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Partially dynamic life cycle assessment of windows indicates potential thermal over-optimization

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Abstract. To reach the environmental goals set by EU, Energy Performance of Buildings Directive (EPBD) and national building regulations will demand reductions in building’s energy consumption. Energy consumption goals for buildings are pursued through high thermal performance building components (HTPBC). Paradoxically, building regulations have no requirements regarding the embodied energy of buildings and components. To meet the requirements set by governments, HTPBCs in most cases require an increasing embodied energy (from insulation), assumed to be paid back during the service-life of HTPBCs. Accounting for decarbonization of the future energy supply, the expected payback might not be feasible in terms of total environmental footprint, since the future energy supplies are expected to be greener than the building’s embodied energy. Using roof windows as a case study, we assess if strict demands for building’s energy consumption, will lead to more sustainable buildings if all temporal variations in terms of global warming impacts across the service-life are taken into account. A comparison of double and triple glazed windows reveals that the expected net energy savings obtained during the use phase are compromised by relatively higher impacts induced in the production stage. The case study indicates requirements of building’s energy performance might compromise the overall sustainability of building component solutions, as the additional embodied energy required to produce triple glazed windows most likely will not be compensated for by saved operational energy, when taking into account the forecasted decarbonatization of the building energy future supply.

1. Introduction
Life Cycle Assessment (LCA) of building components can be used to select environmentally favourable building components. Many building components have service-lives in the order of decades and sometimes half centuries [1]. LCAs of such components are most often conducted in a formalised manner relying on standardized and traditional product system modelling principles assuming that the foreground and background systems of building components remain unaltered across the entire service-life of the building components, even in the case when the service-lives amount to 5-6 decades. For some building components serving solely ornamental purposes, lasting the entire service-life of the
building and not demanding any replacement nor maintenance across the service-life of the entire building, the changes in the background and foreground systems of the product system will most likely only have moderate to low influence on the overall environmental performance of the component. The limited influence of the temporally dependent system changes on the environmental performance of such building components, stems from fact that the changes in the foreground and background systems only will affect processes taking place after installation which for the such “passive” building components is limited to disposal or rather End-of-Life (EoL) processes. On the other hand will the environmental performance of building components serving functional purposes (i.e. structural, thermal, light transmission etc. purposes), needing replacement(s), needing energy supply, demanding maintenance during the service-life of the building in which they are installed, to a much larger extent be influenced by temporal changes in the foreground and background systems. The reason for the much larger influence of temporal changes in foreground and background system on the last group of “active” components is caused by the fact the systems supplying these component e.g. energy supply systems, systems producing replacement components etc. will inevitably change over time most often becoming more resource and often (not always) also environmentally efficient meaning that the overall environmental performance of the building components most often improves if temporal changes are accounted for in LCAs of components. The fact that the LCA framework from early on was not envisioned to account for temporal system changes, makes accounting for temporal changes (obviously) quite tricky, since the most elementary parts on an LCA i.e. inventory data and product system modelling both are designed not to be able to account for temporal changes.

Irrespective of the obstacles encountered by life cycle assessors when attempting to conduct temporally dependent LCAs, a recent review introducing a much-needed terminology for temporally dependent LCAs (see Sohn et al., 2019), reveal that approximately a dozen temporally dependent LCAs have been conducted and published so far. The concept introducing review by Sohn et al. [2] further reveals that time dependency in LCA is not a single concept, but rather a concept that can be applied to all of the four ISO defined phases of an LCA, meaning that a fully dynamic (i.e. dynamic in all 4 LCA phases) LCA (a so-called DLCA – which is yet to be seen) will have to include a fully dynamic goal and scope definition, fully dynamic inventory, fully dynamic impact assessment and a fully dynamic interpretation phase. If not all stages of an LCA are made dynamic the outcome is what is referred to as “a partially Dynamic LCA” or rather pDLCA.

The term dynamic is a word that most often causes a lot of confusion, but which basically can be boiled down to one single modelling issue – time dependency. However, time dependency can as illustrated by Sohn and co-workers be introduced in LCAs using off-the-shelf software and data sources. Basically there are two types of time dependent LCAs: prospective and dynamic LCAs. Two fundamental points in time are needed to distinguish between the two types of time dependent LCAs: \( t_0 \) (the time the first activity in a product system takes place) and \( t_{\text{terminal}} \) (the time where all activities in a product system ends). Depending on the number of (time) steps between \( t_0 \) and \( t_{\text{terminal}} \) the difference between prospective and dynamic LCAs is revealed. If the number of time steps accounted for between \( t_0 \) and \( t_{\text{terminal}} \) equals 1 then the assessment is referred to as a prospective LCA. On the other hand, if the number of time steps between \( t_0 \) and \( t_{\text{terminal}} \) is larger than one 1 then the assessment is considered a (fully/partially) dynamic LCA.

In the study at hand we present comparative LCAs and pDLCA (i.e. a novel form of LCA) of double and triple layered windows assessed as a building component both disregard (i.e. LCA) and taking into account (i.e. pDLCA) carefully selected time dependent changes in the energy systems providing the necessary energy to heat the building in which the windows are installed and the systems that provides the energy needed to produce and dispose of the windows during the service-life of the building in which the windows are installed. The functional unit applied is hence "Allow daylight into a building, through a window with an area of 1.6m² with a light transmittance of at least 0.7, placed in the roof of a residential building, at an angle of 45° for 40 years".

The purpose of conducting such an assessment is to illustrate how time dependent inventory changes in a building LCA may affect the results. Here we are merely illustrating how installation of a window (i.e. double or triple glazed Velux (2019a) [3] and Velux (2019b) [4] affects the environmental
performance across the entire service-life of a single family when assessed in a conventional and dynamic LCA manner and hence a non-standardized form of LCA.

2. Method
For the assessment the attributional LCI modelling framework was be applied, in accordance with the ILCD recommendations for decision context C1 [5]. This study applies cut-off allocation, meaning that recycled materials are considered "burden-free", and only the impacts related to the recycling process and associated transportation are attributed to subsequent cycles of the service-life cycle of a product. However, the primary user does not benefit from producing the recyclable materials either [6].

Figure 1 presents the product system assessed along with the system boundaries of our study. In accordance with Figure 1, the analysis includes all life cycle stages from cradle to grave. The product systems compared include all processes which are required to provide the functions/service of the windows, including upstream stages (i.e. extraction and production of raw materials and manufacturing), the use stage and downstream stages (i.e. disposal and end-of-life).

Figure 1: System boundaries representative for our case study of skylight windows. The dotted line delineates the foreground system which covers the production as well as the use of the windows. Arrows represents mass- as well as energy flows.

Upstream processes include extraction of resources, e.g. mining of metal ore, sawmill activities, extraction of crude oil and production of materials such as aluminium and wood profiles used in the production of the window pane and frame.

Assembled windows are after production transported to retailers and subsequently distributed to residential buildings. The use phase includes, in our case, replacement of the window pane and the sourcing of indoor heating compensating for heat loss/gain through the window (i.e. the systems is
intended to include the thermal properties of/service provided by the windows). Maintenance (i.e. cleaning of the window is excluded in our assessment), as cleaning activities mainly depend on end-user preferences and hence subjective preferences. The EoL of the windows covers disassembly, transport to a waste receiving/processing facility, and terminal disposal of the materials. Steel and aluminium are assumed to be recycled. Glass from a demolition project often end up as landfill, as the recycling processes of window glass are both expensive and complicated [7]. Hence, here the disposal of glass is modelled as landfill. Wood is assumed to be incinerated while plastics and cardboard are disposed of through a combination of landfill and incineration processes.

Figure 2 depicts the temporal scope of the systems assessed. The skylight window is produced in year 0 (here 2018) and the panes replaced after 20 years (2038) in year 20, 70% of the pane packaging material is assumed to be used again. The disposal of the entire window (frame and window pane) takes place in year 40 (2058). The window has an estimated service-life of 40 years inducing an annual impact during the service-life, on top of the pane replacement, proportional to the additional heat consumption induced by the window.

![Figure 2: The temporal scope illustrates which years the processes occur. Short arrows indicate an intermittent process, whereas the long arrow indicates a continuous process taking place the entire service of the building in which the windows are installed.](image)

The service-lives applied in our assessment of the windows and the panes are based on average estimation proposed by the Danish Building Research Institute’s (SBi) and other industry stakeholders [8].

Our study assesses the service-life aggregated environmental performances expressed as climate burdens induced by installation of double and triple glazed skylight windows. The heat consumption, of the windows during their service-lives, is calculated as if the windows were installed in a newly built house, a renovation project and as if meeting the thermal reference requirements E_ref. The provision of district heating (compensating for the heart loss induced by the windows) is modelled according to five different forecasts of the future energy grid. A total of 30 scenarios was hence analysed and are presented in Table 1. The 30 scenarios are split on 3 different “application contexts” of the windows defining the energy balance of the context in which the windows are installed:

- Window installation in a standard/common Danish one family house in the form of the so-called reference as presented by SBi (2018) [9] modelled as a newly built house according to BR18 for a low energy building.
- Window installation in a basic one family house from SBi modelled as a renovation project according to building regulations 1977 [10].
- Using the “raw” energy balance, E_ref, as an average window orientation specific energy balance for the window.

The life cycle inventory (LCI) data of the foreground system in terms of manufacturing were provided by the window manufacturing company. The background system was modelled using average processes in accordance with the ILCD recommendations [5]. All systems were modelled using the ecoinvent 3.4 database.
Table 1: The scenario overview shows the 30 scenarios assessed in our evaluation. An "x" indicates the included window type, calculation method and DHG scenario.

|                  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 2 layers of glass| x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| 3 layers of glass| x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Ref building: New build | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Ref building: Renovation | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Def | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Heat grid 1: Wind | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Heat grid 2: Biomass | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Heat grid 3: Bio+ | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Heat grid 4: Hydrogen | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |
| Heat grid 5: Fossil | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  | x  |

Practical reasons made it necessary to assume that the technology for production and the handling of EoL would not change within the next 40 years, although this might not be temporally representative (at all – hence a partial dynamic assessment!). The new window pane, which is estimated to be installed after 20 years use of the window, will hence be produced applying the same technology as used today. It is considered out of scope for this project, to forecast such waste processing technology innovations. The thermal energy consumption across the use stage was modelled relying on forecasts. Our assessment is hence applying a dynamic perspective for the energy supply.

3. Results
The Global Warming Potential (GWPs) quantified for the LCAs of double and triple glazed skylight windows covers 30 different result sets. In order to organise the presentation of the results, two default scenarios were selected. The default scenarios include the energy composition grid 1 (i.e. wind, pls. see Table 1), while the calculation of the quantification heat consumption is based on the newly built reference house as presented by SBi (2018) [9].

Thus, scenario 1 for the double glazed window and scenario 16 for the triple glazed window are presented here in the paper (more result combination will be presented during the presentation at the conference), unless otherwise stated.
Further diversification of the results in accordance with Table 1, focusing on energy supplied by wind, biomass and hydrogen are presented and compared in Figure 4.

To assess whether the orientation of the windows will induce changes to the conclusions drawn in the study presented here, different window orientations were also tested and assessed. Double and triple glazed windows were (thermally) modelled as oriented south and north, respectively. The results were compared with the weighted orientation used in the remainder of this study.

Figure 4: Accumulated GWP of double and triple glazed skylight windows modelled in 3 different application situations new building, a renovation project and a reference scenario (i.e. raw energy balance of the window). 4 different energy supply scenarios; 2 layers=2 layered glass, 3 layers=3 layered glass, Wind=wind energy dominated scenario, Biomasse=biomass dominated energy scenario, Bio+=biomass+biogas and Brint=Hydrogen
Figure 5: Accumulated GWP of north, south and weighted orientations when windows are applied in the reference house and assessed using a dynamic energy supply. Solid lines represent the 3 layered glass and dotted lines represent 2 layered glass.

Figure 6: Accumulated GWP of double and triple glazed windows modelled with a dynamic energy supply (DES) and a static energy supply (SES). The colours illustrate the same window (i.e. the same application context and amount of glazing units) modelled with a static grid (solid lines) and a dynamic grid (dotted lines).

4. Discussion
For the application of a dynamic energy grid composition which is highly dependent on wind power, the results reveal that triple glazed windows in terms of GWP are performing inferior to double glazed windows as presented in Figure 3.

Figure 4 shows that the accumulated GWP of the double glazed window is lower compared to the triple glazed window independent of the various dynamic future energy supplies. Figure 4 also shows that the four fossil free scenarios for the future Danish energy grid composition induces similar impacts of comparable magnitude for the same window and applications.

The orientation analysis results as presented in Figure 5 does not deviate from the overall results: The orientation of the window does not change the fact that the GWP of triple glassed windows exceeds that of the double glassed windows if changes in the energy supply, compensating for the energy loss induced by the installation of the windows, is accounted for assuming a sustainable (which for a Danish context most likely will be wind power based) future thermal energy supply.
Results presented in Figure 5 on the time aggregated GWP of the double and triple glassed windows show that double layered glass performed better than triple layered independent of whether the windows are installed in a reference building representing the (recent) historical average building or in a new building complying with the Danish 2018 building requirements. On the other hand, Figure 6 shows the importance of using a dynamic approach instead of a static approach. Indeed, the best performing alternative, in terms of climate change, actually flips from triple layered to double layered when assessing the GWP performance of the two windows applying a dynamic approach.

5. Conclusion
Our results show that, when applying a dynamic energy grid, compensating for the heat loss across double and triple layered windows, and assessing the GWP of these two types of windows, reveals a consistent preference for double layered windows. Introducing a thermal energy provision from a temporally dependent source complying with the Danish energy policy, reveals a more complicated picture. Applying a dynamic energy supply reveals that that flip in preference observed yielding and overall preference for triple glazed windows does not occur if the assessment takes into account a greening of the energy supply. Generally the differences in GWP performance are so small that these are considered within the uncertainties of assessment form, meaning that the correct conclusion to the study is that: by taking dynamic changes in the energy supply of buildings into account, it is illustrated that there is no (statistically significant) reason to choose triple glazed windows over double galzed if only considering GWP performance of the building and choosing triple glazed windows could yield GWP over-optimized buildings.

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