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Remanufacturing reclaimed window frames

R van der Plas^{1*}, T Konstantinou¹ and U Knaack¹

¹ Department of Architectural Engineering and Technology, Delft University of Technology, Delft, The Netherlands

*E-mail: r.c.vanderplas@tudelft.nl

Abstract. To reduce material waste and carbon emissions, the manufacturing industry of exterior window frames (aluminium, PVCu and timber) could transition from recycling to remanufacturing. This paper investigates to what extent reclaimable window frames from 1970 to 2010 are technically upgradable to meet current thermal and airtightness requirements, and if the existing (linear) supply chains are able to perform these upgrades. To answer these questions, a multi-method approach was used. Historic window frame designs were retrieved from standard literature. These were assessed to see what minimum upgrades they require to comply to current regulations. Retrieved process models of the existing supply chains were then used to investigate to what extent the existing factories are able to perform these upgrades. The results show that based on the assessed historic window frames, it is possible to upgrade aluminium, PVCu and timber window frames of around 25 years old, depending on the window size. However, from a remanufacturing perspective, all three existing supply chains lack essential steps to perform these product upgrades. Also some existing manufacturing processes can't be used for *remanufacturing*, as they are designed to process unencased, individual profiles. This makes reclaimed encased frames incompatible with the first processes of the linear supply chains. PVCu and aluminium profiles are manufactured in respectively two and three factories, which is a notable impediment for re-finishing the profiles. Two identified opportunities for upgradability and remanufacturing are standardization of interfaces and modularity. Future multi-lifecycle circular window frame designs could benefit from further implementation of these design approaches.

1. Introduction

In order to reach the Dutch 2030 and 2050 circularity goals, the Dutch manufacturing industry is urged to accelerate the transition to a circular economy (1). Facades, which are responsible for 10-30% of a buildings embodied carbon (2) are currently “stuck at recycling” (3). To increase value retention of facades, a shift from recycling to shorter loop retention options is required. Introducing multiple service lives through reuse or remanufacturing could significantly reduce material waste and carbon emissions (4). However, direct reuse of façade components is found to be unfeasible for many reasons (3), of which (the guarantee of) technological performance is a major factor (2). Remanufacturing of facades components is suggested to be a more promising direction (2, 3). Remanufacturing implies a return of dismantled, post-consumer components to the supply chain. Here the components are disassembled in constituent parts, which are checked, cleaned, repaired and possibly upgraded. The result is a guaranteed “as new” façade product (4).



From a product design perspective, the remanufacturing of specifically façade components faces several technical challenges. Firstly there is the large (25-50 year) lifespan combined with exposure to weather conditions (5) leading to functional product obsolescence. Secondly, the applicable performance requirements are liable to change between consecutive service lives, leading to technological obsolescence. This is caused by progressing regulations and by shifting building-specific demands. An upgrade of post-service life products is therefore likely required.

From a supply chain perspective, remanufacturing is also challenging. Façade manufacturers even express “skepticism” about remanufacturing (3). Reasons are that façade supply chains often involve multiple materials, from multiple countries (2), leading to challenging business to business cooperations (6). Manufacturers have to expand their services (3), have to gather data on how components deteriorate (3, 6), lack technical skills for for instance performance testing (6), and require high start-up costs (e.g. retooling) and process costs because of reverse logistics and expensive disassembly (6).

This paper aims to gain more practical insights in the technical feasibility of remanufacturing window frames to resolve technological obsolescence. Furthermore it investigates the upgradability of (reclaimable) historic aluminum, PVCu and timber window frames, and to what extent the existing supply chains are able to remanufacture them. The results will help identify what product and process changes are needed to transition our current supply chains to become circular. The required lessons from the past can serve as input to design new, circular, remanufacturable window frames and circular supply chains. The research question is: How do the historic progression of product characteristics and existing linear supply chains impact the technical feasibility of remanufacturing reclaimed aluminum, PVCu, and timber openable window frames to meet the 2025 thermal insulation and airtightness standards?

2. Methods

To address the research question, six complementary methods were employed, integrating historical analysis, literature review, comparative design analysis, and supply chain evaluation.

First, a historical analysis was conducted to trace the evolution of regulatory window frame performance requirements from 1970 to 2025. This was achieved through a review of historical building regulations, providing insight into the shifting standards over time.

Second, review of standard literature was used to identify the key design aspects required for compliance with current (2025) regulatory performance requirements. This step established the technical criteria against which reclaimed window frames must be evaluated.

To assess the characteristics of reclaimable historic window frames, a document analysis was performed using five educational books on façade openings, published in 1971, 1984, 1992, 2000, and 2011. These standard books provide ‘average’ window frame designs to navigate between the large scope of different brands and types. From each book, the most advanced inside-openable window frame design was analyzed, to give a representative view of the historical products.

A comparative design analysis was then conducted to determine the necessary modifications for upgrading reclaimed window frames to meet current performance requirements. This involved cross-referencing the historic design characteristics extracted from the educational books with the regulatory compliance criteria established in the literature review, focusing on improving the airtightness and thermal insulation.

To examine the current supply chain landscape, process models developed by three Dutch branch associations were used. These models were further validated through standard works on

window frame production and additional verification using online step-by-step ‘factory-visit’ videos. This provided an accurate depiction of contemporary manufacturing processes.

Finally, a feasibility assessment was performed by mapping the identified remanufacturing requirements onto the existing supply chain processes. This step evaluated the technical capabilities of current supply chains to remanufacture the reclaimed aluminum, PVCu, and timber window frames. Through this multi-method approach, the study systematically reconstructs the technical feasibility for window frame remanufacturing, exploring the (im-)possibilities from both a product and supply chain perspective.

3. Results and discussion

The results can be subdivided into four main sections. Section one discusses window frame performance requirements and compliance criteria. The second, third and fourth sections describe the product history, product upgradability, supply chain and remanufacturability of aluminium, PVCu and timber window frames.

3.1. Historic development of regulatory performance requirements

As window frames have an expected service lifespan of roughly 25-50 years (5), this section assesses performance requirements between 1970 and 2025. Although window frames are subject to over 21 performance requirements (7), most of these derive from building-specific design choices. The scope of this research is limited to the U-value and airtightness, see figure 1.

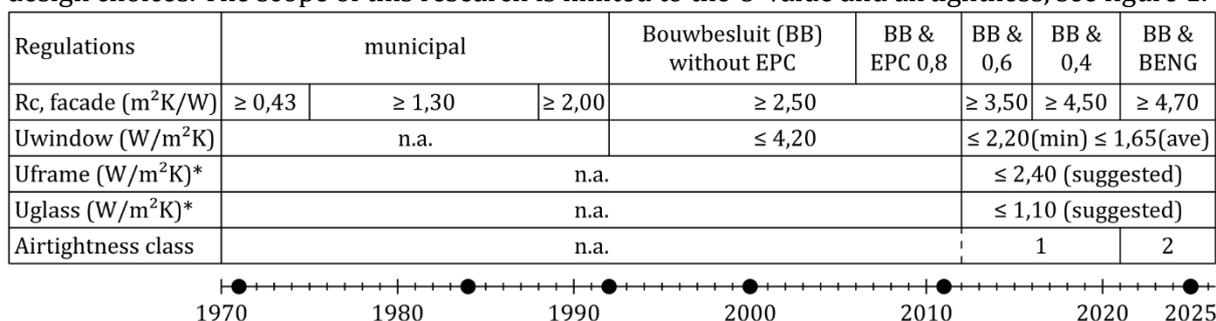


Figure 1. Progression of Dutch product-based regulatory performance requirements from 1970 to 2025. The black dots correspond with the investigated (historic) window frames. Figure based on (8) (9).

3.2. Product performance requirements: thermal insulation and airtightness

This section identifies what window frame design measures are required to comply to the current airtightness and U-value requirements. The required U-window, average of 1,65 W/m²K results from a combination of the U-frame and U-glazing. The required U-frame and U-glass derive from their relative surface areas. As a reference, suggested required values are: U-frame ≤ 2,4 W/m²K and U-glass ≤ 1,1 W/m²K (9).

The required airtightness class of 2 ($q_v; 10 \leq 30-80 \text{ dm}^3/\text{s}$) is achieved by a combination of weatherstrips (gaskets) and window hardware. One continuous gasket is sufficient to comply to current regulations, ideally positioned as far on the interior side as possible (10). As for the required window hardware, two aspects are required. Multipoint locking (2 or 3 points) to tighten the weatherstrips when the window is closed (10). Additionally, both the locks and hinges need to be re-adjustable to sufficiently press the gasket(s) during the entire service life (10).

3.3. Compliance criteria for upgrading window frames

Glass replacement is the easiest and most common way to improve the U-value of the overall window. According to ‘Milieu Centraal’ (independent source) triple glazing has a U-value

between 0,4 and 0,9, but is heavier and thicker than the replaced double glazing (11). vacuum glazing has U-values between 0,4 and 0,7, is lightweight and thin but also expensive (11). A IGU product not mentioned is “CU.i.n.”. It has the thickness and weight of double glazing, but has a low U-value of 0.4 (according to the manufacturer) resulting from a thin plastic middle foil (12).

The unknown U-values of the historic frames are not assessed in this study, as upgrading the profile of the frame is generally complicated. Also it is not necessarily required, depending on the ratio between glazing and frame. Other U-frame upgrades are adding perimetral (polypropylene foam) insulation between the glass settings blocks (see figure 2, image 4). For aluminium and PVCu frames, the middle (EPDM) gasket can be replaced by a chambered gasket (see same figure).

As for the airtightness, possible improvements are a perimetral (replaced) gasket - preferable on the interior side and a perimetral middle gasket (see figure 6, image 4). Also hardware upgrades are required to improve the airtightness. Modern multipoint locks benefit from a standardized groove in the frames and casements of aluminium and PVCu windows. For aluminium frames this is the “Euro groove” (standardized since the 80s) (13) (see figure 2: images 2-4). For timber and PVCu frames there is the standardized “Euronut” groove (see figure 4 (images 1, 2 & 4) & figure 6 (images 3 & 4) (7). Adjustable hinges can employ the same grooves or be added externally.

3.4. Aluminium – Product remanufacturing of reclaimable historic window frames

Figure 2 shows typical aluminium window frame designs from 1971, 1984, 1992, 2000 and 2011. The 2024 design is a reference to see the application of current compliance criteria.

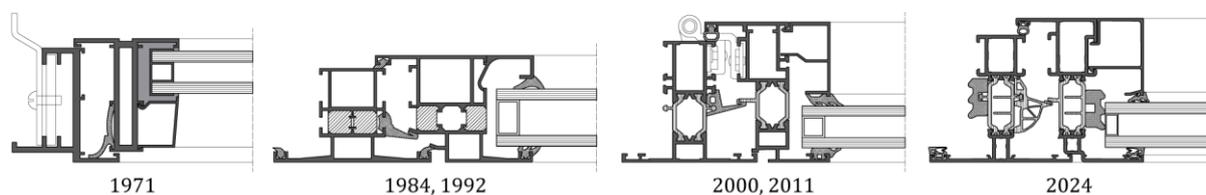


Figure 2. Dutch aluminium window frames from 1971 (14), 1984 (15), 1992 (16), 2000 (17) and 2011 (7). The 2024 profile was retrieved from Archidat (18). Images reproduced by the author. (scale 1:4 (A4))

Based on the findings, the product history can be subdivided into three main stages. The frame of the first stage (1971) is not remanufacturable to current standards. Impediments are the lack of any thermal breaks, as well as the lack of Euro grooves.

The remanufacturability of the second stage (1984, 1992) is unfeasible. While it has three gaskets and is compatible with euro groove standards, there was a great variety of thermal breaks materials, of which some were cast-in (15, 16). Also some of the historic hinges used required large openings on the interior surface of the extrusions (15, 16), which are hard to be filled.

The third stage (2000, 2011) appears to be remanufacturable to current requirements. It has two gaskets, thermal breaks (though short) and is compatible with euro groove hardware.

In conclusion, from a product perspective, the remanufacturing of reclaimed aluminium window frames appears to be feasible for frames from around 2000. Required upgrades are thermal insulation and airtightness. Frames from after 2012 will only need upgrading of airtightness values, as the thermal requirements have not changed since 2012 (see figure 1).

3.5. Aluminium – Required processes for product upgrades

To remanufacture the third stage window frames (2000, 2011), a thermal and airtightness upgrade is required. The thermal value can be improved by replacing the glass and gaskets. This will require opening the beads, removing the glass and gaskets, inserting new (multi-chamber)

gaskets, setting blocks and foam and inserting the new glazing. If high insulating glazing of the same thickness is applied, the beads do not have to be replaced.

The airtightness can be improved by replacing the hardware. Replacement of the lock and handle might require new holes and openings to be drilled and milled. By extension, the old openings might have to be closed for aesthetic or thermal purposes.

3.6. Aluminium – Existing supply chains and remanufacturing processes

Figure 3 shows a typical (Dutch) supply chain for aluminium window frames. The chain is subdivided in three different factories. The first factory is a so called “system house” which extrudes the aluminium billets to profiles, the second factory applies the finishing and (irreversibly) assembles the interior and exterior profiles with thermal breaks. The third factory shortens the finished profiles and assembles all constituent parts to finalize the window frame.

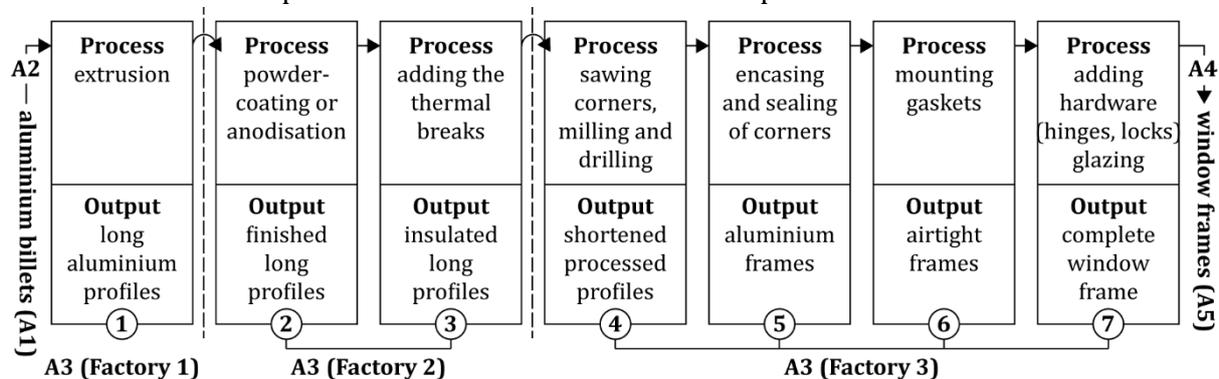


Figure 3. Typical supply chain of aluminium window frames profiles. Based on information discussed with VMRG. Validated using (7) and (19). Image by the author.

Improving the thermal insulation likely requires placement of new glazing. The required steps are manual disassembly of beads, gaskets and glazing, as well as replacement of gaskets and glazing. If triple or vacuum glazing is required, differently sized beads from factories 1 & 2 are required. Also potentially new customized gaskets have to be designed and manufactured by sub-suppliers.

Improving the airtightness through hardware replacement can be challenging. The new locks, hinges and handle require milled openings and or drilled holes in the profiles (7). Supply chain problems emerge if new or other profile openings are required. These openings are applied robotically to individual profiles (step 4). As the fastening of the corners of the frames is irreversible (7), new openings will have to be made manually or will require new machinery. The old (obsolete) openings might have to be closed for aesthetic and insulation purposes.

If the goal of remanufacturing is to reach an ‘as-new’ product, there is a significant supply chain limitation to refinishing the frame through powder coating or anodization. The first barrier is that it would require full disassembly (in factory 3) and transportation of the aluminium parts to factory 2. Another challenge is the removal of the existing finish, which does not appear to a existing process in the supply chain. A third possible challenge is that factory 2 normally applies the finishing to single profiles (see step 2); not to encased frames with thermal breaks.

3.7. PVCu – Product remanufacturing of reclaimable historic window frames

Figure 4 depicts typical PVCu window frame designs from 1984, 1992, 2000 and 2011. The 2024 design is a reference to see how the window frames have developed since. Unlike aluminium, PVCu profiles are not separated by thermal breaks. Instead, thermal insulation is provided by air-chambers integrated in the profile, combined with a relatively low heat transmission of the material (7). Integrated steel reinforcements provide structural rigidity.

The frames of 1984 and 1992 show two gaskets and compatibility with Euronut hardware as well as sufficient space for double glazing. However, it is questionable if the material quality of these old PVCu frames is enough for a second “as-new” service life. A research done in 2005 concluded that the expected performance life of PVCu window frames was limited to roughly 25-30 years (5). This raises uncertainty about the product integrity of PVCu frames from around 1995 and older.

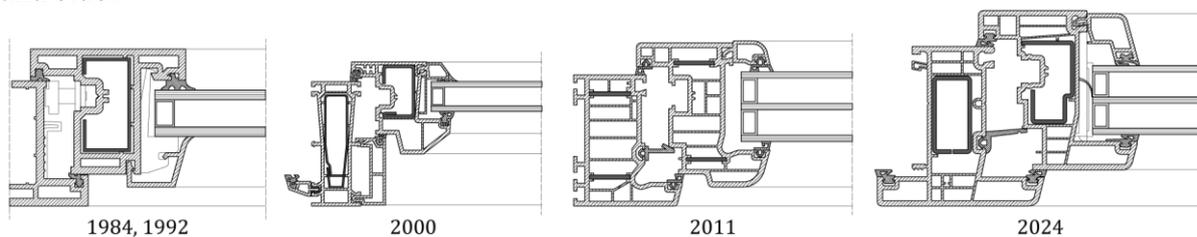


Figure 4. Dutch PVCu window frames from 1984 (15), 1992 (16), 2000 (17) and 2011 (7). The 2024 design was provided by VKG for reference. Images reproduced by the author. (scale 1:4 (A4))

The indicated 2000 frame appears remanufacturable, as it shows two gaskets and Euronut hardware compatibility. Depending on the frame size, high performance glazing could upgrade the thermal performance of the window sufficiently. However, alternate glazing thicknesses will require different sized beads compatible with the outdated frames. Like 1984 and 1992, the limited service span of old PVCu frames limit “as-new” remanufacturing.

The 2011 frame appears more easily remanufacturable. The Euronut grooves are compatible with modern hardware and the profile provides three gaskets and triple glazing.

In conclusion, from a *product* perspective, the remanufacturing of reclaimed PVCu window frames appears to be unfeasible for frames older than around 2000. Frames from 2000 to 2012 will need a thermal insulation and airtightness upgrade. Frames from after 2012 will only need upgrading of airtightness values, as the thermal requirements have not changed since.

3.8. PVCu – Required processes for product upgrades

To remanufacture the 2000 frame to current standards, glass replacement is required to increase the overall U-value. As the profiling of the casement does not allow the thickness of triple glazing, the high performing glazing options are limited to HR++, CU.i.n. or vacuum glazing. The alternate thicknesses of (vacuum) glazing would require a different sized bead, which is likely not part of the current profiling system anymore. Upgrading the airtightness class of the 2000 frame requires disassembly and replacement of gaskets as well as hardware. Hardware replacement requires disassembly of the current hardware, and adjusting or milling new openings for the lock and handle, as well as re-fastening of the new hardware. Openings or drilling holes that have become obsolete likely have to be closed to not compromise the frame’s U-value. Remanufacturing of the 2011 window frame is limited to hardware replacement and involves the same steps.

3.9. PVCu – Existing supply chains and remanufacturing processes

Figure 5 shows a typical Dutch supply chain of PVCu window frames. It consists of two factories. The first is a system house that extrudes and foil-wraps the profiles. The second factory shortens and assembles the profiles with the other sub-supplied constituent parts to finalize the windows. The required processes to remanufacture up to 25 years old PVCu window frames are now projected on the existing linear supply chain.

Improving the thermal insulation requires simple manual disassembly of beads, gaskets and glazing, as well as replacement of gaskets and glazing. The replacement of glazing is likely limited to HR++ or CU.i.n. glazing, as the other options are too heavy or require adjusted beads.

Improving the airtightness of PVCu frames through hardware replacement appears to be less challenging than is the case for aluminium frames. In the PVCu supply chain, the hardware is fastened manually, without requiring pre-drilled holes. As a consequence, the existing linear supply chain does not place barriers for upgrading the hardware of PVCu window frames.

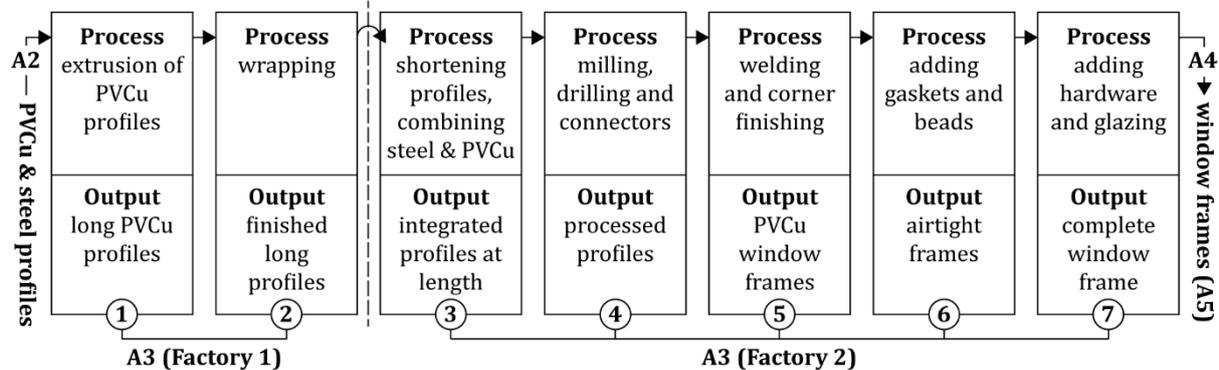


Figure 5. Typical supply chain of PVCu window frame profiles. Based on information discussed with VKG. Validated using (20) and (7). Image by the author.

If the goal of remanufacturing is to reach an ‘as-new’ product, there is a supply chain limitation to refinishing the frame through foil-wrapping. The first barrier is that it would require full disassembly (a process of factory 2) and transportation of the PVCu profiles to factory 1. A required new process is refinishing of the frames. A third challenge is that factory 2 normally applies the finishing to single profiles (see step 2); not to encased frames. As the corner fasteners of PVCu window frames are irreversible (like aluminium frames), factory 1 will need to adjust their existing processes to re-finish reclaimed window frames.

3.10. Timber – Product remanufacturing of reclaimable historic window frames

The design of timber window frames is relatively consistent from 1971 until 2024 (see figure 6). The outer frame developed from a simple L-shape, to an L-shape with an extra recess allowing recessed and (double) gaskets. The most notable development is seen in the profiling thickness of the casement, which has gradually increased to allow double glazing and triple glazing.

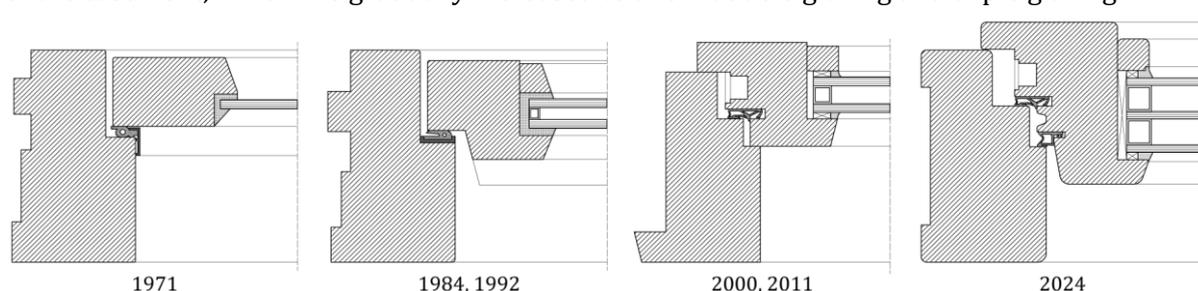


Figure 6. Reclaimable Dutch timber window frames from 1971 (14), 1984 (15), 1992 (16), 2000 (17) and 2011 (7). 2024 was retrieved from Archidat (18). Images reproduced by the author. (scale 1:4 (A4))

When it comes to U-values, the outer timber window frames generally show a consistency in overall profile sizes. Therefore, from a product point of view, the outer frames of timber window frames from 1971 should be remanufacturable to current thermal standards, see also figure 7. However, in practice it is difficult to disassemble timber window frames from the façade, as -in the Netherlands- they are often glued or screwed to a secondary timber frame (the so called Dutch “spouwlat” or “subframe”) hidden between the inner and outer façade slabs (7).

Regarding the *casement* of timber window frames, the thin profiling from 1971 will likely not comply thermally nor does it provide a recessed gasket. The casements of 1984 and 1992 are able to hold CU.i.n. or vacuum glazing, but require milling of Euronut grooves, as well as profile expansions to allow an interior gasket (see figure 7). The casements from 2000 and onwards appear more easily remanufacturable, as they already have standardized Euronut grooves. Figure 7 depicts three options: expanding the casement profile to allow thicker triple glazing, or maintaining the casement as-is and applying HR++, CU.i.n. or vacuum glazing.

As timber is a relatively “mouldable” material, profile upgrades are relatively feasible and are explored in figure 7. A possible barrier however is that the applied type of timber needs to be assessed, as combining different types of timber could lead to problems under exterior conditions.

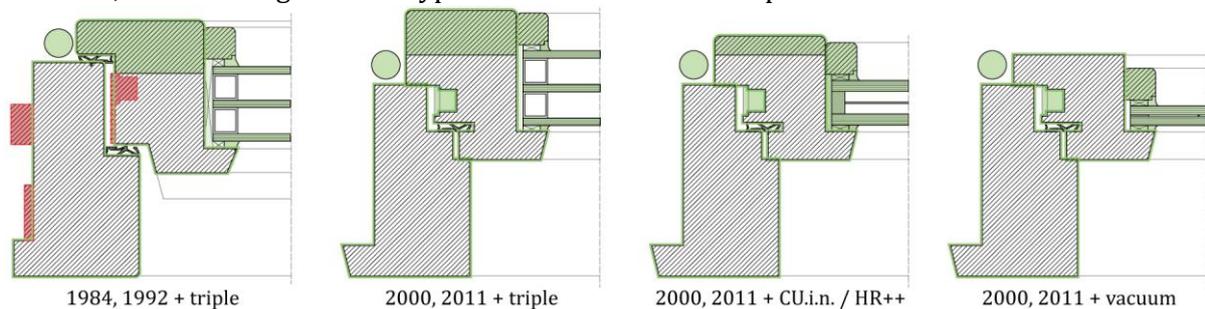


Figure 7. Remanufacturing options for timber window frames to comply to current (thermal and airtightness) requirements. Green: additions, red: removal. Images by the author. (scale 1:4 (A4))

Remanufacturing of the outer window frames requires separation from the (glued or screwed) subframes. As the remanufactured frame should provide new (cavity-specific) subframes, the intricate profiling (1971, 1984, 1992) could be flattened to allow a new subframe. To do this, the manufacturer needs to be certain there are no metal fasteners remaining in the frame. Another likely required new process is filling of the millings that were previously used for the recessed hinges. These fillings also require refinishing of the frame.

Remanufacturing of the casements requires milling of the encased frame and or profile expansion for the frames (in the case of thicker glazing). Profile expansion can be done by laminating new custom timber parts. In all cases refinishing is required, which requires prior disassembling of all other constituent parts, including removal of the sealants around the glazing.

3.11. Timber – existing supply chains and remanufacturing processes

Figure 8 shows the supply chain for timber window frames. All (A3) supply chain processes are performed by a single factory. Resultingly, little business-to-business coordination is required.

As the outer frames need to be separated from the subframes, screw removal is required – which is a process not included in the as-is supply chains. Sawing and milling of encased frames are other processes that would need to be added to the supply chain.

Remanufacturing the encasements requires milling but especially expansion of encased profiles. Both processes are part of the current linear supply chain (see step 2 and step 4). However, milling is only applied to single beams – not to encased frames. As step 4 (addition of subframes) is applied to already encased frames, it is likely that the current a timber frame factory should be able to remanufacture window frames to comply to current regulations. The filling of the recesses formerly used for hinges is a process that will have to be added to the supply chain. Also sealant and paint removal required to refinish the window frames are not part of the existing supply chains, and will have to be added.

Unlike the aluminium and PVCu supply chains, the existing timber window frame factories have the advantage of applying the finishing to already encased frames.

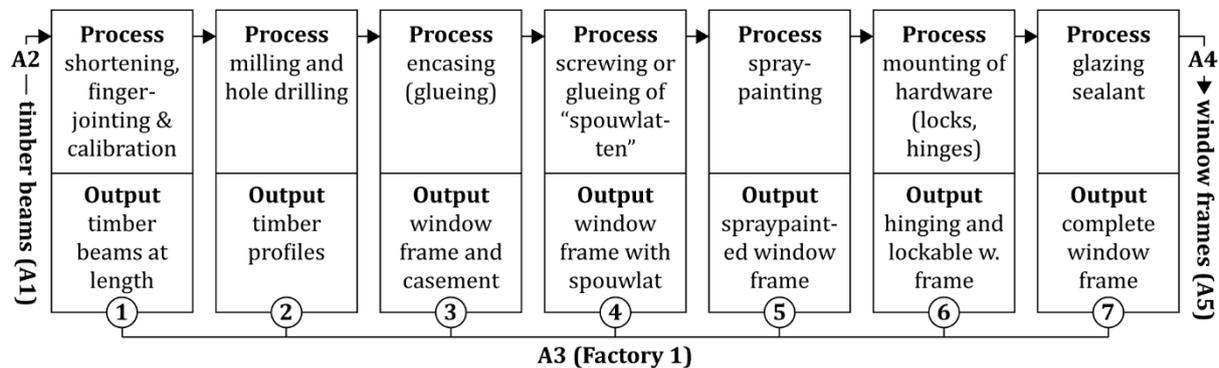


Figure 8. General impression of a current (linear) supply chain of timber window frame profiles. Based on information discussed with NBVT. Validated using (21). Image by the author.

3.12. Discussion

Based on the retrieved historic window frames, and depending on the glass frame surface ratio, aluminium, PVCu and timber window frames of around 25 years and younger can be upgraded to comply to current thermal and airtightness standards. This is done by replacement of glazing, gaskets and hardware. The glass upgrade can be challenging for aluminium and PVCu frame profiles, as alternate (possibly outdated) beads are required. Reclaimed PVCu frames of 2000 and older risk being compromised by weather influences. Remanufacturing of the outer timber frames can be extended to 50 years old, granted they can be disassembled from the facade.

Hardware replacement might require different sized or adjusted openings. This could conflict with the existing openings. Obsolete openings might need to be closed for thermal reasons.

From a supply chain perspective, all three linear supply chains lack processes to allow full remanufacturing. E.g. refinishing likely requires pre-treatment of the profile surfaces, that is currently lacking. A determining impeding step of all three supply chains is the encasing of the individual profiles to a frame. The irreversible corner fasteners hinder the remanufacturing processes that are applied to 'unencased' profiles (finishing, milling and drilling of hardware openings).

The one-factory timber supply chain appears to perform best at remanufacturing. It requires less business-to-business cooperation and applies finishing on encased frames. Aluminium and PVCu remanufacturing is hindered by the multiple involved factories, complicating refinishing and the coordination required for retrieving alternate beads to allow high performance IGUs.

For all three materials, key driving factors for product upgradability are the easy replaceability of IGUs (modularity), and the uniform hardware interfaces (standardization). Future circular window designs could therefore benefit more from these principles.

4. Conclusions

How is remanufacturing of reclaimed openable window frames impeded by product design(s) and the current linear supply chains? Remanufacturing of aluminum window frames of around 1990 and older frames is impeded by outdated thermal breaks and outdated incisions required for new hardware. For aluminum window frames from 2000, placement of thicker or thinner glass will require an alternate bead size. The aluminum supply chains impede remanufacturing by inability to process encased frames.

Remanufacturing of PVCu window frames older than 2000 is hindered by the expected shorter lifespan of the material. Upgrading of the IGUs might require alternate (outdated) bead sizes. The existing supply chains impede refinishing of the frames, as the finish is applied on pre-encased profiles, by another factory.

Product barriers to remanufacturing timber window frames are largely limited to the openable parts of 1992 and older, mostly by lack of a recessed gasket and standard Euronut grooves. The outer frames are remanufacturable from 1970, granted they can be disassembled from the façade. The supply chain lacks surface treatment process required before refinishing.

Further co-creation research with manufacturers will investigate possible combinations of product and supply design improvements required for future multi-lifecycle window frames.

5. Acknowledgements

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