Conservation of windows and glazing

Pottgiesser, U.; Rexroth, Susanne

Publication date
2025

Document Version
Final published version

Published in
Dealing with Heritage

Citation (APA)
Pottgiesser, U., & Rexroth, S. (2025). Conservation of windows and glazing. In B. Lubelli, U. Pottgiesser, W. Quist, & S. Rexroth (Eds.), *Dealing with Heritage: Assessment and Conservation* (pp. 73-109). Delft University of Technology.

Dealing with Heritage

Assessment and Conservation

Barbara Lubelli
Uta Pottgiesser
Wido Quist
Susanne Rexroth

Table of Contents

5 – Conservation of windows and glazing

Uta Pottgiesser & Susanne Rexroth

'The loss of traditional windows from our older buildings poses one of the major threats to our heritage' (Pickles et al., 2017, p.1)

5.1 – Introduction

A window is an 'opening especially in the wall of a building for admission of light and air that is usually closed by casements or sashes containing transparent material (such as glass) and capable of being opened and shut' (Merriam Webster, 2021). Until medieval times windows were openings closed by leather, fabric or wooden shutters in most parts of Europe. Windows are essential functional elements of a building and, at the same time, they are comprehensive architectural and design elements of the massive building envelope. As a building component, the window has to fulfill a wide variety of tasks and requires the collaboration of different craftsmanship techniques in its manufacture. The diversity of the historical, national and regional types of windows is large and as diverse as architecture in general (Koolhaas, 2018). They represent different design characteristics depending on time and region and they include technical and structural developments that respond to different functional requirements, e.g. impermeability, ventilation possibilities, light permeability and operability. Despite or precisely because of this diverse functionality and significance, windows are subject to a particularly high pressure for change (VDL, 2017). Similar to other heritage authorities, Historic England has stated that unsympathetic replacement of windows and doors represents the number one threat of heritage buildings, and that this affects no less than 83% of defined conservation areas (Pickles et al., 2017, p.1). Traditional windows are threatened for many different reasons: they are often completely replaced to improve a building's energy efficiency, even when simple technical and thermal upgrading options (e.g. draught-proofing, secondary glazing, shutters) would be also feasible at much less cost. Other reasons are safety and security requirements, material decay or the simple wish for change and modernization.

This contribution focusses on the historic values of windows and their conservation and refers to the experiences, approaches and recommendations of heritage authorities in England, Switzerland, Germany and the Netherlands. All of them emphasize the importance of windows as resource for the overall appearance and significance of buildings.

FIG. 5.1 Historic glazing / Photo: M. Olmeda

GLASS IN MONUMENTS

Glass panes in old buildings are different and each of them is unique: their appearance, the context in which they are used, their reflections and possible distortions, should be taken into account for the chronological and significance assessment. The aim is to preserve them, as they belong to our heritage.

5.2 – Material and construction

Glass history and types

Early glass produced from 3500 BCE until 50 CE was mainly used for jewelry and artisanal objects. The Romans recognized further functional uses of glass, namely for glazing their windows. The oldest known window pane in situ can still be visited in the Thermae in Pompeii (buried under ash and pumice in the eruption of vulcan Vesuvius, in 79 CE). After the fall of the Roman Empire around 476 CE, glass production in Europe continued, but on a much reduced scale (in Gallia and the neighborhood of Cologne for instance) as a product for the elite. By creating large, glazed openings, Gothic architecture played an important role in preserving many of the achievements of the Romans – both through safeguarding artefacts and fabrication techniques. Early medieval window glass is well known from archaeological sites of churches and palaces all over Europe. However, it was mainly applied in stained-glass windows and only produced in small size and quantities.

Being an expensive and exclusive material, very few residential buildings made use of it in medieval times. Glass as flat glazing became a standard element of window constructions during the Renaissance in the 15th-16th century. It replaced other translucent materials such as alabaster or the use of only wooden shutters to fill the window opening. It was only in 19th century that the industrialization of glass production made glass affordable for general application in the building sector.

Hereafter, the most common types of glass are briefly illustrated and their fabrication process explained (Wigginton, 1996 and Schittich et al., 2021). When found in monuments, the types of glass from the past should be identified and analysed and, if possible, protected [FIG. 5.1].

FIG. 5.2 Roman glass from the German site of Haselburg / Photo: https://de.wikipedia.org/wiki/Datei:Haselburg_Glas.jpg 2007, accessed Aug. 2021

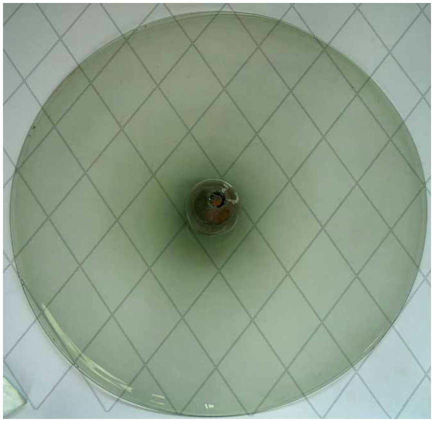


FIG. 5.3 The term 'bull's eye' refers to the thicker centre area of crown glass around the pontil mark / Photo: RCE

FIG. 5.4 Crown glass was one of the most common glass types until 19th century / Photo: pixabay.com

Crown Glass (400 CE onwards): to make crown glass, a bubble of glass is transferred from the blowpipe to a pontil iron and after perforating the glass balloon, is spun at high speed so that the centrifugal force causes it to flatten into a round 'crown'. The central piece, the 'bull's eye' was often used for cheaper (domestic) windows. Crown glass was one of the most common processes for making window glass in Europe until the 19th century [FIGS. 5.2/5.3/5.4].

Cylinder Glass (1080 CE onwards): to make cylinder glass a bubble of glass is manipulated into a cylinder by spinning it around. After cutting this elongated bubble open on both sides, the remaining cylinder was cut open along the length, and gently reheated and pressed flat to form a sheet. Like crown glass, this method was commonly used until the end of 19th century [FIG. 5.5].

Stained glass (1080 CE onwards): coloured and painted glass not only adds light but also beauty to medieval churches. Setting glass in (strong yet malleable) lead required skilled craftsmen. Lead as matrix for glass pieces however was already known to the Romans [FIG. 5.6].

Polished Plate Glass (1665 CE onwards): made by first pouring molten glass on to a table and rolling it until flat, then grinding and polishing it into a plate. Advancements in the process led to feeding the molten glass though continuous rollers, grinders and polishers. Plate sheet glass is no longer produced commercially in most European countries. As splendor had become a fundamental requirement, a whole new branch of industry could develop: the large scale production of polished plate glass. To get perfect flat and smooth panes, the cast glass has to be polished. This is a very time consuming and elaborate process. Glass has to cool slowly or it will crack due to internal stress. This very expensive glass type was for long only used for very specific buildings (both for windows and mirrors). Being almost undistinguishable from the best quality of modern industrially made float glass, it was also used for big shop windows into the 20th century [FIG. 5.7].

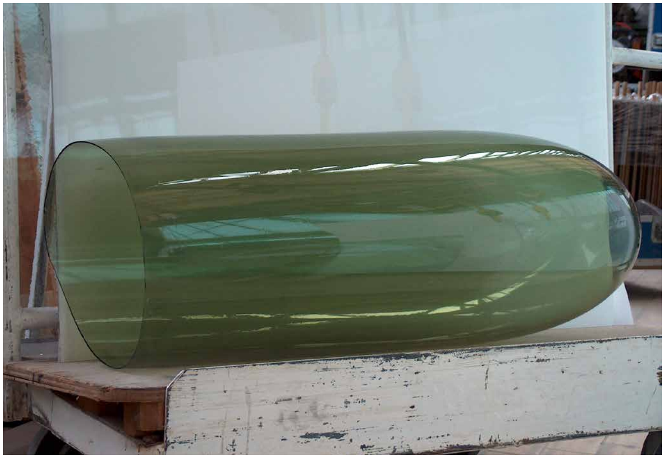


FIG. 5.5 Cylinder glass was another common glass types until 19th century / Photo: RCE

FIG. 5.6 16th century leaded glass in St. Johns' cathedral Gouda / Photo: S. Naldini

FIG. 5.7 Amalienburg hall of mirrors at Parc Nymphenburg (Munich) built in 1739 / Photo: https://en.wikipedia.org/wiki/Amalienburg#/media/File:Amalienburg_Spiegelsaal-1.jpg, accessed Aug. 2021

FIG. 5.8 Bauhaus Dessau, staircase, office and workshop glazings were originally using polished plate glass to achieve a precise and industrial look / Photo: pixy.org

FIG. 5.9 Wire mesh glass, Lochal Tilburg / Photo: W.J. Quist

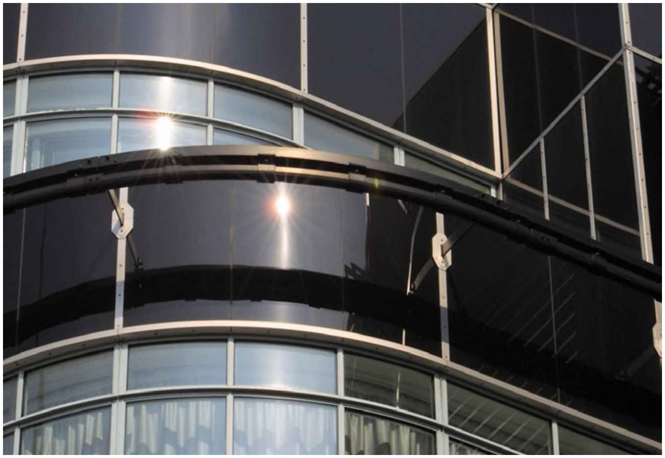


FIG. 5.10 Vitrolite spandrels at former Daily Express building by Ellis and Clark, 1932, London / Photo: https://en.wikipedia.org/wiki/Daily_Express_Building,_London#/media/File:Express_Building.jpg, accessed Aug. 2021

From the 19th century onwards, the demand for better quality, cheaper and faster produced glass rose. Around 1900, Art Nouveau, Art Deco and modern architecture made use of more and larger window panes, for shop windows, commercial and residential buildings [FIG. 5.8]. Pender and Godfraind (2011, p.431) point out that 'many special forms of decorative glass were developed over the course of the 20th century', some of them are introduced here: pigmented structural glass, pressed and prism glass, patterned glass, drawn and float glass. For a timeline see FIG. 5.13.

Wired Cast Glass (1898 onwards): also known as Georgian Wired Glass or Wire Mesh Glass is a glass with safety and fire-resistant abilities, first patented by Frank Shumann in the USA in 1892 and first produced by Pilkington in 1998. The wire mesh embedded into cast glass helps the glass to stay in place when breaking. It does not necessarily conform with current standards and regulations for safety glass [FIG. 5.9].

Pigmented Structural Glass (1900 onwards): is a high-strength, coloured glass developed in 1900 in the United States by adding fluorides into the molten glass, which made the glass opaque. It was widely used in interiors, for signs and partitions and as facade cladding in the first half of the 20th century. Manufactured first in white, black or beige and later in a variety of colors, in flat panels or curved, it could be opaque or translucent, with a wide range of finishes: carved, cut, inlaid, laminated, sandblasted and textured. It was produced until the early 1960s in the US and until later in the UK and Europe. It was most commonly known under its trademarked name 'Vitrolite', but it was also sold as 'Argentine', 'Carrara glass', 'Glastone', 'Marbrunite', 'Nuralite', 'Opalite' or 'Sani Onyx' or as 'Detopakglas' in Germany [FIG. 5.10].

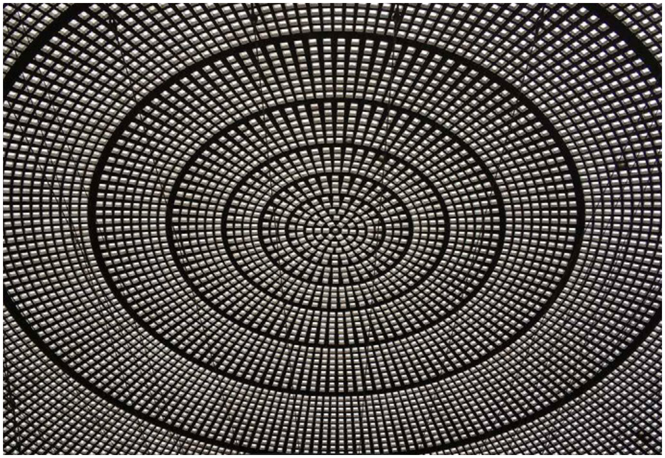


FIG. 5.11 Pressed glass, Ravenstein gallery Brussels / Photo: W.J. Quist

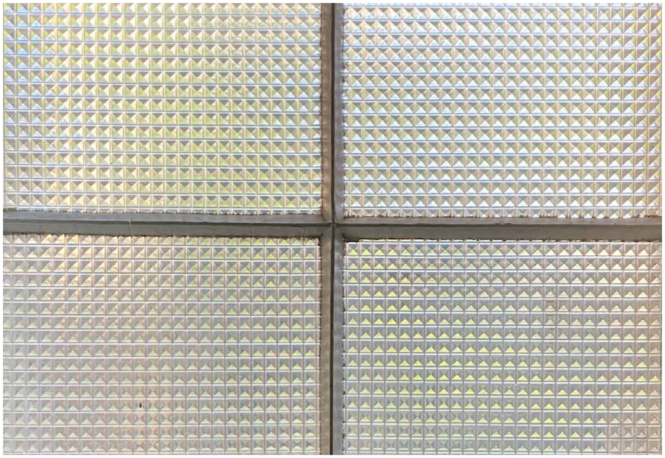


FIG. 5.12 Patterned glass, F.W. Braat's office, 1932, Delft / Photo: W.J. Quist

Pressed Glass (1900 onwards): is used to make glass blocks (or bricks), concrete glass and glass roof tiles and was first produced as blown hollow glass bricks by the French glazier Gustave Falconnier or as prismatic blocks by the German company Luxfer Prismen Gesellschaft. It was only in the 1930s that Saint-Gobain and the Owens Illinois Glass Cooperation pressed the viscous glass mass in a mould. This produced open glass bodies that are welded together to form a glass block allowing for a good homogeneous translucent illumination of interiors [FIG. 5.11].

Patterned Glass (also Textured Glass, 1919 onwards): is cast and rolled flat glass that gets its shape and its special patterned surface through a rolling process. The liquid glass mass is passed through structured rollers whose patterns are then reproduced in the glass. The uneven surfaces result in less transparent, but always translucent glass. The translucency depends on the density of the patterns. It provides a high level of light transmission in combination with privacy (sight reduction). It was often used in industrial context an in interiors [FIG. 5.12].

Drawn Glass (1913 onwards): was produced by drawing out vertically and then cooling semi-molten glass through a series of metal rollers set up on automatic machinery. This process, known as the Fourcault process, was invented by Émile Fourcault (Belgium) using the debiteuse. In parallel, Irving Colburn developed a similar drawing process where the glass was drawn horizontally. In 1913 the Libbey Owens Sheet Glass Company started producing large quantities of drawn sheet glass. The methods were used all over the world until the 1970s. Both processes cause slight irregularities on the glass surface (referred to as 'roller waves'), which distort light and lead to non-specular reflections that are particularly apparent when the glass surface is viewed tangentially.

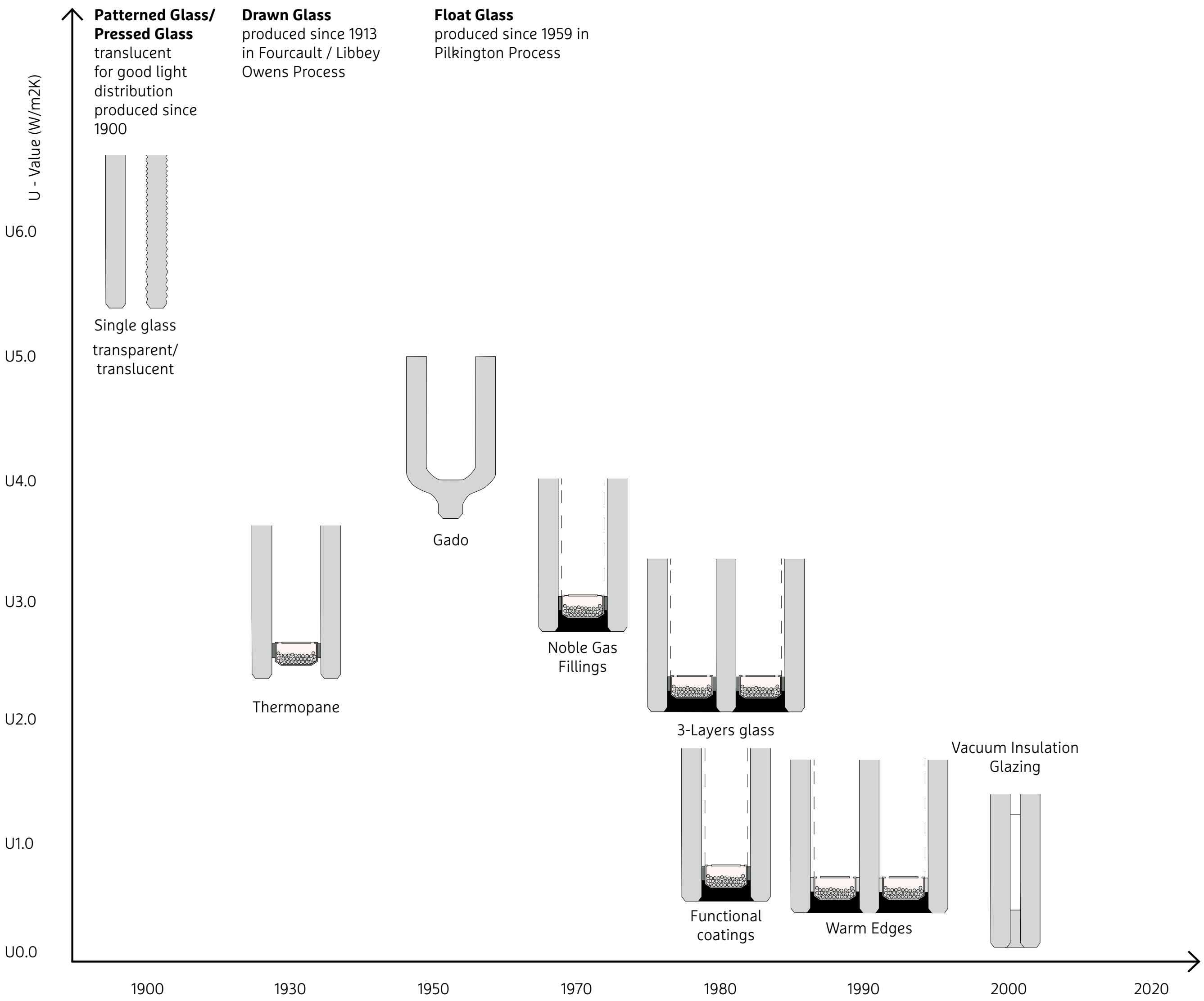


FIG. 5.13 Timeline of modern glass and glazing developments since 1900

Float Glass (also Annealed Glass, 1959 onwards): invented by Sir Alastair Pilkington in 1952, the float glass process was used to make flat glass without the 'roller wave' surface irregularities characteristic of drawn glass. The process was put into practice in 1959. Molten glass from the furnace flows by gravity and displacement onto a bath of molten tin, forming a continuous ribbon. From here it is led onto guiding rollers, which run it through an annealing furnace (lehr) where it is cooled under controlled conditions. It is characteristically flat, with virtually parallel surfaces and a smooth, even finish. Float glass that has not been heat-treated is referred to as annealed glass, different from tempered and heat-strengthened glass. Today, over 95% of window glass produced is using the float process.

Restoration Glass: a term used for different types of machine-drawn glass types that resemble historic glazing (SCHOTT AG, 2019, 2020). They are available under different names and produced by different companies up to 3.00 m and in 4 mm or 6 mm thickness. All restoration glass can be processed into insulating glass, laminated glass or toughened safety glass. Also blown window glass produced through traditional processes - e.g. slug, plate and cylinder technology - is still produced in a few glass factories in Europe.

Functional Glazing (1930 onwards): glass panes - mainly drawn and float glass - can be further coated, heat-strengthened, laminated, assembled into insulation glass units (IGU) or vacuum insulation glass units to improve thermal, mechanical or safety properties.

Glass Composition

Soda Lime Silicate Glass: is the most used glass in construction today. It has a greenish colour - particularly visible in thicker glass panes - due to traces of iron oxide present in the quartz sand.

Low-iron Glass: by using quartz sand with a low iron oxide ratio, any green colouring can be almost eliminated. This type of high-clarity glass and is also referred to as low-iron oxide glass or white glass.

Borosilicate Glass: adding boron (13% boric oxide) to the manufacturing process, results in glass with a very low coefficient of thermal expansion and more resistant to thermal stresses. While mostly used in laboratories, for electronics, cookware, optics or lighting, it is also manufactured as flat glass for use as fire protection in the construction sector.

Window History and Types

Windows discussed in this book are fixed or openable units with sash and frame constructions and single or multiple glass panes. They are mainly categorised here by their construction, function and design. The European standard (European Committee for Standardization EN 12519, 2018) describes windows terms officially used in EU Member States. The main construction types and glazing bars are mentioned there:

- fixed lights and fixed windows
- pivoted windows
- sash windows
- sliding, projecting and casement windows
- tilt and turn windows
- louvered windows
- folding windows
- glazing bars

Depending on their function and location, roof windows and lanterns, bay and oriel windows, French and witch windows or emergency exit windows can be distinguished. The number of glass panes is relevant to their thermal properties and their contribution to heat transfer: historically single and double-paned windows are known; triple - and quadruple - paned windows are commonly used for new constructions.

Windows Timeline

Wooden shutters	Hinged wrought iron casement	Larger timber frames	Cast iron frames	Mild steel	Metal casements hot rolled steel	Aluminium, nonferrous materials frames
No glazing	Leaded lights	Clearer larger sheets of glass	Cylinder and crown glass	Stronger biggeer plate glass	Galvanisation and polyester powder	Large float glass panes
Plain or moulded mullions	Diamond shaped glazing moulded in frame	Sidehung hinged casement	Curved top smaller	Sash horns	Drawn sheet glass	Thermally separated frames
Vertical wooden/ iron bars		Vertical/horizontal Sliding sashes	Sash frame	Small glazing bars		Insulation Glass

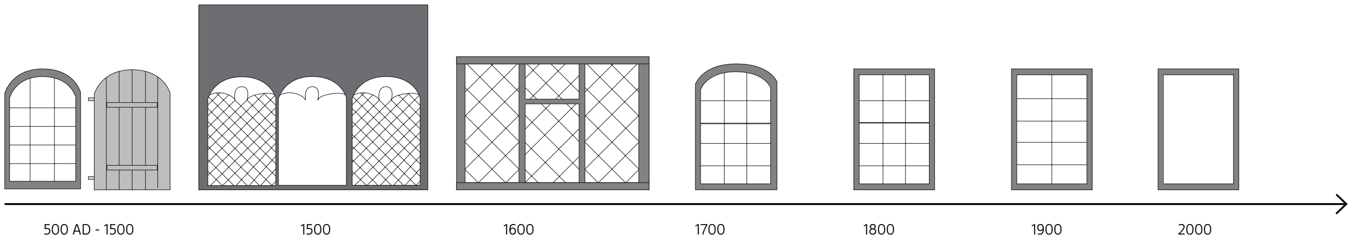


FIG. 5.14 Timeline of window development since 500 BCE

The historic development of windows and of the materials used is important in the heritage context. The main materials used for sash and frame constructions until the 19^{th} century were wood and wrought iron [FIG. 5.14]:

- *12^{th} -15^{th} century:* leaded windows are used in commercial and luxurious residences[1] ;
- *18^{th} century:* wooden frames for domestic buildings, wrought iron frames for industrial buildings (which provided better fire-resistance);
- *1856:* hot rolled steel allowed mild steel window frames to be produced (cheaper than wrought iron);
- *late 19^{th} century:* the steel frame became strong, slim, cheap and could open wider than wooden frames; glazing technology made production of larger glass panes possible;
- *early 20^{th} century:* non-ferrous metals (e.g. bronze, brass, aluminium) became more common for window frames;
- *after 1950:* galvanized steel window frames were used to prevent corrosion: molten zinc dip forms a molecular bond with the steel. Aluminium and PVC became widely used for window frames; double-glazed panes and insulation glass units became standard glazing;
- *1970s:* use of polyester powder coating as decorative finish, applied on top of galvanisation; late 1970s: thermal separation of steel, aluminium and PVC's frames was introduced to reduce thermal bridges and heat losses.

1 Picture and rose windows, stained glass windows and Dalle de verre are not discussed here, since there are many specific publications about them available (e.g. Pender and Godfraid, 2011 and RCE, 2004).

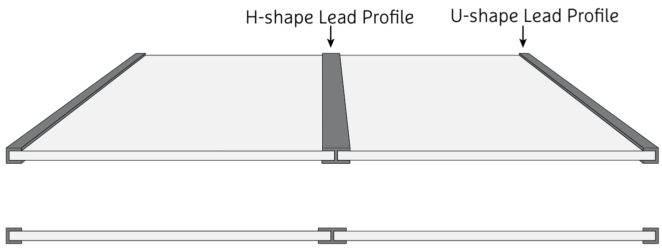


FIG. 5.15 Schematic section of leaded windows with U- and H-shaped lead profiles

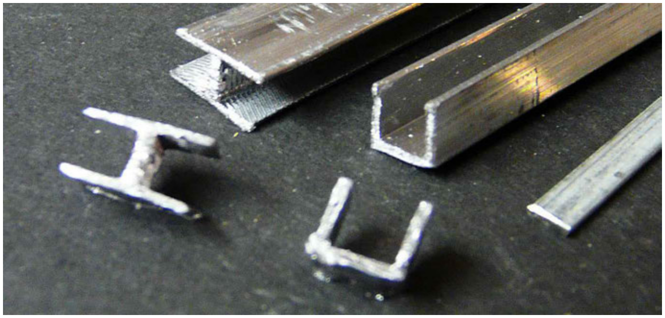


FIG. 5.16 U- and H-shaped lead profiles / Photo: https://commons.wikimedia.org/wiki/File:Blei.jpg, accessed Aug. 2021

FIG. 5.17 Wooden window with muntins (glazing bars) connecting small glass panes / Photo: RCE

FIG. 5.18 Puttied glass in wooden windowframe (in need of repair) / Photo: W. J. Quist

Until the 17th century, glazed windows were directly attached as a fixed glazing to the wall opening. Thus, they were separated from the smaller movable ventilation part made of wood (shutters), metal, leather or textiles. It was only in the 15th-16th century, that the entire wall opening - with jambs, windows and framing decorations - became a central, facade-structuring building element.

Leaded windows (leaded lights or leadlights): were used until the 15th century and constructed by connecting smaller individual glass pieces by using U- and H-shaped lead bars rods or profiles to form a glass pane [FIGS. 5.15/5.16]. The lead profiles were connected with a soldering agent consisting of lead (40%) and tin (60%), called ‘glazier’s lead’. Putty was used to make the windows waterproof and more stable. Larger window areas were often stabilised with so-called wind irons, to distribute the wind loads into the frame or wall construction.

Muntins or glazing bars: were used to join the smaller glass panes to form a window [FIG. 5.17]. The fine wooden (or metal) bars were grooved on both sides to hold the glass pane and were inserted into each other without glue. The thicker frame pieces were grooved on one side and connected with the bars. Wooden connections were used at the frame corner joints. Thus, window frames were not inherently stiff and the system had the disadvantage that broken glass panes could only be replaced if the window was disassembled. This type of glazing, already used in England, was introduced in the Netherlands and continental Europe at the end of the 17th century and continued to be used to combine small sized glass panes until the middle of the 19th century.

Putty glazing: was used to fix the glass panes against the muntins or glazing bars [FIG. 5.18]. Those had rebates on the outside which were treated with linseed oil varnish before the panes were placed and secured with glazing triangles and then sealed with putty. The linseed oil putty used as window putty is a pliable, kneadable mass with a high plasticity and is still commercially available. It consists of about 85 % slurry chalk (calcium carbonate) and 15 % linseed oil or linseed oil varnish. More recent linseed oil putties from the 1960s and 1970s may contain asbestos fibres. Putties have been used since the late 17th or early 18th century, but they only became widespread in the course of the 19th century. Similar to wood putty, it can be used to repair damaged areas on wooden components.

Wooden sash windows: became popular and spread in the 17th century. The combination of blind frames with movable sash frames represented the first reasonably wind and watertight window construction (Wohlleben and Moeri, 2014). Early wood sash windows were marked by thick muntins and small panes, or lights, due to the high price of glass.

As glass technology improved and prices decreased, lights became larger and muntins became thinner.

Next steps of development were double-wing pivot windows with overlap and the improvement of fittings technology, weather legs and protection and secondary front windows to improve the insulation in winter. Later, single glazed box windows were developed and used because of their good thermal insulation and windproofness. The technical improvements in glass production during the second half of the 19th century led to the enlargement of glass surfaces and thus to the reduction of the number of muntins and finally resulted in the composite window (double-glazed window) - to overcome the disadvantages of the box window, which included condensation in the cavity space and the effort required to manufacture two windows connected by a wooden box (Wohlleben and Moeri, 2014). Wooden frames were common in residential and public architecture until the mid 20th century [FIG. 5.19].

Basic constructions of window types are [FIG. 5.20]:

- single glazed window (consisting of one window sash) and single window with attached glass pane;
- double window (two window sashes mounted one behind the other);
- compound window (two window sashes mounted on top of each other);
- box window (two window sashes connected by a wooden box).

FIG. 5.19 Wooden frames were the most common material for residential buildings until mid 20th century. From early 20th century onwards larger glass panes were used in residential architecture / Photo: pxhere.com

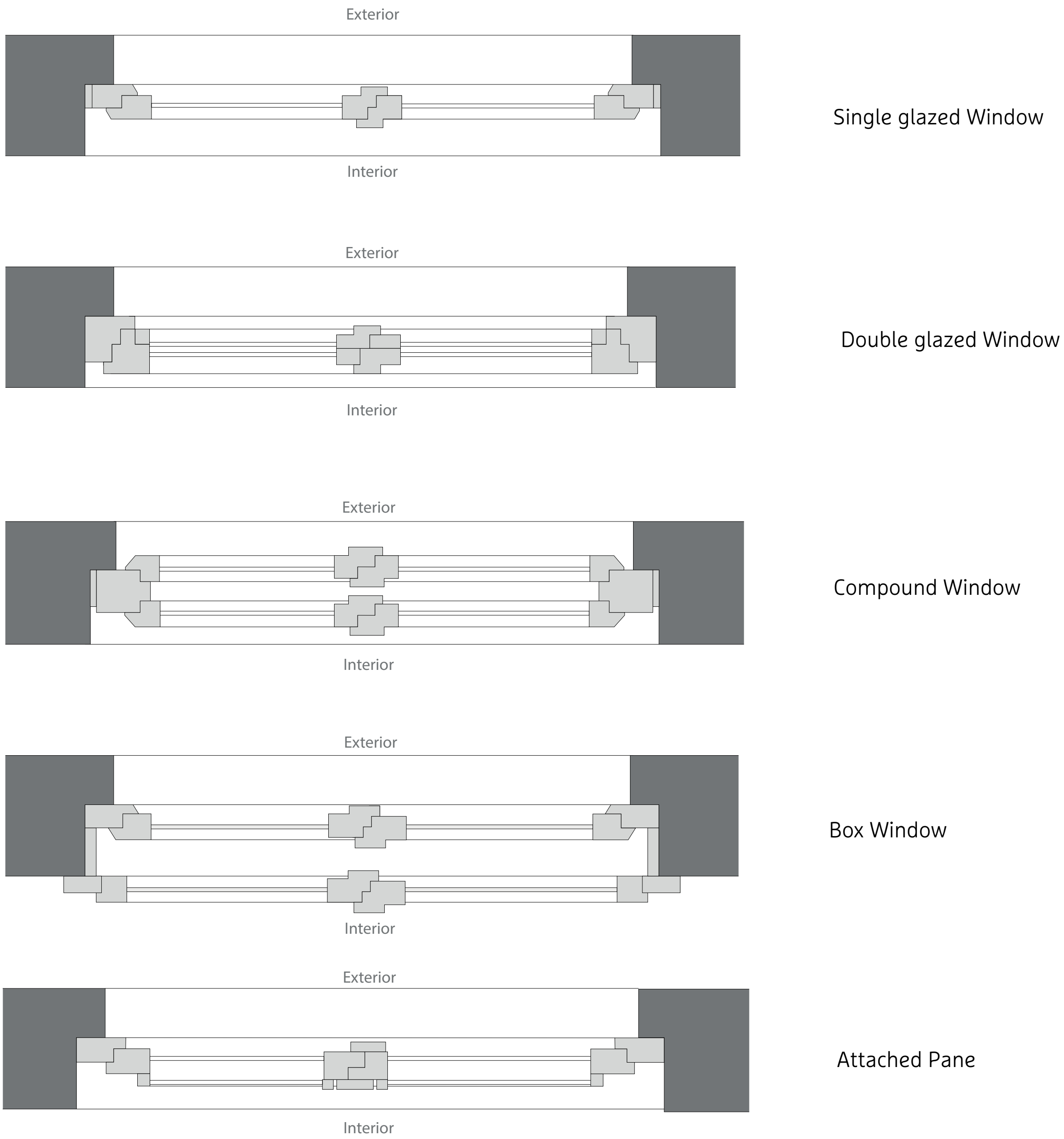


FIG. 5.20 Basic single and double glazed wood window constructions

FIG. 5.21 Metal framed windows were used in industrial architecture since 18th century, and became standard in 20th century with mostly patterned or wired glass, Zollverein Coalmine, 1932 / Photo: U. Pottgiesser

FIG. 5.22 Large metal framed windows were introduced to residential architecture in early 20th century, and became famous with buildings like the Farnsworth House, 1951 / Photo: A. Ayón

Hinges: the Gothic and Renaissance periods were dominated by long, angular and lappet hinges (fixed with a metal plate on the frame) for fixing windows. Sash locks short sliding or locking latches were used for window fastening and for locking (sash windows were in use from the end of the 17th century in the Netherlands). As an innovation, the Baroque era brought the often richly shaped and chiselled chased S-bands, also called spiral bands, which differ only in form from the older lappet hinges. The Baroque period also saw the appearance of fish bands. Fish hinges lobes are embedded or driven into the wood. They are still used today. New, more convenient and better closing window locks (bar locks) were also introduced in the Baroque period.

Metal frames out of wrought iron and later steel were commonly used until mid-20th century in industrial architecture. From early 20th century onwards, metal frames were also used in commercial and residential architecture. For industrial purposes patterned glass was often used since it was cheap, industrially produced and translucent, which provided a good and more homogeneous light distribution compared to transparent glazings [FIG. 5.21]. After 1920 the architecture of the Modern Movement promoted new large-scale glazed surfaces [FIG. 5.22]. The increasing use of industrial and thinner steel frames for administrative and residential buildings allowed for larger glass surfaces to further fuse exterior and interior spaces. Historic profile systems are documented in old construction manuals (e.g. Mittag, 1957) and publications on general construction materials (e.g. Jester, 1995).

After 1950 post-war modernism introduced new types of window openings, such as the pivoting sash. Steel frames were mostly replaced by aluminum frames after 1960. With better heat and noise protection, insulation glass units (IGU) replaced earlier glazing and window types. Frames became thicker again to be able to accommodate the IGU. In the residential sector, Unplasticized Polyvinyl Chloride (uPVC) windows started to dominate the market after the 1970s and led to the replacement and loss of many wooden windows.

Until the middle of the 20th century, residential building's window frames were usually made of wood. In central Europe the share of single glazing in existing windows is supposed to be very low: in Germany it is estimated 2%; the number of box windows is about 70 Mio. and that of compound windows about 40 Mio. (Klos, 2011). The majority of existing windows today is equipped with insulation glass units (IGU) of different ages; however only a few of them form part of listed buildings.

By 2020 the share of the various frame materials in the residential market in Western Europe has remained constant for several years: uPVC is at 58 %, aluminium remains unchanged at 22 %, wood only reaches 17 % and the combination wood-aluminium is 3 %. The share of frame materials in the total window market in Western Europe shows percentages of metal at 36,8 %, PVC at 29,4 %, wood-aluminium at 15,3 %, wood at 14,0 % and uPVC-aluminium frames is at 4,6 % (IC, 2019) [TABLE 5.1].

TABLE 5.1 Comparison of current window materials and their properties (compiled from Cremers 2016 Wikipedia, 2021 and Hildebrandt and Arztmann, 2013).

MATERIAL FRAME / GLAZING	THERMAL RESISTANCE	DURABILITY LIFE SPAN	EFFORT MAINTENANCE	COST INVESTMENT	RECYCLABILITY FRAME
Hardwood **Softwood**	very good very good	40–100 years 30–50 years	Low/medium ****	medium	high
Steel zinced * **Steel zinced ****	low very good	40-50 years	very low	high	typically > 85% high > 98%
Aluminium * **Aluminium ****	low very good	40–60 year	very low	low	typically > 65% typically > 95%
uPVC (“vinyl”)*	very good	25–50 year	very low	low	medium typically > 80%
Fiberglass	very good	40–60 year	very low	high	medium
Composites ***	very good	30–50 years	very low	high	medium
Single glazing	low	60–100 years		low	high
Double glazing	very good	20–30 years	medium	high	medium/low
Putty	medium	8–15 years	high	low	very low
Seal profile	medium	15–25 years	medium	low	low
Sealant (silicone)	medium	10–25 years	medium	low	very low
Sash seal profile	medium	15–25 years	medium	low	low

** thermally separated, ** not thermally separated, ***Aluminium-Wood/uPVC, ****regular maintenance can increase life span significantly*

Value and Damage Assessment

‘Surviving historic fenestration is an irreplaceable resource which should be conserved and repaired whenever possible.’ (Pickles et al., 2017, p.3)

The significance of windows and their contribution to the overall significance of a building can be defined through value assessment. This is the key first step in deciding the right course of action when dealing with historic windows [FIG. 5.23]. Significance can be derived from the assessed heritage values. Myers (1981) defines the following five steps for the assessment of wooden windows:

1. are original,
2. reflect the original design intent for the building,
3. reflect period or regional styles or building practices,
4. reflect changes to the building resulting from major periods or events, or
5. are examples of exceptional craftsmanship or design.

VDL (2017, p.8) states that if windows are ‘important parts of architectural monuments and bear historical or design information’ they are most likely to be ‘constituent parts of the monuments’ [TABLE 5.2].

The value assessment is followed by the damage assessment of existing windows and glazing [TABLE 5.3] which makes use of different methodologies: visual inspection, measurements, documentation, analysis of materials and components.

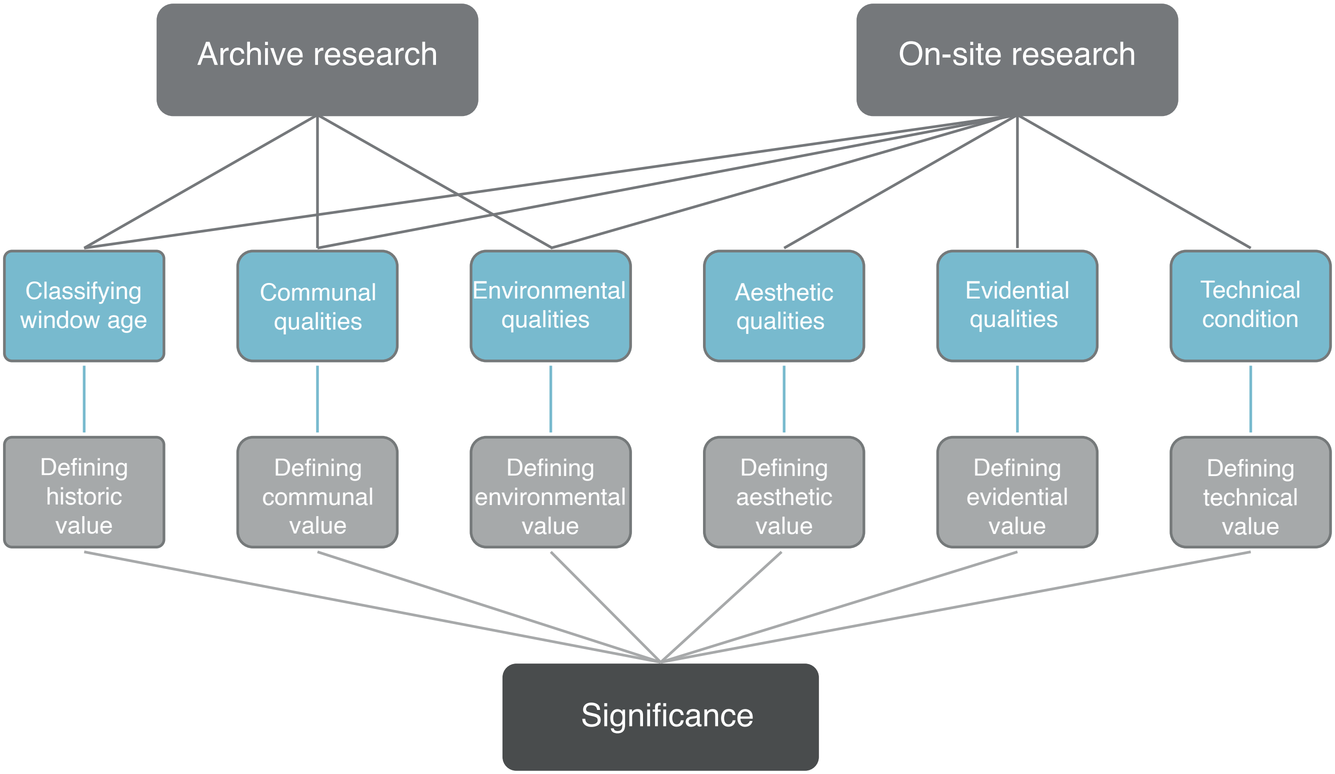


FIG. 5.23 A systematic significance assessment of historic windows includes archival and on-site research, the building context and all window components: frame, fittings, glazing, colour layers, shutters

TABLE 5.2 Assessment of Heritage Values of windows*

HERITAGE VALUES	HOW TO EVALUATE THE DIFFERENT HERITAGE VALUES OF WINDOWS?
Historic value	historic windows document the design, technical and craftsmanship possibilities of their respective time of origin; glass quality improved from blown to drawn and from drawn glass to float glass and historical glazing also documents time of origin; the older the glass is, the more clearly irregularities are visible and perceptible and characteristic: a shop window in a domestic building, for example, may carry considerable historic value indicating the development of the function of the building.
Communal value	may sometimes be found in public buildings and places of worship, this value may not be affected by changes to windows unless they contain commemorative glazing,
Environmental value	window construction represents a typical climate-adapted and localized solution, original windows are material resources (embedded energy).
Aesthetic value	the fenestration often forms an integral part of the design of the building and contributes to a building's visual interest, if later in date, the aesthetic qualities of fenestration may add to or detract from the interest of a building, replicas or recreations of fenestration of aesthetic quality will maintain this value, in contrast, much off-the-peg joinery and modern glazing do not replicate historic appearance and so can detract from the aesthetic value of the building, irregularities such as colour nuances, varying glass thicknesses, warping, inclusions and streaks give the glass its characteristic (aesthetic) appearance.
Evidential value	reflects the potential of a window to yield information about the past rarity adds to the evidential value, an old fabric will probably have a considerable evidential value, a replaced modern standard window will have no evidential value.
Technical value	construction, material and craftmanship can be significant expressions of certain technological developments, windows may be part of an overall building service system (e.g. ventilation).

** compiled from VDL, 2017, p. 9, and Pickles et al., 2017, p.4*

TABLE 5.3 A systematic damage assessment of historic windows and their components*

Wood frames and sash constructions	Warping of frame construction due to poor wood selection or strong temperature and material humidity differences Shrinkage and cracking of the wood Surface weathering (brown/black discoloration of unpainted wood Wood destroying fungi and insects Mechanical damage (local cavities and dents in the longitudinal direction of the wood, loosening of parts of the wood)
Metal frames and sash constructions	Corrosion of metal framing or signs of rusting Distortion of the frame Mechanical damage Casements that do not move properly, or at all, due to an excessive build-up of paint, rust or distortion of the frame
Paints and Coatings	Embrittlement, cracks, wrinkles, spalling in paint coatings Blisters under and detachment of paint film Leaching or chalking of the colour pigment, in particular oil-based paints Jamming of rotating beam due to ink packs or drip noses in the folds, in the rabbits or in the moving part
Glass and Glazings	Glass breakage and scratches Glass corrosion resulting in opaque surfaces Embrittlement or breakout of the mastic
Fittings and Hinges	Corrosion and material fatigue leading to failed hinges and fittings Deformation resulting in malfunction Insufficient contact pressure or jamming closure
Panels and Spandrels	No or insufficient insulation, mechanical damage or condensation resulting in humidity within the insulation Corroded or insufficient joints and fixings
Wall-Window Connection	Pointing between the frame and the wall opening is cracked, loose, or missing, allowing moisture and draughts to penetrate around the window frame.

** compiled from VDL, 2017, p.11-12*

Following the both value and damage assessments, windows can be categorized in terms of their heritage value and damages. VDL (2017, p.9) distinguishes four main categories with regard to interventions:

A windows from the original building period or from major periods and events of the building - should be maintained,

B windows without any contribution to the value of the monument/building, which do not lead to structural damage or diminish the value of the monument/building - may be kept or removed,

C windows that are disturbing or diminishing the value of the monument/building - should be modified/ removed or replaced,

D windows which, due to their technical design and/or structural-physical performance cause substantial damage to adjoining building components of the monument/ building - should be modified/removed or replaced.

5.3 – Intervention Principles and Categories

The relevance of maintenance, repair and careful upgrading of windows is continuously emphasized by heritage experts and authorities. These interventions do not only allow windows to remain serviceable for years, they also allow them to achieve comparable performance results and a better return on invest compared to replacement windows (Pickles et al., 2017; NTHP, 2012; VDL, 2017). Despite all the efforts of heritage and conservation experts, and against the knowledge of practising architects, the replacement of historic windows by new ones is very common. In some European countries, uPVC windows have a high market share. Heritage authorities consider this as the result of marketing campaigns that have persuaded private home-owners that their old timber windows are rotten, draughty and beyond economic repair (Pickles et al., 2017) and that uPVC windows have lower investment costs compared to wooden or even steel windows. However, compared to plastic windows, wooden windows are characterized by their durability and better maintenance and repair capabilities.

With reference to historic architectural glass Pender and Godfraind (2011, p.431) state that 'few (glasses) are still made, so repair often means reusing salvaged materials'. But usually this results in replacement of the glass itself with new functional glass panes.

The choice of window interventions should pursue the goals of architectural conservation in combination with safety and security concerns, increased energy efficiency, economical and user-friendly solutions. Future use and required functionalities—including energy and sustainability requirements—have to be taken into account:

- *Materials decay:* is a result of deterioration often accelerated by lacking or reduced maintenance.

- *Safety and security:* safety and security requirements have significantly changed over time and buildings and components mostly need to be adapted when the lives and health of users are at risk.

- *Energy efficiency:* energy performance requirements have significantly changed in the recent decades and the energetic improvement of the building stock is a major priority in Europe and worldwide.

- *Indoor environmental quality:* user's comfort is a crucial factor in further using buildings.

Taking all aspects into account, the building must be considered and treated as a unit, not as a conglomerate of independent components. Only by understanding how the whole building works can renovation mistakes be avoided (Wohlleben and Moeri, 2017).

Overview of Interventions

The following main intervention categories are defined and used:

- *Maintenance:* includes regular measures to preserve the visual and essential functional properties, e.g. cleaning and painting. All measures must ensure that no mechanical or constructional damage occurs to the component.

- *Restoration:* when smaller damages to the frame or glazing occur, it may be necessary to carry out restoration works, which are limited interventions that allow for the selective replication of missing or severely deteriorated components. Interventions must be preceded by an exact documentation inventory in order to enable the detailed planning of measures.

- *Rehabilitation/Retrofit:* when construction-related defects lead to increased wear and repeated damage, the constructions have to be adapted and improved to such an extent that damage is avoided and the time between repair actions is extended. Rehabilitation work is often implemented when new requirements apply or functioning needs to be improved or the original glass panes have been lost, and are no longer commercially available, or where it is not financially feasible or desirable to replicate them. Interventions also depend on the thickness and state of the frame. The tried and tested technical possibilities for improving the function of windows, i.e. above all for improving energy efficiency and sound insulation, are many and varied—but they lead to more or less severe changes in the substance and/or appearance.

- *Replacement:* intervention when, despite the significance of the windows, the original frames and glazing cannot be kept and need substitution. When the windows are replaced for a functional improvement, the building fabric is irretrievably lost.

TABLE 5.4 shows the principles and measures for improving the qualities of a window.

TABLE 5.4 General Intervention categories for window constructions and glazings*

PRINCIPLES	MEASURES	DESCRIPTION
Maintenance	Cleaning	Removal of dirt, biological growth to keep surface in function.
	Painting	Wooden and steel frames need regularly repainting.
	Regrouting putty	Putty joints must be checked regularly for completeness and supplemented or replaced if necessary.
Restoration	Weather stripping or draught proofing (carpentry overhaul)	Improving the airtightness of an existing window by sealing gaps at head, sill, meeting rail, and at vertical edges to reduce air leakage. Common types are: spring-metal, plastic strips, compressible foam tapes, and sealant beads.
	Surface-mounted film	Improving the impact safety of the glass and enhancing visible light protection and/or interior UV protection, sun and glare control; retaining the original glazing, although thin films lead to visual impact through small overlaps and joints.
	In-kind glazing	Replacement with a new single glazing with similar visual appearance and thermal performance as the original glazing.
	Laminated glazing	Replacement with a new laminated single glazing within the metal frame to improve the impact safety and/or interior UV protection; visual appearance depends on glass selection.
	In-kind thermally non-separated frames	Replacement with a new frames with similar visual appearance and thermal performance as the original frame.
Rehabilitation or Retrofit	Coated glazing	Replacement with a new coated single glazing to improve the thermal performance; the visual appearance depends on glass selection.
	Secondary glazing (Interior window)	Additional frame applied to the inside of an existing frame to achieve higher levels of thermal and sound insulation without compromising the outer appearance of the building.
	Secondary glazing (exterior window)	Additional frame applied to the outside of an existing window to protect from weather and to improve energy performance without compromising the inner appearance of the building
	Insulating shades, curtains or shutters	Additional shading element applied to the inside (shades, curtains) or outside (shutter) of the window which also improves the thermal insulation.
	New insulation glazing	Replacement with a new double insulating glazing with different visual appearance and better thermal performance than the original glazing; can often be mounted in the original frame; due to its thickness, triple glazing is normally not used.
	New vacuum glazing	Replacement with a new vacuum glazing with similar visual appearance and better thermal performance than the original glazing; can often be mounted in the original frame.
	Combination of several measures	There are many combinations of preservation and rehabilitation measures which can be applied to wooden as well as metal windows.
Replacement	New, high performance replacement window not visually distinguishable	Replacement with new, high-performance window to improve thermal performance and airtightness - visually adapted.
	New, high performance replacement window visually distinguishable	Replacement with new, high performance window to improve thermal performance and airtightness - visually different.

* *compiled from Ayón et al. 2019; NTHP, 2012; Pickles et al., 2017; Kantonale, 2014 and TU Delft, University course CSI, 2021.*

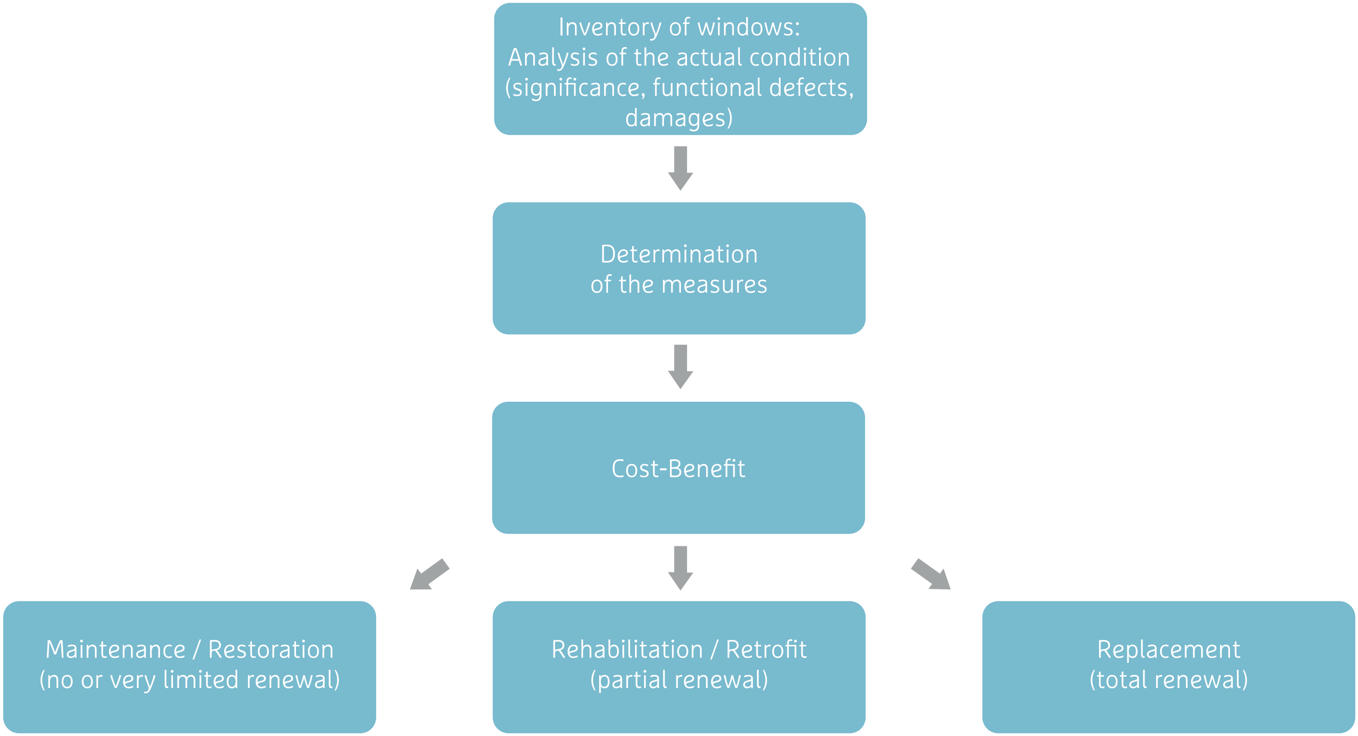


FIG. 5.24 Decision making between intervention categories for a single window

Depending on construction, condition, existing requirements (e.g. monument protection) and desired improvements (e.g. airtightness, thermal insulation, sound insulation), the decision results for maintenance, restoration, rehabilitation/ retrofit (partial renewal) or replacement (total renewal) are shown in [FIG. 5.24] in a flowchart. Decisions are made per window. Categories can also be combined in one building depending on the value and damage assessment.

Temporary Interventions

Temporary measures such as curtains or shutters can significantly improve the thermal comfort of a window. In principle, they reduce heat loss. The thermal insulation of windows is verified using the U_w value in $W/(m^2 K)$ and U_g value in $W/(m^2 K)$. The U-value denotes the heat transfer coefficient of a building component (Unit of heat transfer). In the case of windows, the index w stands for ‘window’, the index g for ‘glass’.

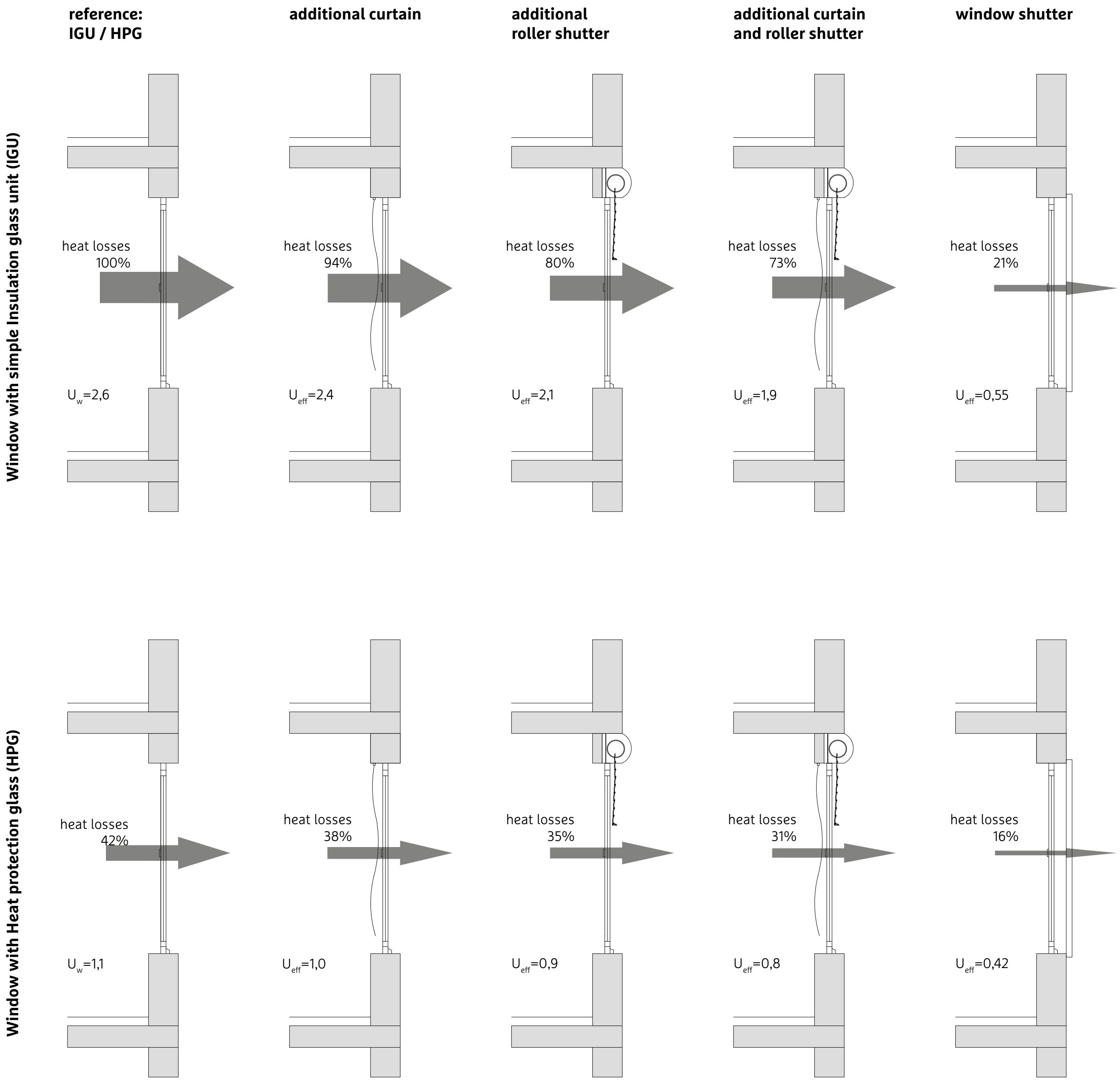


FIG. 5.25 Insulating shades, curtains or shutters are reducing heat loss (indicated in %) and improve the thermal performance of windows (according to Wohlleben and Moeri, 2014, p.34 and Cremers, 2016, p.58).

FIG. 5.26 Window with a historic irregular glass surface left and a new flat float glass surface right / Photo: H. v.d. Ven

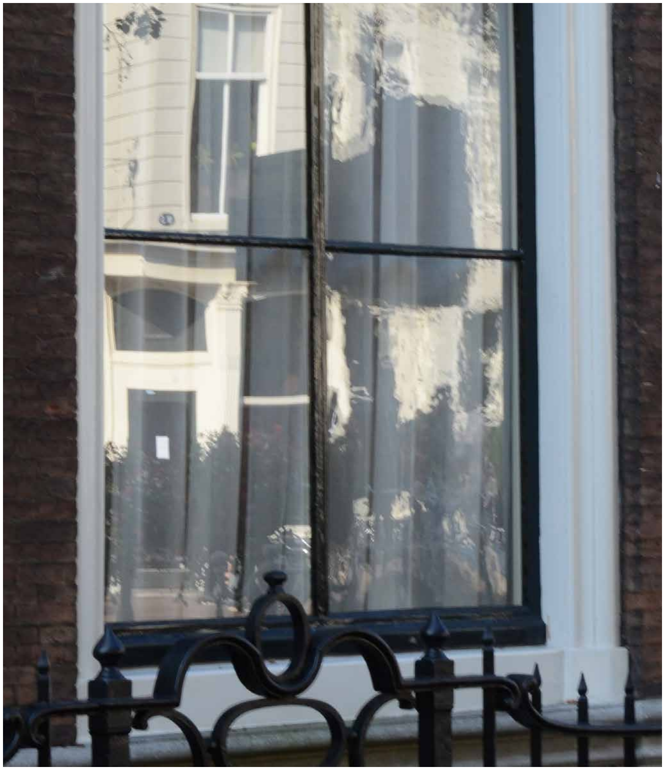


FIG. 5.27 Historic window with float glass panels (lower left) / Photo: W.J. Quist

In FIG. 5.25 the U_{eff}-value considers the reduction of heat loss by measures such as curtains or shutters. The index eff stands for 'effective'. The figure shows the original U_w-value in W/(m² K), its reduction with the U_{eff}-value in W/(m² K) and the heat demand in percentage. However, the curtains must be long enough (ideally extending over the windowsill) and the shutters must be installed without thermal bridges. If they are partially transparent or translucent, they also serve as sun protection, depending on the total energy transmittance value. In principle, these interventions are suitable for wood and steel windows.

Baker (2017, p.18) indicates 'that whilst low-e secondary glazing has the greater impact on reducing heat loss through the whole window (68% reduction in heat loss), curtains are also an effective option'. In addition, curtains also reduce the heat loss through the frame effectively.

Interventions to glazings

Today it is common to replace historical glass with float glass. The use of float glass as replacement for original drawn or plate glass may require some compromises to be adopted. Aside from the visual differences between the products, there are limitations to the sizes available for today's float glass sheets which may pose additional challenges for reglazing interventions at modern buildings that require large sizes (Ayón, 2019) [FIGS. 5.26/5.27].

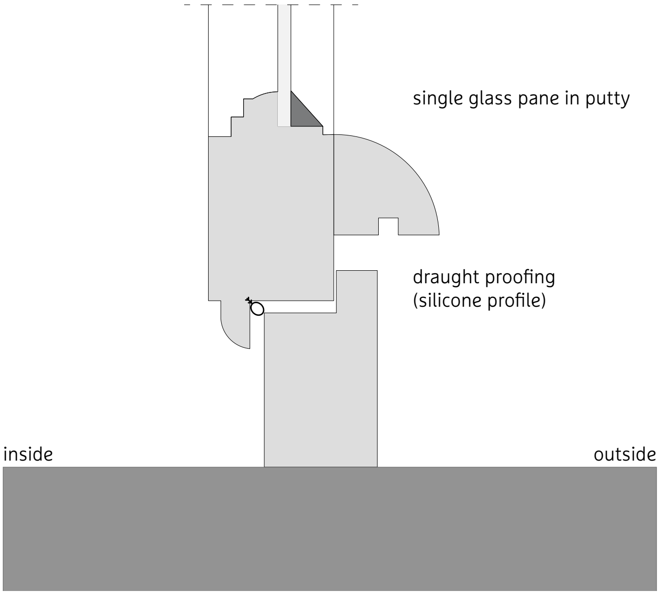


FIG. 5.28 Sash frame with new sealing: a) Image and b) schematic drawing / Photo: S. Rexroth

New developments in glazing technology and the need to increase energy efficiency of buildings resulted in thicker triple-glazing elements, which are seen as being critical due to their weight and their need for thicker frames. Thin vacuum glazing has the advantage of having less weight and of better fitting into historic frames. It is not yet widely available on the market and therefore quite expensive.

Interventions to wooden windows

A common and less invasive measure for restoring und slightly upgrading wooden windows is first of all a carpentry overhaul that can be applied to single, composite or box windows. The windows are entirely closable and serviceable and a silicone tube profile seals the window sash (or in the inner window sash in case of compound and box windows) against draughts. This reduces ventilation heat losses. Draught leaks are usually caused by warped sash frames of which the rebates no longer close evenly. To remedy this, they should first be reworked by craftsmen. Gaping irregularities can be closed flexibly by installing concealed crimp seals in the frame rebate of the sash frame, which also improves sound insulation [FIG. 5.28]. It is important that the seal is loose enough to close the existing gaps on the one hand, and on the other hand that the closing function is not impaired, e.g. by bulging. It should be recognized, however, that the improvement in tightness and heat loss reduction may be accompanied by a reduction in the hygienically required air exchange.

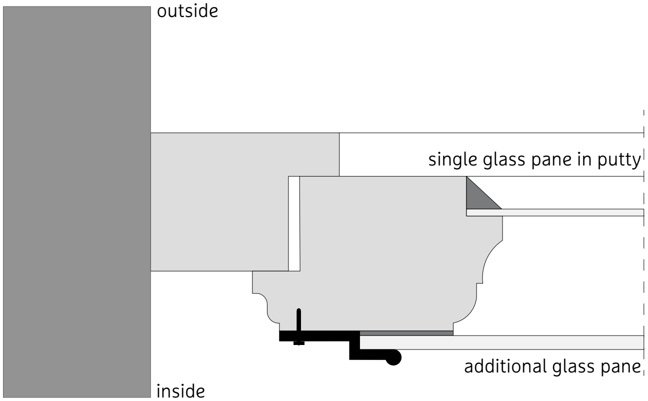


FIG. 5.29 Single glazed wooden window with a frameless additional pane fixed with clips

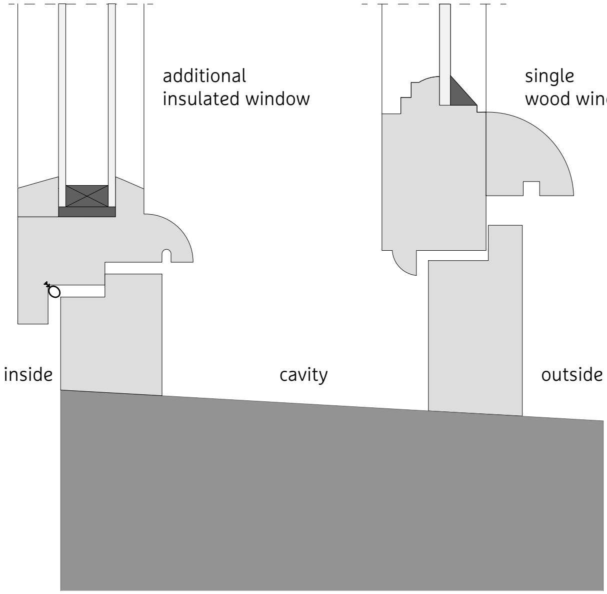


FIG. 5.30 Single wood window converted in a double window with an additional insulated window at the inside (cavity)

Single windows can be converted into compound windows by attaching additional panes. The additional sashes, equipped with seals and possibly coated glass, are mounted on the existing window frame. If it is frameless, the additional sash, equipped with seals, is pressed to the existing window frame by means of sash locks or clips. Another possibility is to mount an additional framed pane adapted to the existing window. Usually, the frameless or framed panes are mounted on the inner sash frame. This creates a composite system for each sash. The new sash is only opened for (infrequent) cleaning purposes [FIGS. 5.29/5.30]. The advantage of this measure is the relatively low interference with the substance, but can however result in reduced transmission and an additional load that the existing frame has to bear. The U-value of the window is reduced to around 40 % (approx. 2.1 W/(m^2 K) with a pyrolytic coated pane (assumption: usual frame share with a U-value of 2.0 to 2.4 W/(m^2 K)).

Adding a second, insulated glazed window to the outside or inside of the single window turns the single window into a double window [FIG. 5.31]. The original window (usually on the outside) remains unchanged and is supplemented by a recessed interior window that can be installed either in the reveal or on the interior wall. The wide layer of air between the two window levels improves significantly heat and sound insulation. In principle, this intervention is suitable for wood and steel windows.

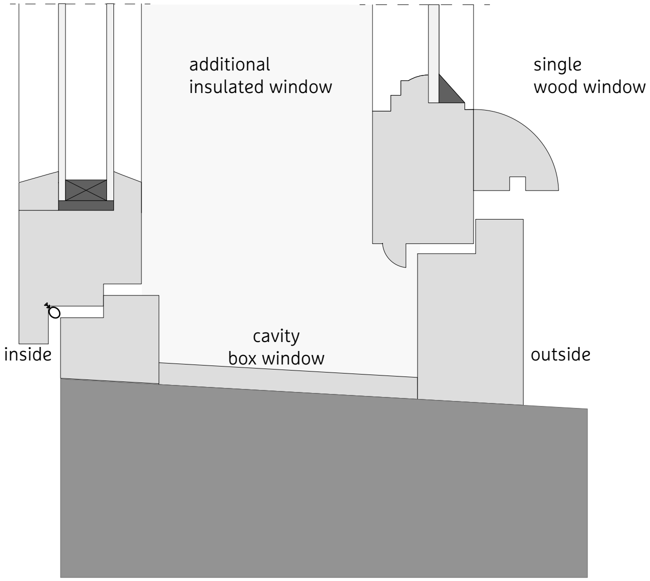


FIG. 5.31 Single wood window converted in a double window with an additional insulated window at the inside (box)

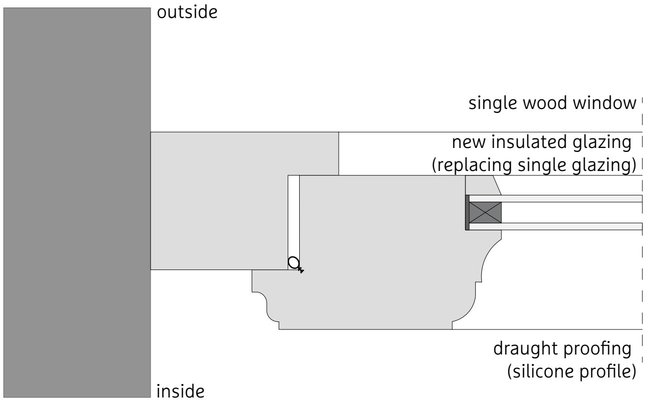


FIG. 5.32 Single wood window frame with inserted profile seals and new glazing, here: double insulation glass

If the frame profile of a single window is wide enough and has sufficient load-bearing capacity, the single glazing can be replaced with double insulating glazing or (slimmer) vacuum glazing [FIG. 5.32]. Lower heat loss is achieved simply by replacing the single pane with a pyrolitic-coated pane (Low-E-Glass, 'K-glass™'). However, it should be noted that the coating is sensitive to mechanical damage. The U-value of the window is reduced to around 56 % (approx. 2.7 W/(m² K) with a 10 mm insulation glass filled with Argon (assumption: usual frame share with an U-value of 2.0 to 2.4 W/(m² K)).

If new glass panes are installed, special attention must be paid to the glazing bars. They are usually placed on the glass panes as so-called superimposed Viennese bars ('Wiener Sprosse'), a spacer is mounted in the space between the panes [FIG. 5.33].

In the case of compound windows, it is technically possible to replace the glazing in the inner or outer sash with insulating glass panes [FIG. 5.34]. Similarly to single windows, the frame must be appropriately wide and the rebate appropriately deep.

Box Windows: With a window lining between the windows, the double window can be considered as an energetically favourable, historically widespread type of box window.
In addition to refurbishing both sashes as in the case of single windows and milling a concealed crimp seal (usually in the frame of the inner sash), the glazing can also be replaced. With an insulated glazed window level the U-value of the window is reduced to around 27 % (approx. 1.3 W/(m² K) with a 20 mm insulation glass unit (IGUs) filled with Argon (assumption: usual frame share with a U-value of 2.0 to 2.4 W/(m² K)).

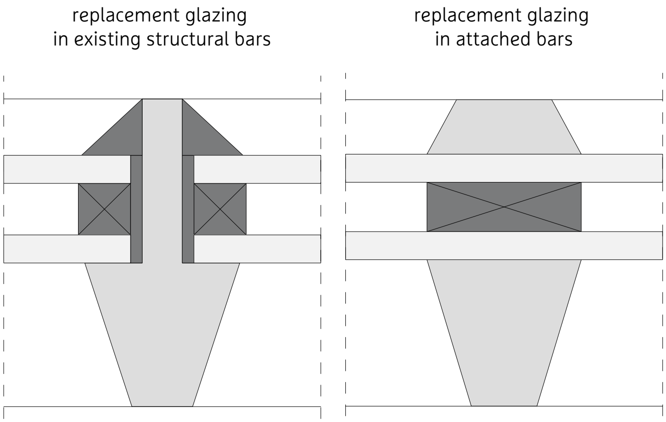
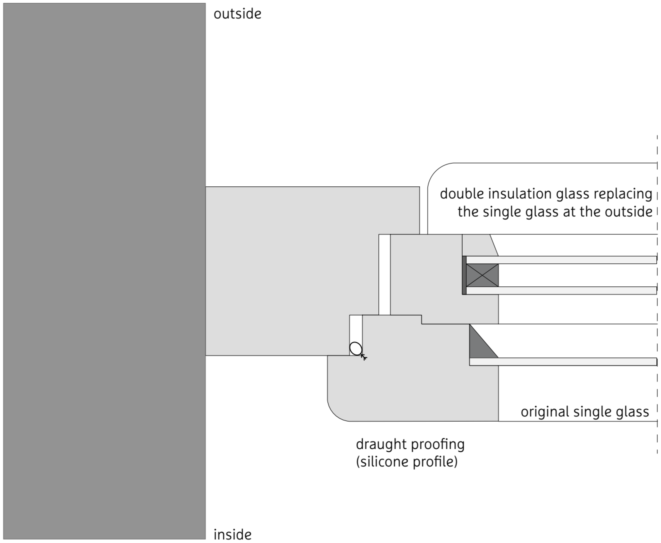


FIG. 5.33 Attached glazing bars are used when the existing structural bars are not wide or deep enough to accommodate double glazing



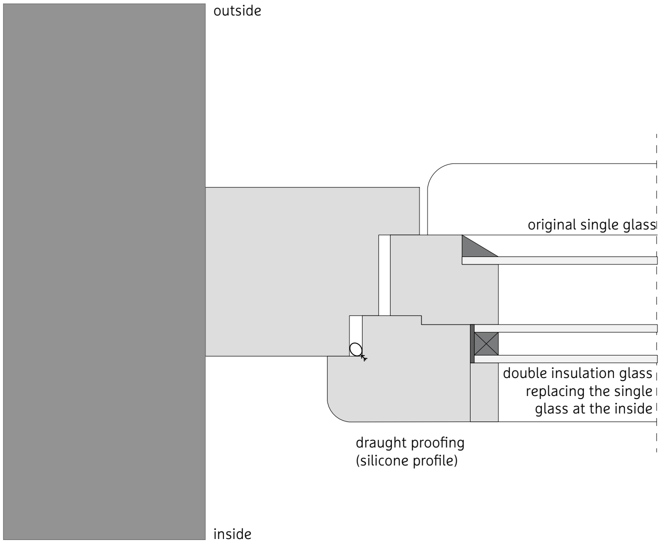


FIG. 5.34 Compound window with a replaced glass pane, left: double insulation glass outside, and right: double insulation glass inside

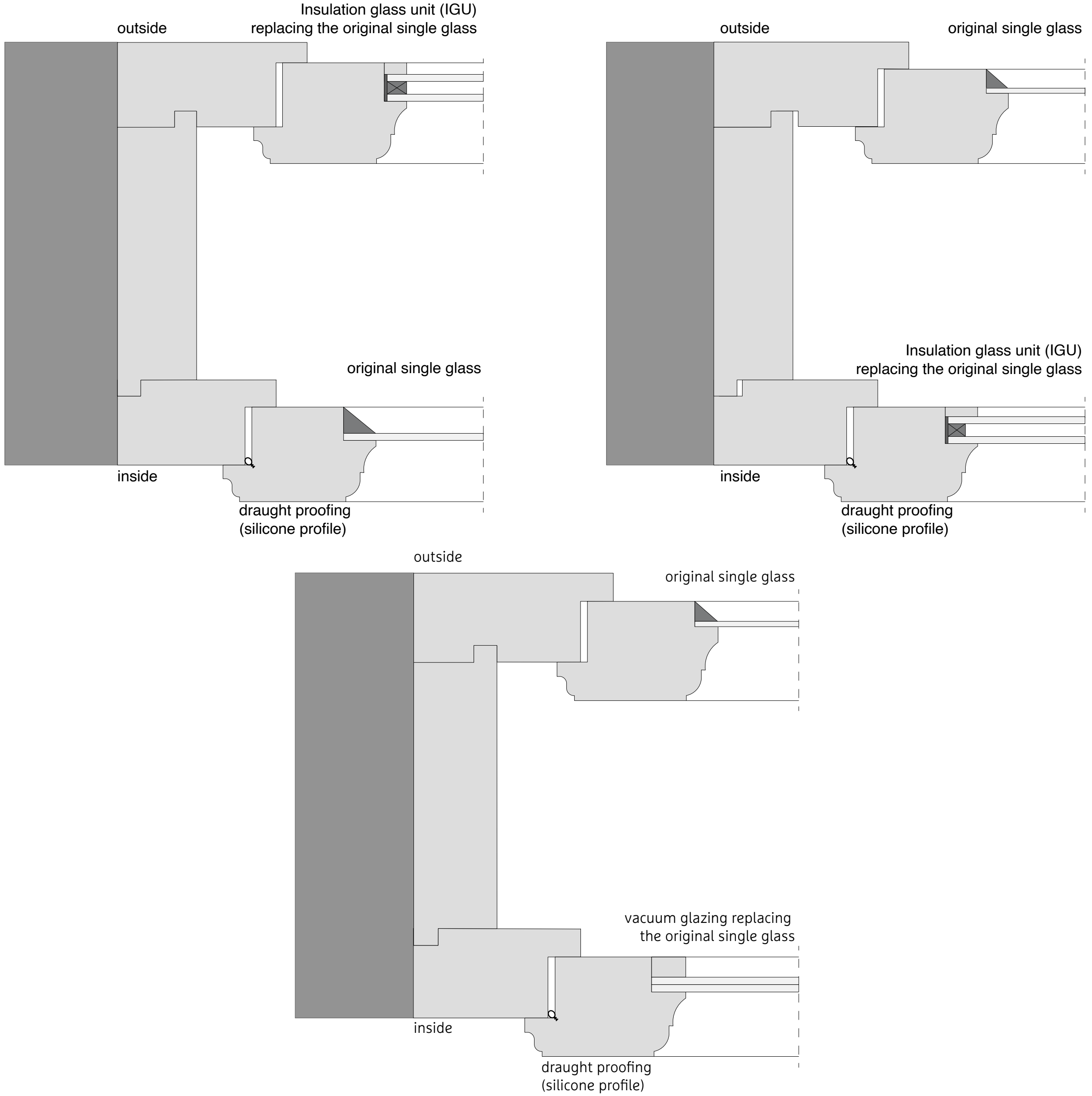
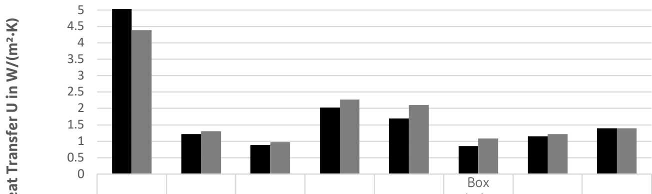


FIG. 5.35 Main intervention categories to improve energy efficiency and comfort of box windows: a) replace with insulating glazing outside, b) replace with insulation glazing inside, and c) replace with vacuum glazing inside

The replacement of the existing glazing should be considered as part of an overall building physics concept: thicker panes improve sound insulation, specially coated glass acts as heat and sun protection, and frosted panes or decorative glass serve as privacy screens. The glass industry offers reduced insulation glass units (IGUs) with a total thickness of 12 mm (3/6/3 mm); special insulating glass is even available with a total thickness starting at 8 mm, vacuum insulating glazing with a total thickness of 6.2 mm (3/0.2/3 mm). If it seems expedient to replace the entire window sash, this is usually done on the inner window to preserve the external appearance [FIG. 5.34]. This measure is also often chosen for reasons of building physics, as the inner sash then seals the box airtight, thus preventing condensation from forming in the space between the windows. The intervention to improve the outer window is a feasible renovation variant if the box window is to be upgraded during operation (e.g. while the building is let), because the inner sash remains functional at all times.

The intervention is demanding in terms of building physics, because the minimum air exchange must not be impeded. In general, the thermal insulation of any energetically retrofitted window must not be better than that of the wall, because otherwise condensation can form, especially in the window reveal, associated with a risk of mould.

(Rexroth et al., 2020) demonstrated that box windows with a carpentry overhaul have the lowest energy consumption compared to the other glazing variants and for different orientations. Measurements proved that the reworked box-type window ranked first towards the south, while the energetically optimized box-type window with double insulating glass in the outer frame ranked first towards north and east. Of course, the results depend on parameters like outside temperatures and solar radiation on the glazing.



	Single glazing, 2mm	Double-insulation-glazing	Triple-insulation-glazing	Composite window	Box window	Box window with double insulation glazing	Sun protection glazing	Vacuum glazing
Uw measured	5.03	1.22	0.88	2.03	1.69	0.85	1.15	1.4
Uw calculated	4.39	1.31	0.97	2.27	2.11	1.08	1.22	1.4

TABLE 5.5 Comparison between measured and calculated U_w-values in the research project 'Fenstervergleich' at HTW Berlin.

Especially the glazing types without coated panes (single glass, laminated and box windows) benefit from the solar irradiation. The study also showed that the calculation of the U_w-value according to the relevant standard (DIN EN ISO 10077-1 | 2020-10 Thermal Performance of Windows, Doors and Shutters - Calculation of Thermal Transmittance) does not represent the achieved values. Tests in the double climate chamber determined better Uw-values shown in Table 5.5.

The results also show that Uw-values mainly depend on the apportioning of wood frame and glazing. The windows in the research project are rather small. A Box window with a 20 mm double insulation glazing in a standard format has a U-value 1.3 W/(m^2 K).

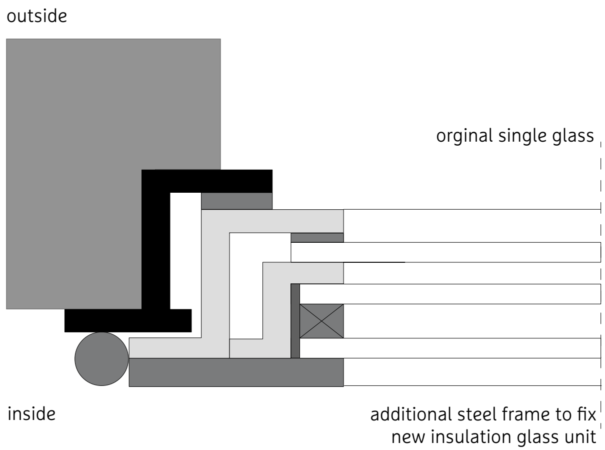


FIG. 5.36 Single glass window converted into compound window

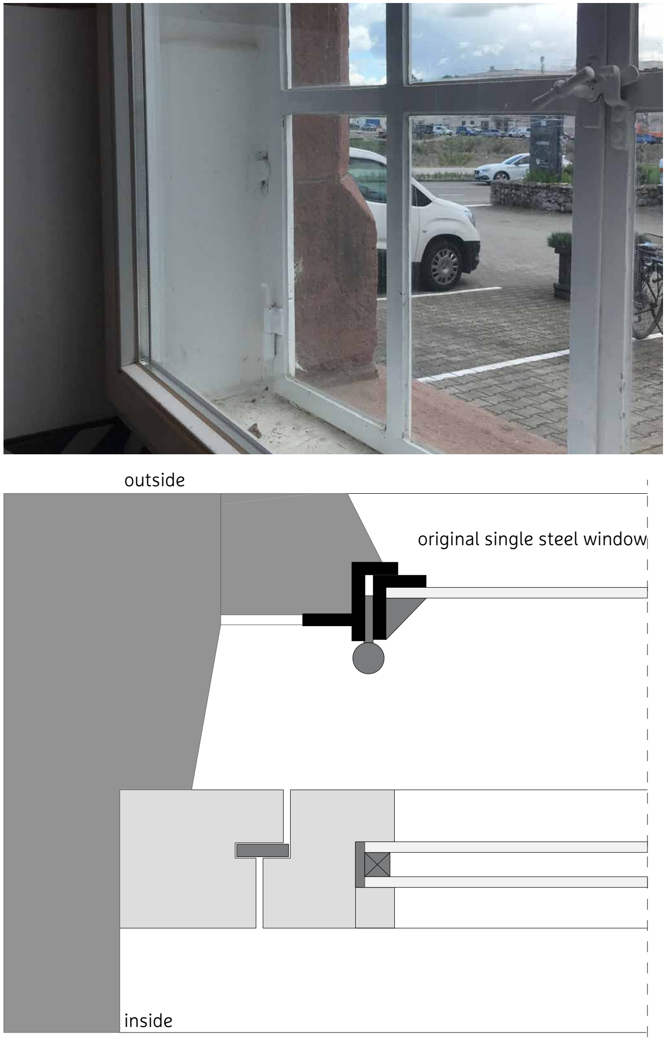


FIG. 5.37 a) Single steel windows with new secondary wood-framed glazing at the interior and b) scheme / Photo: S. Rexroth

Interventions to Steel Windows

Windows with steel frames have particularly high heat losses due to the high thermal conductivity of material. They are also susceptible to condensation and thus to corrosion. Also, the mostly slim frames - compared to wood frames - make it more difficult to replace the glass and to create a thermal separation. Still, most interventions suitable for wood windows can also be applied to steel windows. A general overview of preservation approaches to modern architecture is available in (Prudon, 2008), more detailed examples can be found in (Ayón et al., 2019, RCE, 2008 and Stazi, 2012).

Single windows can also be converted into compound windows by attaching additional panes, although this is less commonly applied to steel than to wood windows due to the higher risk of thermal bridging [FIG. 5.36]. The additional sashes, equipped with seals and possibly coated glass, are mounted on the existing window frame. Another possibility is to mount an additional framed pane adapted to the existing window.

Adding a secondary insulated glazed window to the outside or inside of the single window turns the single window into a double window [FIG. 5.37]. With a larger distance between the frames, it can be considered as a type of the energetically favourable and historically widespread box window.

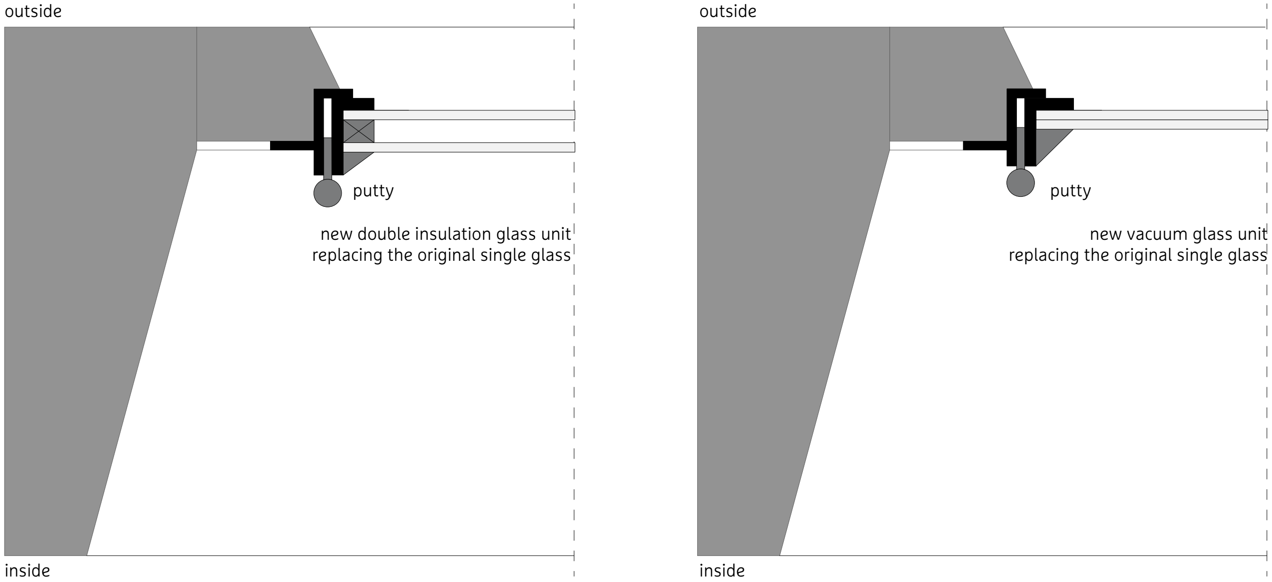


FIG. 5.38 Single steel windows with new double insulation glass, left, and right new vacuum glass unit

The original window (usually on the outside) remains unchanged and is supplemented by a recessed interior window that can be installed either in the reveal or on the interior wall. In the simplest version of this approach, the secondary glazing consists of an additional interior operable inward-swinging sash with single-pane glass located immediately adjacent to the original single-pane sash at the exterior glazed enclosure. When closed, this creates an air-tight cavity between both glazed assemblies while allowing for maintenance and cleaning when required. A more elaborate solution includes the installation of a new insulated interior partition on the inboard side of the exterior walls. The insulated partition includes a new steel (or aluminium or wood) frame assembly in front of the existing exterior openings. The secondary glazing includes an inward-swinging sash with insulation glass units (IGUs) for cleaning and maintenance.

The installation of new IGUs in restored frames usually means that the old putty or glazing beads need to be removed, and new glazing beads designed to accommodate the new glazing are added [FIG. 5.38]. Given that an IGU is thicker and heavier than the original single-pane glass, the replacement glazing bead is typically shallow and high-strength in order to be able to retain the IGU in place. Industry standards relating to the required bite size, face and edge clearances must also be considered when designing IGU and glazing bead installations on existing frames. It is advisable to coordinate the location of the replacement IGUs with the interior programs. Instead of implementing a building-wide wholesale glass replacement, consideration should be given to doing so only at strategic locations where the program requires enhanced performance (e.g. offices or residential spaces with permanent occupancy). As an alternative for the IGU thinner vacuum glazing can be used as replacement glazing. Electrical frame heating can be applied to avoid condensation forming on the frames.

FIG. 5.39 New National Gallery, Berlin: original glazing (above) and three variants for the rehabilitation. In order to avoid glass breakage in the future, a double-thick laminated safety glass (2 x 12 mm) was used (second variant from above). The other two variants would have distorted the appearance of the construction too much. / Photo: F. May

FIG. 5.40 New National Gallery, Berlin: New facade with a single glazing in a thermally non-separated construction / Photo: F. May

Thermally separated steel frames are chosen when thermal losses and energy consumption should be minimized, resulting in optimum environmental performance. Thermal separation can only be achieved through replacement with a new frame construction and at greater expense. This solution is suitable in cases where enhanced environmental performance is desired in addition to retention of the historic appearance. The replacement steel frames for these assemblies can be made of custom hot-rolled components assembled through a proprietary systems (e.g. used studio windows at Bauhaus Dessau, Germany), or tailor-made cold-formed hollow metal works (e.g. at Zeche Zollverein, Germany) or a combination of the two (e.g. Guggenheim Museum, USA).

A currently prominent example for the handling of such demanding window types is the renovation of the Neue Nationalgalerie (New National Gallery) in Berlin. The facade construction, which was not thermally separated, in conjunction with the relatively high humidity during exhibition operation, led to a high level of condensation from outside temperatures below 4° C. In order to minimize condensation, a detailed feasibility study was carried out at the beginning of the preliminary planning phase to investigate the use of double-glazed insulating glass. After weighing up the arguments relating to the preservation of monuments and technical aspects, David Chipperfield Architects however made the decision in favour of single glazing in a thermally non-separated construction [FIGS. 5.39/5.40], as this was the best way to preserve the appearance of the high-ranking monument (Bauwelt, 2021).

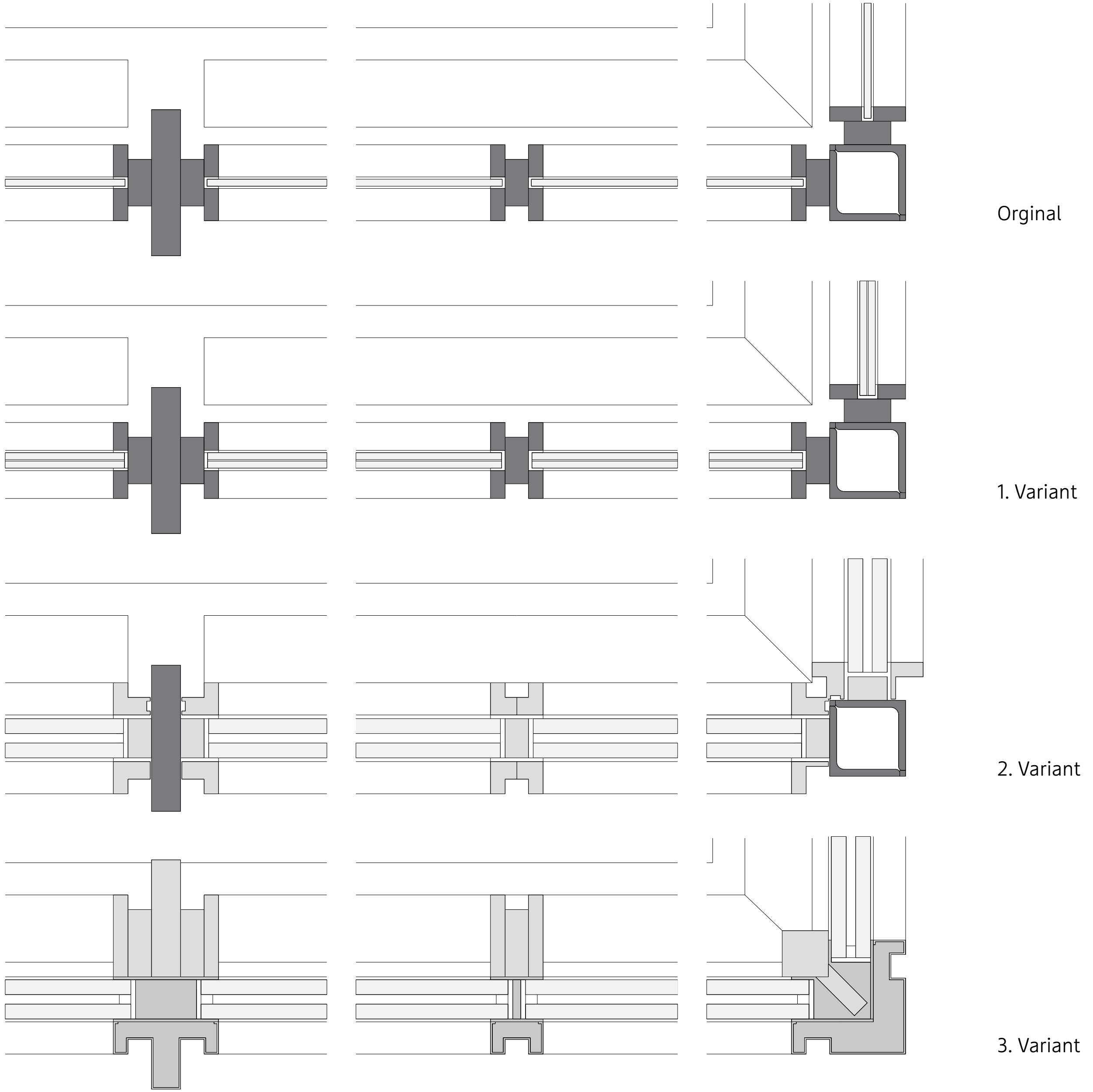


FIG. 5.41 New National Gallery, Berlin: Original facade construction with steel windows and three variants of their rehabilitation. The first variant was used (David Chipperfield Architects, 2021).

The results of several studies have showed that window maintenance and rehabilitation options have the potential to significantly improve the energy efficiency of a building with existing leaky, single-pane, or historic compound and box windows (NTHP, 2012; Rexroth et al., 2020). The particular effects depend substantially on rehabilitation options, energy costs, climate conditions and specific funding or incentives. NTHP (2012, p.50) states that 'retrofit options fall into the range of expected performance that a replacement window might achieve (specifically exterior and interior storm windows, especially when combined with cellular shades), showing that retrofit options should be a first consideration before replacements'. It is the intention of this publication to shed more light on the common successful strategies and techniques to maintain and conserve existing window construction as significant part of the built heritage.

5.4 – Future research

Studies mentioned above identified a number of future research opportunities that could provide a more comprehensive understanding of window rehabilitation/ retrofit and replacement options for older leaky, single-pane windows. These include to understand window rehabilitation as part of holistic building retrofit: in many cases, choosing to retrofit or replace windows may not be the most cost-effective or efficient way to improve the energy performance of an older building. A detailed analysis is needed to evaluate how to prioritize window upgrades in the context of other energy-efficiency measures such as applying wall and roof insulation, whole-house air sealing, and upgrading existing heating and cooling equipment.

Life Cycle Assessment: further research is needed to understand how interventions to windows correlate with impacts to the environment or to human health taking into account material production, transportation, maintenance, replacement, or disposal over the anticipated life span of the windows. Due to the wide range of material choices that exist for window rehabilitation/retrofit or replacement measures, regionally different result might be expected.

Valuation of thermal insulation of existing windows according to normative calculation methods: in detail, the problem is as follows: according to normative calculation procedures, the entire box-type window is evaluated with a default value of 2.5 W/(m^2 K). According to the normative calculation procedure, the glazing of a box-type window has the same value as a double glazing (without coating), namely between 2.76 and 2.88 W/(m^2 K). The windows are evaluated under the boundary condition of steady-state conditions. The air layer in the space between the panes is inaccurately taken into account. Therefore, it is necessary to measure and evaluate existing windows under real conditions, in-situ. A critical mass of data and its evaluation can help to adequately assess rehabilitation options of existing windows (Rexroth et al., 2020).

Thermal breaks and coatings: in the fenestration frame industry, additional research and development of thermal break materials is required. Stiffer materials with increased thermal performance are needed, particularly for use in thermally broken steel frame systems which typically have slim and shallow frame profiles that pose a challenge to replacement interventions. Further development of thermal break materials and frame installation systems during the last decade has created some innovative and suitable products. Still, more competition and availability of such systems in the marketplace are needed to overcome increased project costs.

5.5 – Conclusions

Historic windows and glazing need to be preserved as they constitute an integral part of a monumental building. Classifying them in terms of their monumental value requires analysing and evaluating them according to window type, construction and material used. Checklists help to take a differentiated look at the state of preservation of a window. Only after establishing the value of the windows and their components, and their state of preservation, the choice for a suitable intervention can be made, also considering the (new) function of the building.