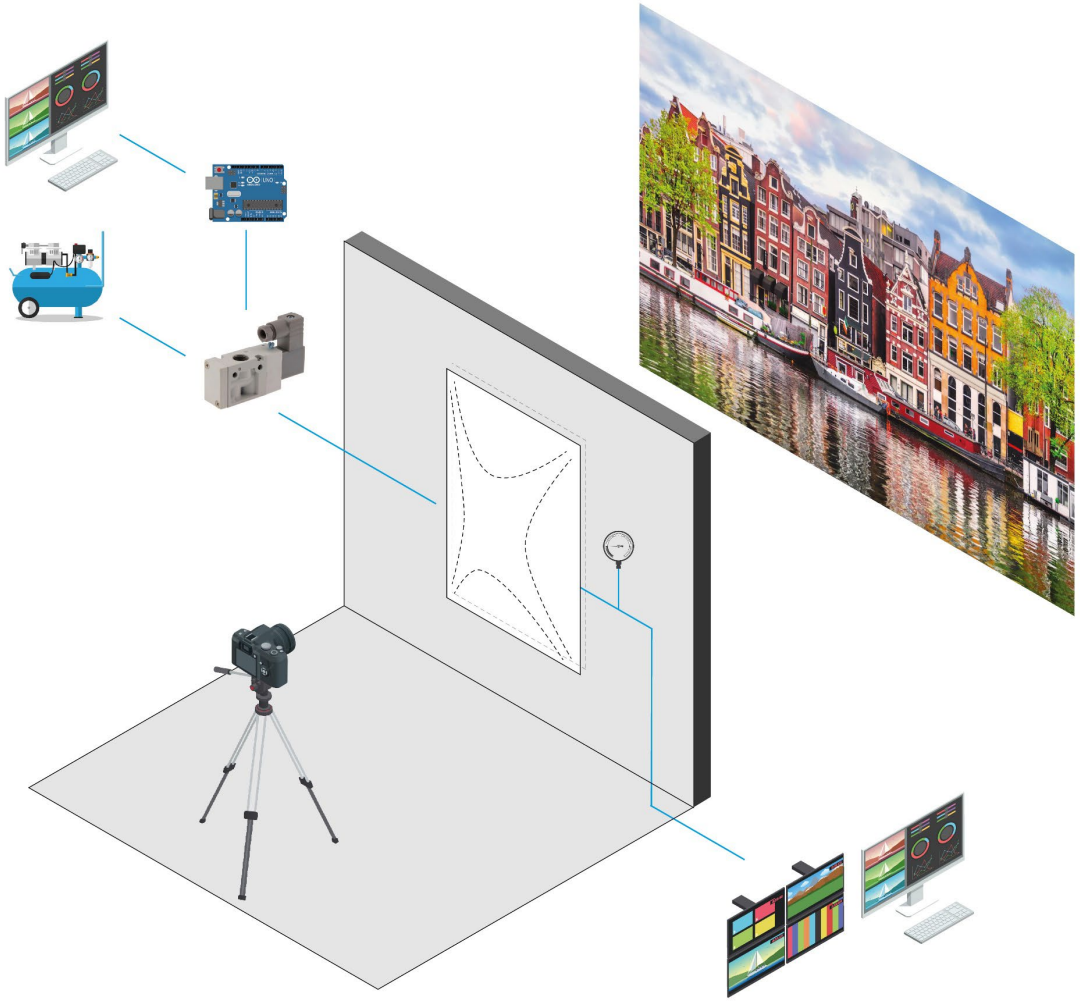
Application

- Subjective tests
- Include multiple persons
- Include VR setup
- Mechanical behavior using strain gauges, laser serial input generator
- Optical tests for reflections
- Optical tests with varying distances and angles between target and camera



Application

- Subjective tests
- Include multiple persons
- Include VR setup
- Mechanical behavior using strain gauges, laser serial input generator
- Optical tests for reflections
- Optical tests with varying distances and angles between target and camera
- Optical tests with different views



Application

- Subjective tests
- Include multiple persons
- Include VR setup
- Mechanical behavior using strain gauges, laser serial input generator
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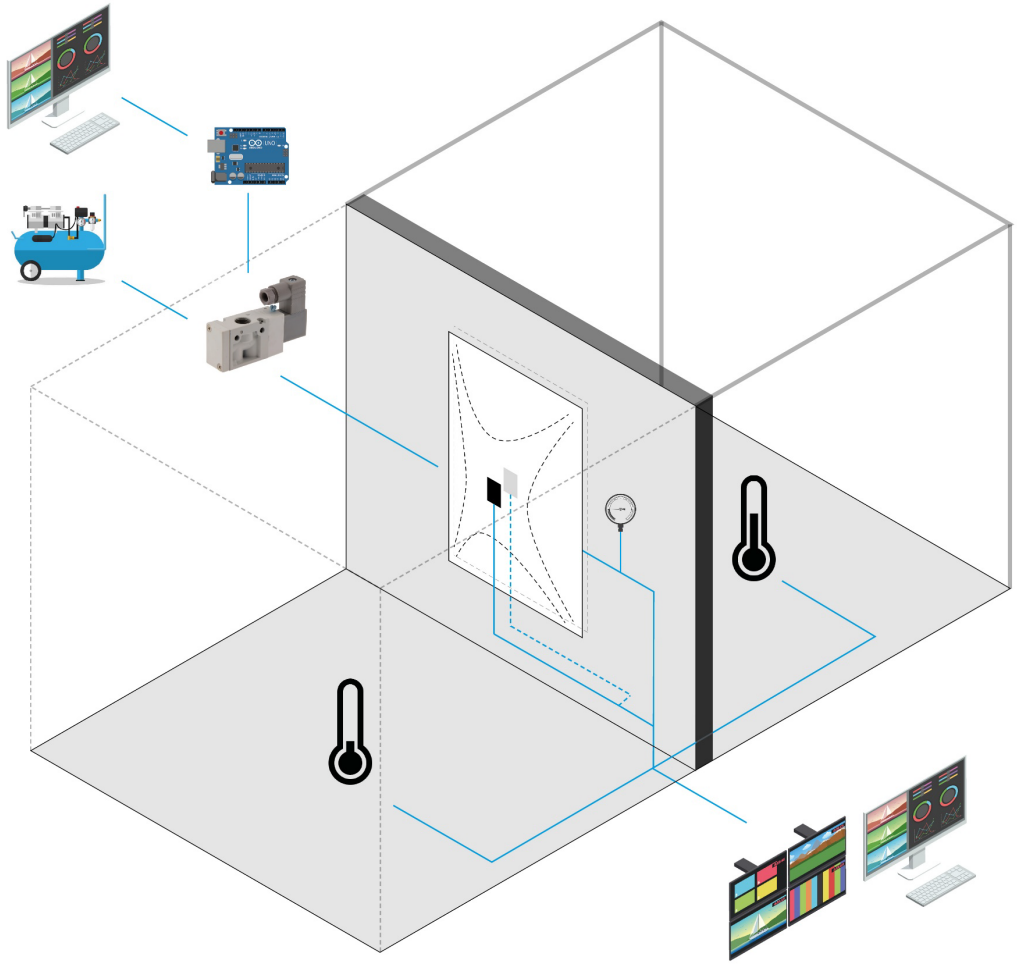
- Optical tests with varying distances and angles between target and camera
- Optical tests with different views
- Thermal insultation tests at different pressure steps



Application

- Subjective tests
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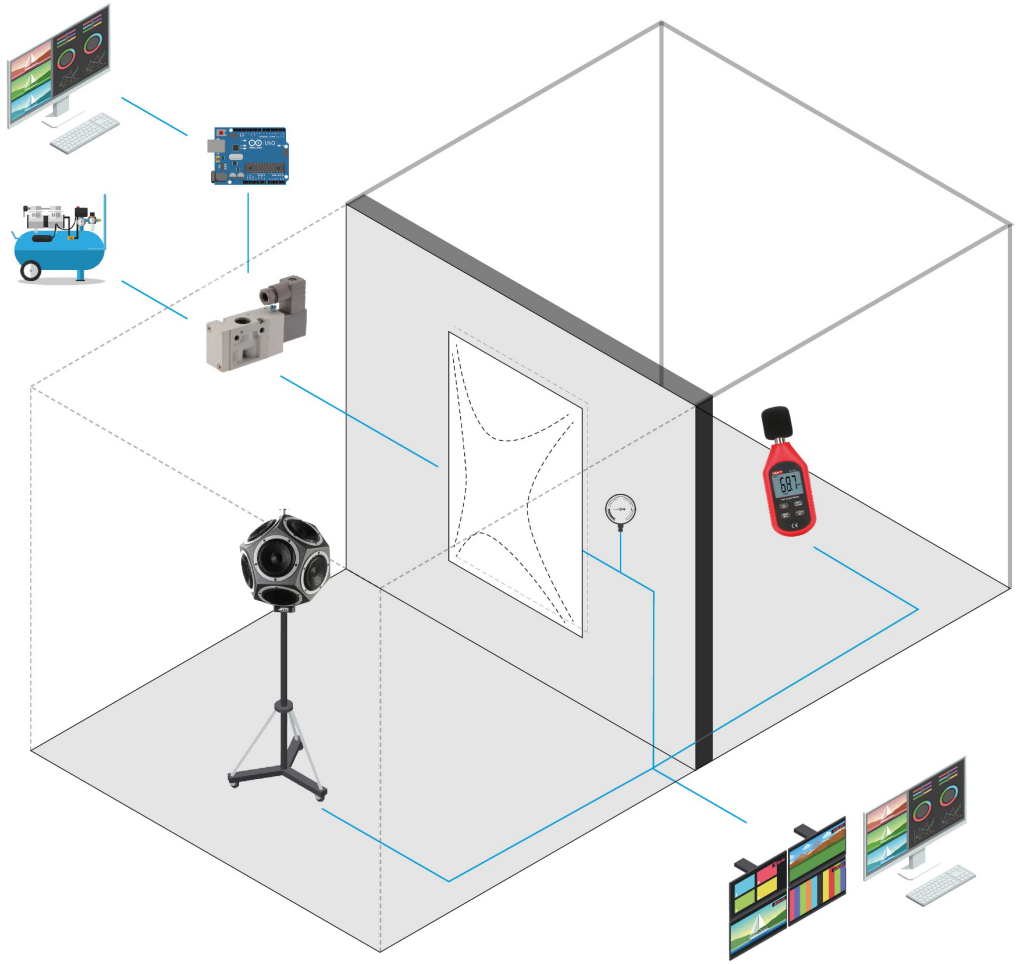
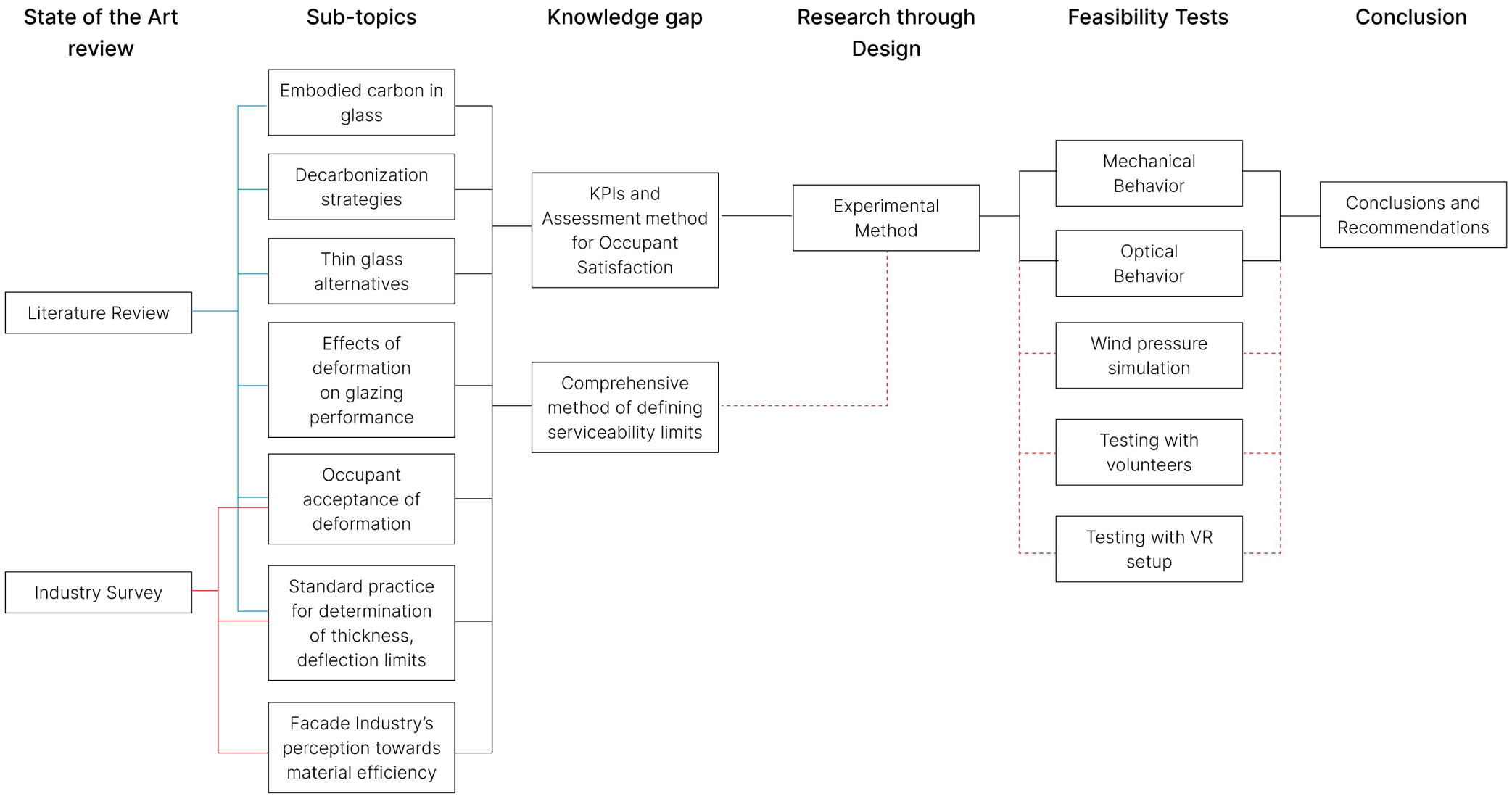
- Optical tests with varying distances and angles between target and camera
- Optical tests with different views
- Thermal insultation tests at different pressure steps
- Acoustical insultation tests at different pressure steps



Next Steps


State of the Art review
Sub-topics
Knowledge gap
Research through Design
Feasibility Tests
Conclusion
Literature Review
Industry Survey
Embodied carbon in glass
Decarbonization strategies
Thin glass alternatives
Effects of deformation on glazing performance
Occupant acceptance of deformation
Standard practice for determination of thickness, deflection limits
Facade Industry's perception towards material efficiency
KPIs and Assessment method for Occupant Satisfaction
Comprehensive method of defining serviceability limits
Experimental Method
Mechanical Behavior
Optical Behavior
Wind pressure simulation
Testing with volunteers
Testing with VR setup
Conclusions and Recommendations

Thank you!

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