Report on Cascading and Carbon Storage

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Executive summary

The purpose of this study was to:

- create a model that realistically describes the storage of atmospheric carbon in timber products in the built environment pool,
- examine whether the choice of carbon decay function had any significant effect upon the outcomes,
- determine the effect of the product lifetime upon carbon storage,
- explore the additional benefits (in terms of carbon storage) that might arise if a proportion of the material is cascaded at end of life, rather than oxidised.

The main findings were:

- The exponential decay function underestimates the amount of stored carbon initially and then overestimates this metric in later stages,
- the gamma and normal distribution give nearly identical results,
- the linear decay distribution falls mid-way between the exponential and the other distributions,
- based on these findings, only the normal and exponential distributions were used for the cascading study,
- extension of product lifetime from 90 to 100 years was found to have a greater influence on total stored carbon and delayed time to reach equilibrium (stable carbon storage) when the cascade lifetime was 30 years.
- Using an extended cascade lifetime of 90 years was more effective in terms of total carbon stored compared with a life extension from 90 to 120 years with no cascading. This was with a recovery level of 40% for the cascade. This represents a scenario where the building is disassembled and components are re-used.
- The best strategy from the point of view of carbon storage is life extension combined with a high level of recovery and re-use of components.

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Introduction

The use of harvested wood products (HWPs) in the built environment can be used as a potential climate change mitigation strategy because the HWPs represent a store of sequestered atmospheric carbon and also by substitution for higher embodied GWP products. This section deals with the issues surrounding carbon storage in HWPs only; any issues associated with carbon storage in the forest are not dealt with here.

Atmospheric carbon in carbon dioxide is stored by plants during the process of photosynthesis. During the growth of woody biomass in forests, this carbon accumulates year on year and when the trees are harvested, this carbon continues to be stored in the HWPs until the wood is oxidised and the carbon returns to the atmosphere. This eventual loss of stored carbon to the atmosphere has led to some critics claiming that there is no net-benefit.

Part of the purpose of this study is to examine whether there is any climate change mitigation benefit in the storage of atmospheric carbon in HWPs. One thing that is clear at the outset is that any potential positive impact must be linked to time of storage, since if wood is used as an energy source very soon after harvest (instant oxidation) then no carbon storage benefit can be claimed.

Estimating the amount of atmospheric carbon stored in the HWP pool requires knowledge of the quantity of material entering and leaving each year. There is usually data available that quantifies the amount of different HWPs entering the pool annually, but determining losses is much more problematical. Brunet-Navarro et al. (2016) stated that there was a lack of reliable data on the utilisation and lifetimes of HWPs to accurately estimate the carbon stocks and fluxes. They concluded by stating 'if the sector wants to demonstrate the environmental quality of its products, it should make it a priority to provide reliable lifecycle inventory data, particularly regarding aspects of time and location'. Information regarding the lifetimes of buildings and building components is often lacking and many models are therefore based upon assumed lifetimes, often with little justification for those assumptions. Since data are lacking regarding the loss of timber from the built environment HWP pool, it is necessary to model this using an appropriate decay function.

First-order (exponential) decay is the method recommended by the IPCC for harvested wood products (IPCC 2019) and in most cases, is the only practical way of estimating carbon stocks in the HWP pool. Removal from the stock each year is assumed to be proportional to the quantity in the total stock. First-order decay is not the only method for describing the loss of wood products from the HWP pool, but it remains the dominant approach.

Marland and Marland (2003) discussed the implications of using first-order decay. The highest rate of loss of carbon from the pool will occur in the first time-increment (Marland et al. 2010). This approach is useful for products that can be treated as a single pool and for which decay occurs most rapidly just after production, such as paper used for newsprint. As the lifetime of the product increases, it is less likely that the oxidation rate follows an exponential decay profile (Cherubini et al. 2012). In the IPCC guidelines, estimated service lives (and half-lives) are given for different HWP categories (Appendix 1). The usual method for calculating the storage of atmospheric carbon stored in the HWP pool is to use a single pool approach, where the age of the HWP product is not important and only the total amount of material in the pool is of consequence.

However, longer-lived products, such as those used in the built environment, it is unrealistic to assume that the highest rate of loss of carbon from the pool will occur after the first year of service and a more realistic representation of this behaviour needs to be introduced. The rate of loss of stored atmospheric carbon is better described by a distributed pool approach, where the input for each year is treated separately. In a distributed pool model, the loss of carbon from the pool is related to the age of products in the pool and is better modelled by a probability distribution, rather than exponential decay. This method treats each year's production separately and recognises that the probability of loss of carbon from a new product is lower than that from an older product. It is also necessary to select an appropriate function to represent the loss of carbon from each product pool. A variety of decay functions have been investigated, including linear, exponential and different logistic functions (Pingoud 2016). They investigated the effect of using different decay distribution functions on the carbon stock in HWPs and reported this as supplementary information in their paper. They simulated a constant product input of 1 tonne per year and a product half-life of 50 years, using a distributed approach and running the model until a steady state was reached. This has also been investigated in the current study by examining exponential, linear, normal and gamma distributions, with an input of one tonne per year and using different half-lives. Different results have been obtained in the current study for the exponential function compared with the results reported by Pingoud et al. (2016).

The residence time of atmospheric carbon in the HWP pool can be increased through the use of cascading. The concept of a materials cascade chain was first defined by Sirkin and Ten Houten (1994), who borrowed the idea from the thermodynamic concept of an energy cascade. A materials cascade can be described as a strategy for extending the residence time of a material in an economy through sequential exploitation of its properties on its path to 'equilibrium' (by which is often assumed to mean a thermodynamic equilibrium). This idea of a material approaching an equilibrium is not scientifically accurate, but it does contain within it the concept that the usefulness (or rather value) of the material is being reduced through successive lifecycles.

Thus, although cascading involves a reduction in utility of a material with each cycle (downcycling), the material is retained in the value chain for longer than would be the case if it was only used for one product cycle. In principle, this should result in environmental benefits, because less virgin material is required to provide the same function(s) and the sequestered atmospheric carbon in the cascaded wood is stored for a longer time. In addition, more value is potentially derived per unit of material because it is used in more product cycles; although each cycle produces less value for a given amount of material, compared with the previous cycle (value hierarchy).

The application of cascading to wood value chains was first discussed as a theoretical concept by Fraanje (1997). An exergetic LCA in a study of cascading was undertaken by Cornelissen and Hirs (2002) who concluded that the production of chipboard from waste wood results in less depletion of natural resources, when compared with co-

combustion in a coal burning electricity plant. However, the use of exergy as a universal indicator for determining environmental impact is not widely accepted in the LCA community. Sathre and Gustavsson (2006) reported on the energy and carbon balances of different wood cascade chains, compared with the same products made from virgin wood. They concluded that the most important contribution from wood cascading was due to carbon storage in unharvested biomass because of reduced wood demand. Substitution effects were also found to be important, where there were savings in carbon emissions due to the replacement of carbon-intensive materials by functionally equivalent timber alternatives. However, no account was taken of the temporal aspects of carbon storage, nor the use of damaged or contaminated wood in their study. Sikkema et al. (2013) concluded that significant greenhouse gas savings could be realised due to a combination of fossil fuel, material substitution and temporary carbon uptake in wooden products as a result of cascade use. Höglmeier et al. (2015) used LCA methodology to determine the impacts associated with wood cascading to particleboard compared with different counterfactuals, including substitution of non-biogenic building materials. Although there were benefits arising due to cascading, it was important that high materials utilisation efficiency levels were realised, with efficiency levels of over 70% necessary to achieve benefits over wood energy use. Risse et al. (2017) performed an analysis of cascading to quantify the resource use efficiency compared with the use of virgin material, concluding that wood cascading resulted in lower resource consumption compared with the use of primary wood to produce the same function.

In the above studies, there is no clear description or visualisation of how the use of cascading affects the flows and storage of sequestered atmospheric carbon in the harvested wood products pool. Many of the published studies are complex and often difficult to follow.

The purpose of this current study is to understand how cascading affects the carbon dynamics of the HWP pool and in particular, what the extra benefit is in terms of carbon sequestration as a strategy for climate change mitigation.

The principle of sequestration is simple, but often misunderstood, so the basic principles will be outlined here, since they are crucial to understanding the potential benefits.

As timber is felled and processed and used in buildings, the atmospheric carbon stored in the material is transferred from the forest to the HWP pool. This means that a proportion of the carbon that was stored in the forest has been transferred to the HWP pool. Provided that the timber has been harvested in a sustainable manner and the forest carbon pool is static, or growing, there is extra carbon storage provided by the HWP pool. There are also emissions of GHG gases and other associated environmental burdens associated with the harvesting and processing of timber, but these are not dealt with here.

The timber products in the HWP pool have a finite lifetime and eventually the carbon will leave the pool, primarily through oxidation, and return to the atmosphere. Provided the rate at which carbon enters the pool exceeds the rate at which it leaves the pool, the pool is increasing and there is a net climate change mitigation benefit. However, at some point in time, a state of equilibrium is reached, where the rate of carbon gain is balanced by the rate of carbon loss. When this equilibrium point is reached, there is no longer any climate change mitigation benefit and the HWP pool is a carbon store, rather than a sink (as in a mature forest).

The point of equilibrium and the total amount of carbon stored are important pieces of information for understanding the climate change mitigation benefits of different timber utilisation strategies.

The main purpose of this study is to understand what mitigation benefit might be realised by the adoption of a timber-cascading strategy.

The carbon accounting in this report is based upon reporting carbon flows into and out of the HWP pool, with outflows being reported as negative carbon and inflow as positive carbon (stock change approach). This is the opposite convention to that used for the atmospheric flow approach.

MODELLING – cycle 1

A model was created in Excel which described the stocks and flows of carbon in an HWP pool over a period of 500 years. The model is set up to use a distributed pool approach so that the input for each year is dealt with separately. As a default, the input for each year was set at 1 tonne of carbon per year in order to study the behaviour of the pool under different product lifetimes, but it is possible to change this in the model. Various functions were used to describe the loss of carbon for each years' input, up to a total loss of 1 tonne. The decay functions chosen were a linear decay, exponential decay, normal distribution and a gamma distribution (Appendix 3). These functions were chosen as representative of the wide range of different functions that have been used by researchers, with the intention of examining the difference that choice of decay function makes to the final outcome in terms of the amount of carbon stored and time to equilibrium. This was a preliminary study before the effect of cascading was investigated. The functions were generated using those provided by Excel. In order to examine the way that the different decay functions affected the results, it was decided to use the 50% and 95% loss of carbon values as comparators. How these were determined is explained for each function separately. In all cases, the study starts at year zero and by default there is no loss of material in year zero (in practice, this is only important for the linear and exponential decay models).

The loss of material from each year's input was described by the decay functions and parameters were chosen to represent the rate of this loss to describe solid timber products and particleboard. For the first cycle, only solid wood products in construction were considered, whereas for the cascade two product categories were chosen: solid wood products in construction and particleboard used non-structurally.

This section examines the behaviour of the different decay functions and the effect of varying the HWP lifetime upon the carbon storage properties of the HWP pool. The effect of cascading is examined in the following section.

Linear decay

The linear decay loss is set up to calculate the loss in % per year, based upon the entry of the 50% loss time. This can result in a fractional loss at the end the time period and the spreadsheet is designed to calculate this – so that the total loss for each time period is not greater than or less than the quantity that entered for that period. The spreadsheet is also set up so that there is no loss of material in year zero – the first loss occurs in year 1.

The loss for 30, 60, 90, 120 year-half-lives is shown in Figure 1, below:

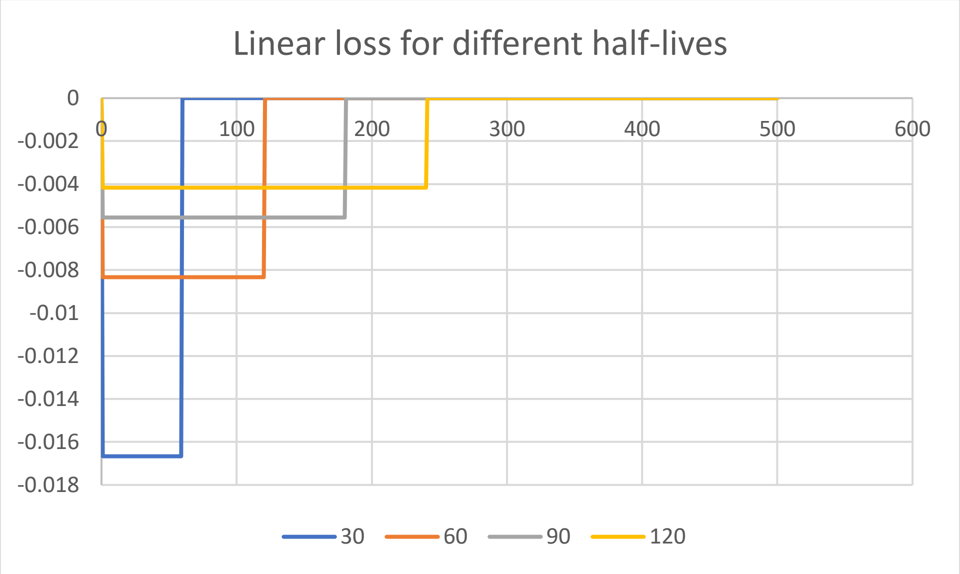

Figure 1: Linear loss of carbon for different half lives

The change in the carbon stocks for different half-lives is shown in Figure 2.

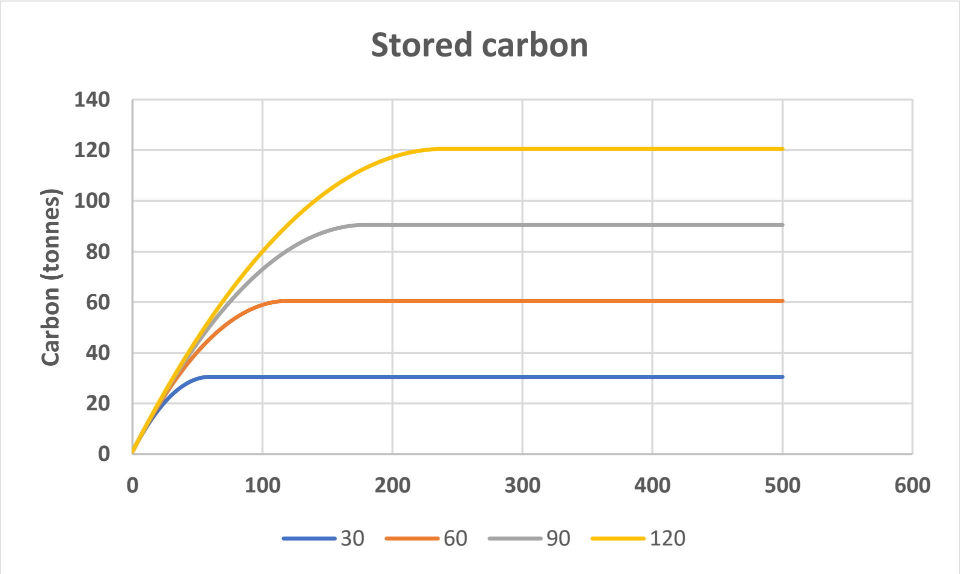

Figure 2: Change in stored carbon for different half lives

The total amount of carbon stored in the HWP pool at equilibrium for different half-life periods is shown in Table 1.

Table 1: Total carbon stored at equilibrium – the effect of life extension

50% loss time	95% loss time	Total carbon (tonnes)
30	57	30.5
60	114	60.5
90	171	90.5
120	228	120.5

Winjum et al. (1998) used a linear decay function with the following half-lives:

Sawnwood 100 years (boreal), 50 years (temperate), 25 years (tropical); wood-based panels 50 years (boreal), 25 years (temperate), 12.5 years (tropical).

Exponential decay

The exponential decay is calculated using the embedded Excel function, which has the following syntax:

EXPON.DIST(x,lambda,cumulative)

Where x is the time in years, lambda is related to the half-life (λ=ln(2)/(half-life)), cumulative is a logical argument that specifies the type of distribution to be calculated. This can have the value TRUE or FALSE, meaning:

TRUE	-	Calculate the cumulative distribution function
FALSE	-	Calculate the probability density function

The negative value of the distribution was used and the loss through exponential decay started in year 1 (not year zero).

Because of the shape of the exponential function, the highest loss of carbon occurs in the first year and the decay came is very extended. This type of decay function is more representative for short-lived products, but not realistic to represent HWPs in the built environment. The rate of loss is controlled by the half-life of the function only (Fig. 3).

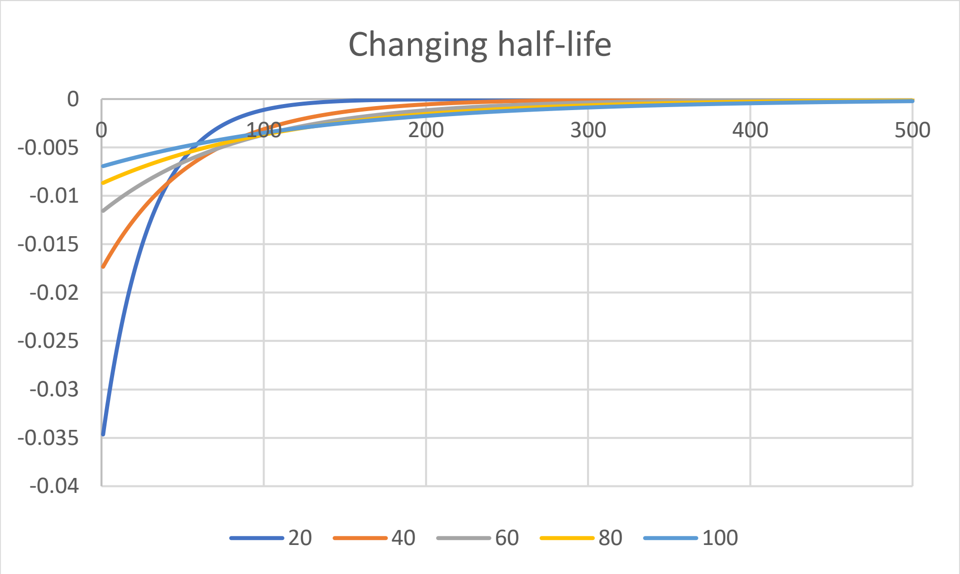

Figure 3: Shape of the exponential distribution for half-lives from 20 to 100 years.

There is no inverse function in Excel to calculate the 50 and 95%-iles, but the GAMMA.INV function can be used:

GAMMA.INV(probability,1,(1/λ)

The effect of different half-lives on the 'total' carbon stored (at 500 years) in the HWP pool is shown in Figure 4, below (note that equilibrium is only approached asymptotically using the exponential decay function):

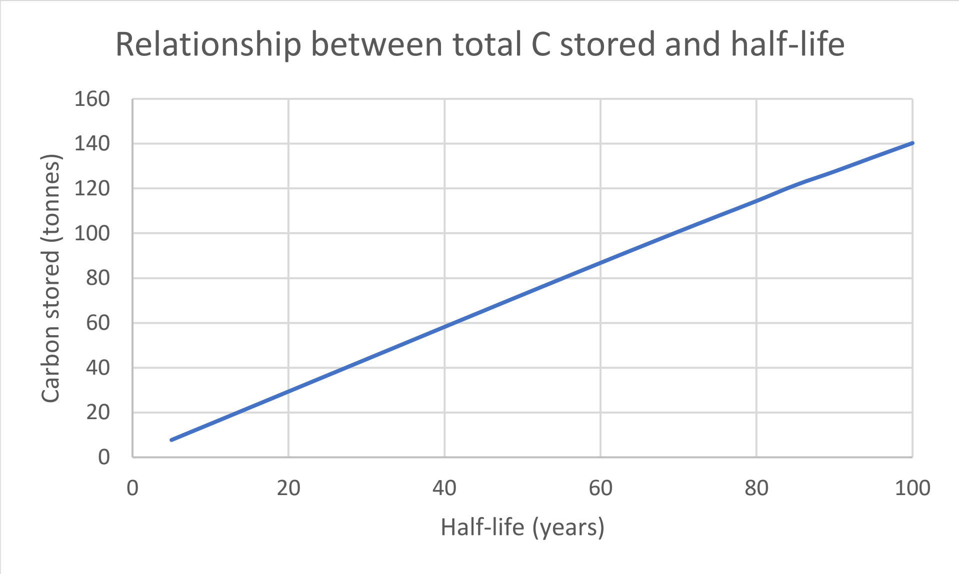

Figure 4: Relationship between half-life and stored carbon at 500 years.

The change in the carbon stocks for different half-lives (30, 60, 90, 120 years) is shown in Figure 5.

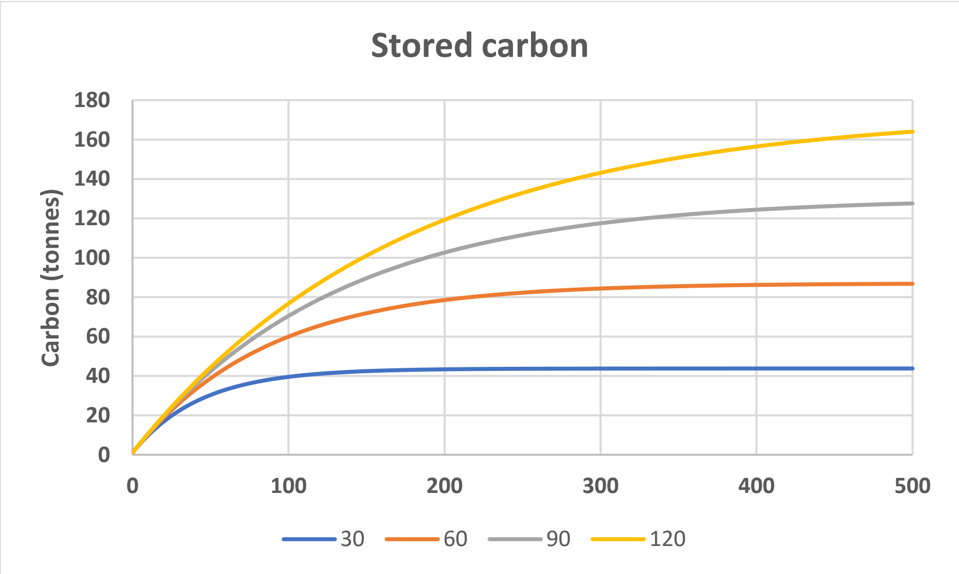

Figure 5: Relationship between half-life and stored carbon

In common with all studies, half-lives of 30, 60, 90, 120 years were chosen (Table 2).

Table 2: Relationship between 'total' carbon stored in equilibrium in the HWP carbon pool and the half-life of the exponential decay function.

50%-ile	95%-ile	Total C
30	129.66	43.78
60	259.32	86.79
90	388.97	127.58
120	518.63	163.99

The spreadsheet is set up so that there is no loss of material in year zero.

Rather than use a gamma distribution, which requires two parameters to define the shape of the curve, Cherubini et al. (2012) argued for the use of a chi-squared distribution, which is a special case of the gamma distribution, requiring only one parameter to define its shape.

Braun et al. (2016) investigated the apparent half-lives (HLs) and carbon content in three HWP product categories (construction, furniture, packaging) in an Austrian context and deduced that the average HLs were 33.9 years for construction, 8.5 years for furniture and 1.4 years for packaging. Wall elements, CLT were considered to have HLs of 48.8 years and houses 71 years.

Apart from the IPCC default values, Jasinevičius et al. (2018) also used a half-life of 45 years for timber in log houses.

Normal distribution

The embedded normal distribution function in Excel has the following syntax:

NORM.DIST(x,mean,standard_dev,cum), where x is the time in years, and cum = TRUE or FALSE. If cum is FALSE, then the probability density function is displayed and if cum=TRUE, then the cumulative distribution function is displayed.

The shape of the function is controlled by the mean and standard deviation values (Figs. 6, 7).

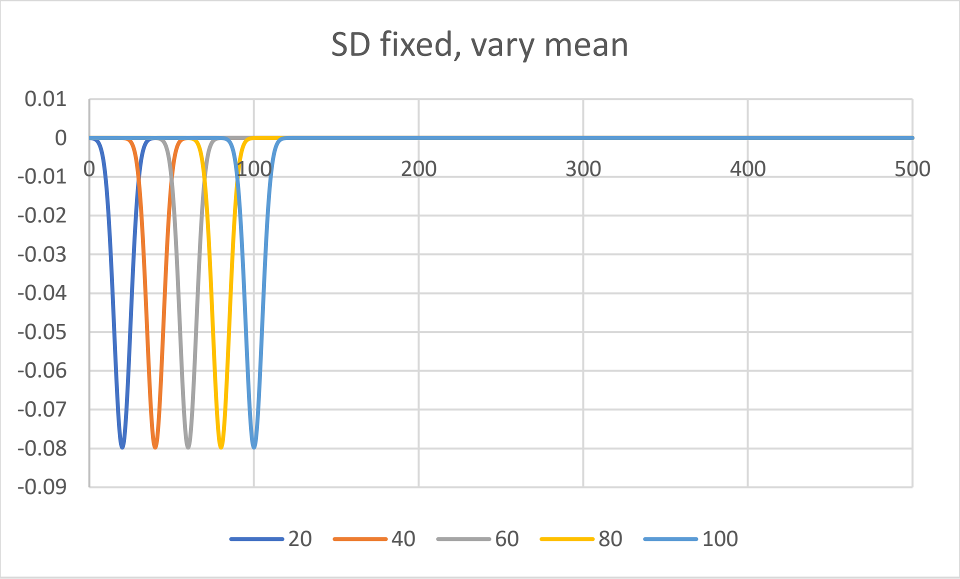

Figure 6: Shape of the normal distribution for a fixed standard deviation (= 5) and variable mean (from 20 to 100).

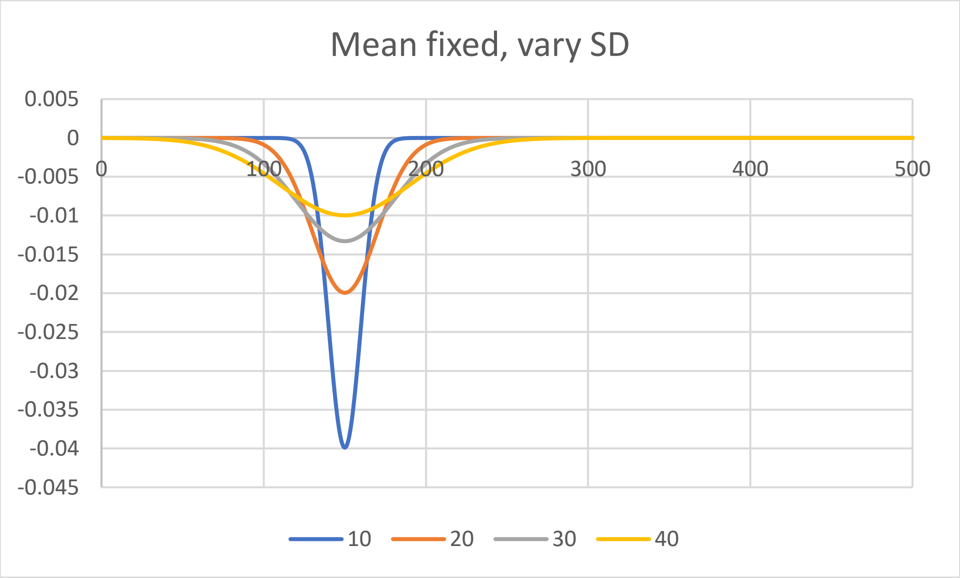

Figure 7: Shape of the normal distribution for a fixed mean (= 150) and variable standard deviation (from 10 to 40).

The 50- and 95-percentiles are calculated by using the normal distribution inverse function that is available in Excel. The syntax of this function is:

NORM.INV(probability,mean,standard_dev), where probability can take a value from 0 to 1.

The relationship between total amount of carbon in the pool and the time taken to lose 50% of carbon from each year's input is shown below (Figs. 8). The total amount of carbon stored in the pool is only affected by the value of the mean. The standard deviation only affects the time to equilibrium, not the total amount of carbon stored. The total amount of carbon stored in the pool (in tonnes) is equal to the mean (in years), the only exceptions occur when the normal distribution is truncated and the mean value is low and the standard deviation is high, so that part of the function is not visible. For this reason, it is recommended that SD values do not exceed 25% of the mean.

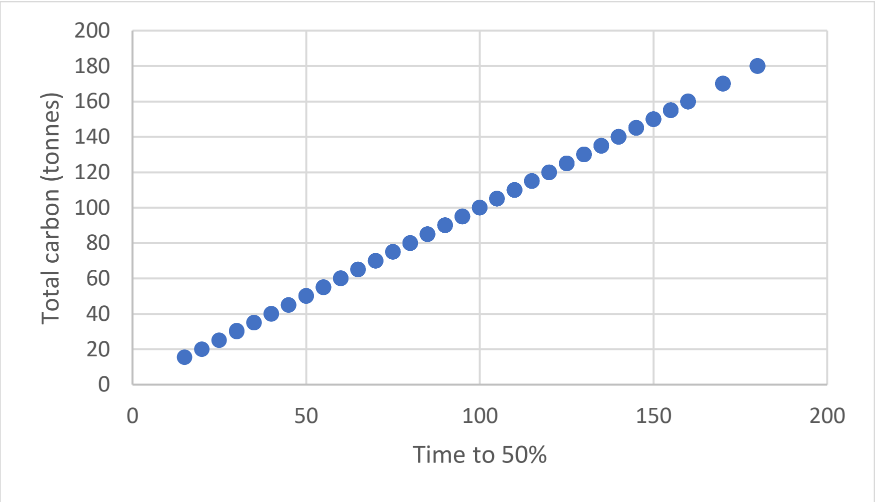

Figure 8: Relationship between time to 50% carbon loss in the normal distribution and the total amount of carbon stored in the pool at equilibrium (500 years).

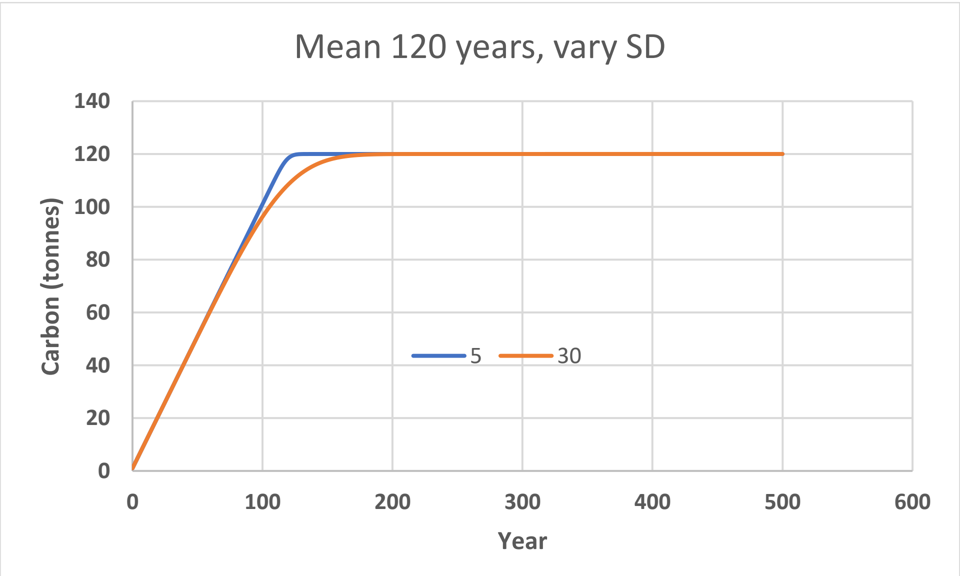

Figure 9: Relationship between time to 95% carbon loss (=2xSD) in the normal distribution and the total amount of carbon stored in the pool at equilibrium (500 years) for a mean of 120 years.

The quantity of carbon stored at equilibrium is not affected by changing the standard deviation, but the time to equilibrium is longer for a higher SD (Fig. 9).

The parameters used for the different product types, are shown in Table 3, below, showing time to 50% carbon loss, time to 95% carbon loss, mean, standard deviation (SD) and total carbon stored.

Table 3: Parameters used to describe product type and total carbon stored

50% loss (y)	95% loss* (y)	Mean (y)	SD (y)	Total C (t)
30	40	30	6.08	30.00
60	70	60	6.08	60.00
90	120	90	18.24	90.00
120	150	120	18.24	120.00

*Two standard deviations

The carbon storage curves for these parameters are shown in Figure 10.

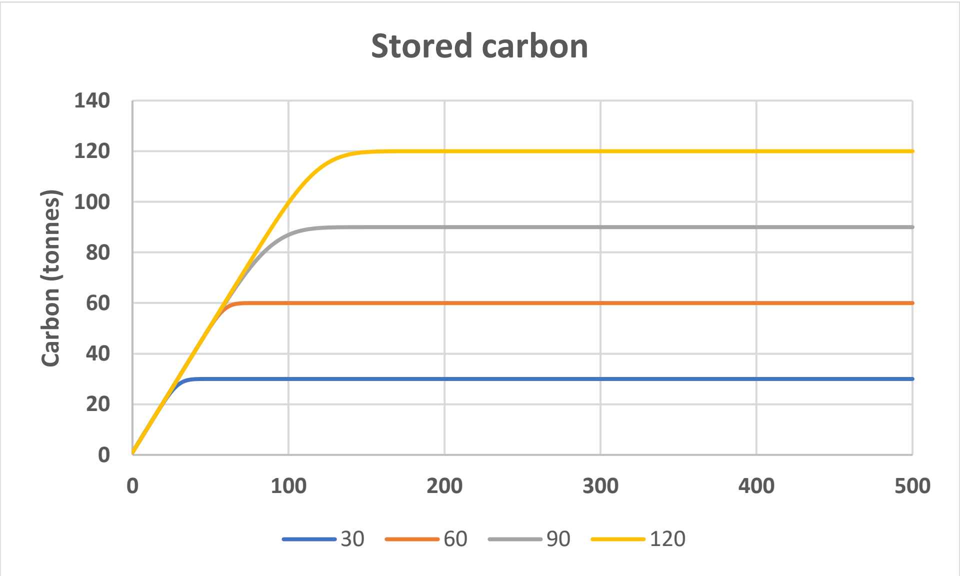

Figure 10: Relationship between time to 50% carbon loss in the normal distribution and the total amount of carbon stored in the pool at equilibrium for a mean of 30+/-10, 60+/-10, 90+/-30, 120+/-30 years (where +/- refers to two standard deviations).

A normal distribution was used as a decay function in a materials flow analysis by Müller et al. (2004) for the XYLOIKOS model, who assumed that carpentry products (defined as being part of the building fabric) had a lifetime of 100+/-20 years and joinery products (defined as moveable items, such as furniture) had a lifetime of 30+/-10 years.

Gamma distribution

The embedded gamma distribution function in Excel has the following syntax:

GAMMADIST(x,α,β,cum), where x is the time in years, and cum = TRUE or FALSE. If cum is FALSE, then the probability density function is displayed and if cum is TRUE then the cumulative distribution function is displayed.

The shape of the gamma distribution is controlled by two parameters, α (the shape parameter) and β (the scale parameter). The effect of altering those two parameters on the shape on the gamma distribution is shown below (Figs. 11, 12).

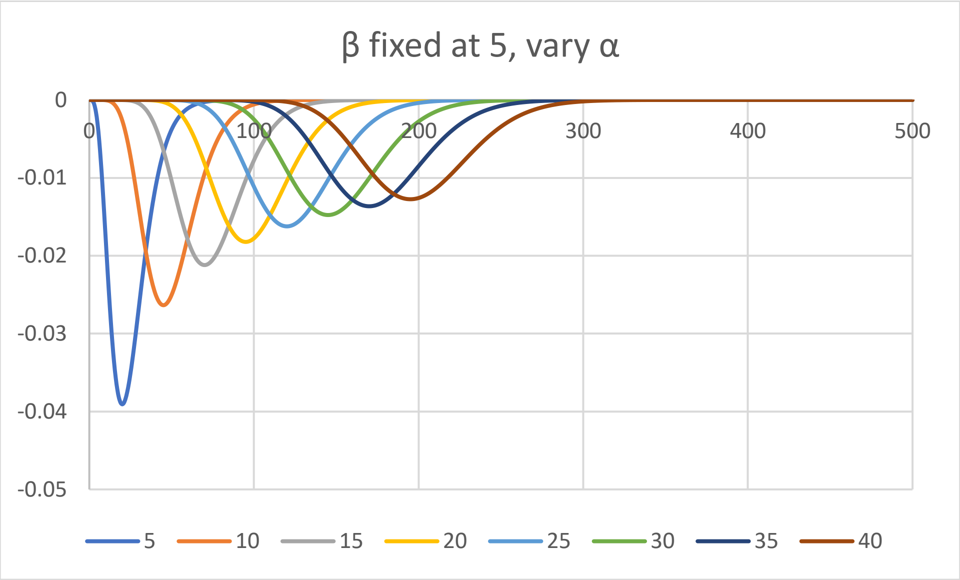

Figure 11: Shape of the gamma distribution for a fixed value of β (= 5) and variable α (from 5 to 40).

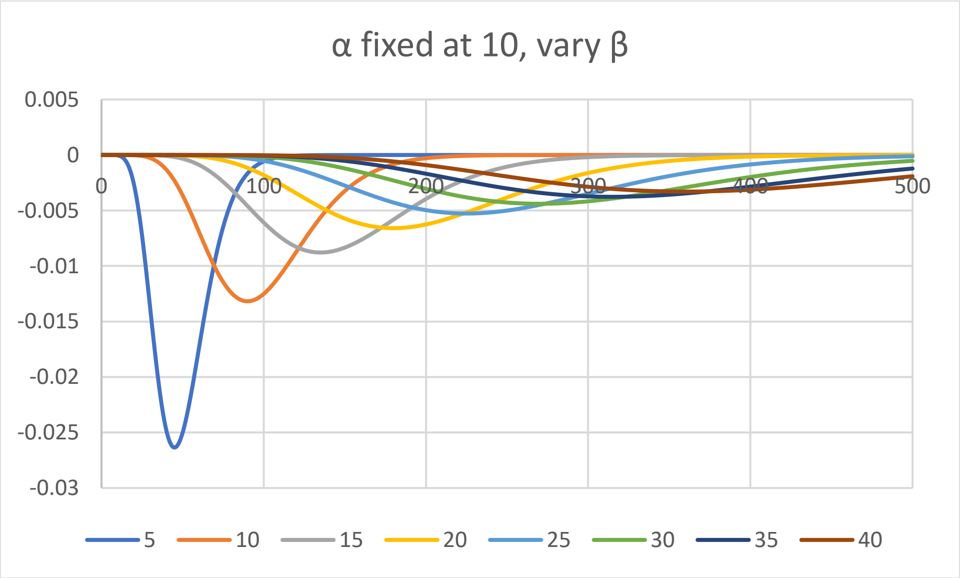

Figure 12: Shape of the gamma distribution for a fixed value of α (= 10) and variable β (from 5 to 40).

In order to calculate the 50- and 95-percentiles, the inbuilt inverse gamma distribution function was used, which has the following syntax:

GAMMA.INV(probability,α,β), where the probability has a value between 0-1.

The relationship between the total amount of carbon in the pool at equilibrium and the time to 50% and 95 % carbon loss in the gamma distribution is shown in Figs. 13-16 below. This shows the variation in total carbon stored for a fixed time to 50% loss of 30, 60, 90, 120 years and the effect of the variation in time to 95% carbon loss.

Figure 13: Relationship between time to 50% carbon loss of 30 years and variation in the time to 95% carbon loss in the gamma distribution and the total amount of carbon stored in the pool at equilibrium.

Figure 14: Relationship between time to 50% carbon loss of 60 years and a variation in the time to 95% carbon loss in the gamma distribution and the total amount of carbon stored in the pool at equilibrium.

Figure 15: Relationship between time to 50% carbon loss of 90 years and a variation in the time to 95% carbon loss in the gamma distribution and the total amount of carbon stored in the pool at equilibrium.

Figure 16: Relationship between time to 50% carbon loss of 120 years and a variation in the time to 95% carbon loss in the gamma distribution and the total amount of carbon stored in the pool at equilibrium.

The 50% carbon loss time of 30 years (95% loss of 40 years) is used to represent the use of particleboard in buildings, the effect of life extension is modelled by the use of a 50% loss time of 60 years (95% loss of 70 years). For the use of solid timber, the chosen 50% carbon loss times were 90 years (95% loss 130 years) and the effect of life extension used a 50% loss time of 120 years (95% loss 160 years). The parameters are given in Appendix 2, Table 2. These times are arbitrary and other values are possible. The objective here is to show the effect of life extension and how the equilibrium carbon storage is affected.

The total carbon stored at equilibrium based upon the different decay functions is shown in Table 4, below. It is interesting to note that the total carbon stored at equilibrium is equal to α times β.

Table 4: Total carbon stored at equilibrium – the effect of life extension

50% loss time	95% loss time	Total carbon (tonnes)
30	40	30.34
60	70	60.19
90	120	91.01
120	140	120.79

This shows that the amount of carbon stored in the HWP pool increases as the residence time of the products in the pool increases.

The relationship between these parameters and the carbon storage curves is shown in Figure 17.

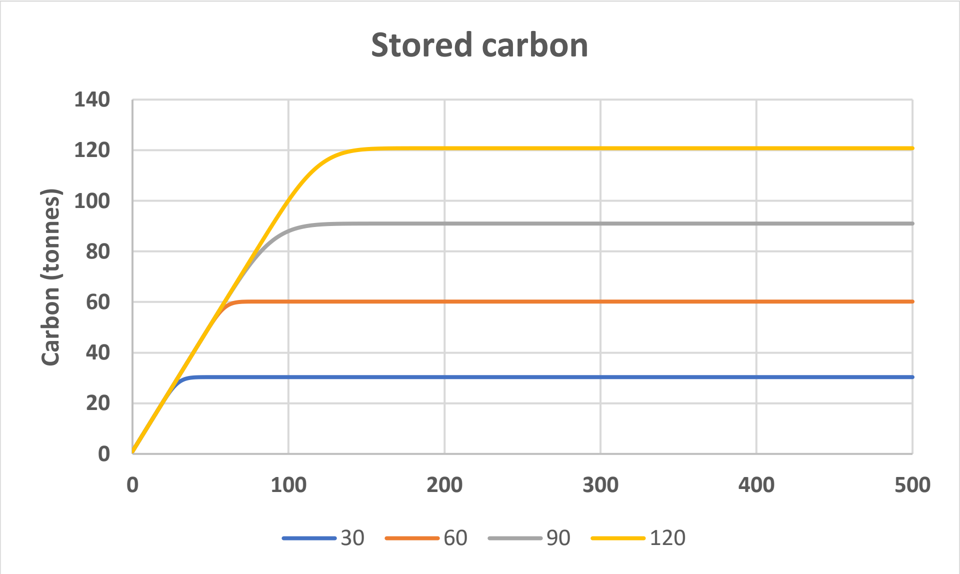

Figure 17: Relationship between time to 50% carbon loss of 30, 60, 90, 120 years and the total amount of carbon stored in the pool at equilibrium.

Marland et al. (2010) used a gamma distribution to model the carbon loss and considered both a single- and a distributed-pool approach. They included different product lifetimes in their model and the possibility of recycling, using parameters which were based on assumptions for oak products, using data supplied by Forest Research in the UK. The gamma distribution parameters used to model these different pools were listed in the paper and these are reproduced in Appendix 2 (Fig. 1). These values do not correlate exactly with the values used in the current study; because they used time to maximum loss, rather than time to 50% loss as one of the criteria. The use of oak in construction is quite limited and some of the product categories listed (such as particleboard) do not use oak in any case. For these reasons, the parameters reported by Marland et al. (2010) were not used in the present study.

Cherubini et al. (2012) used a chi-squared distribution (which is a special case of a gamma distribution, where β = k/2 and α = 2), k is the year of maximum oxidation rate.

This was compared with exponential decay and a delta function. This work was used to model the impacts of temporal carbon storage upon LCA using different time horizons (20, 100, 500 years) and is not directly relevant to the current study.

Iordan et al. (2018) also used a chi-squared distribution (which is a special case of a gamma distribution) to model the loss of carbon from HWP pools in Norway, Sweden and Finland. Timber utilisation was dominated by softwoods. They studied a time-series for HWP production in these three countries running from 1960-2015. Product lifetimes were based on those used by Guest and Strømann (2014), assuming 43 years for particleboard for furniture and 140 years for solid wood for buildings.

Comparison of models

The difference in the carbon storage for the four models for 50% half-lives of 30, 60, 90 and 120 years are shown in Figs. 18-21.

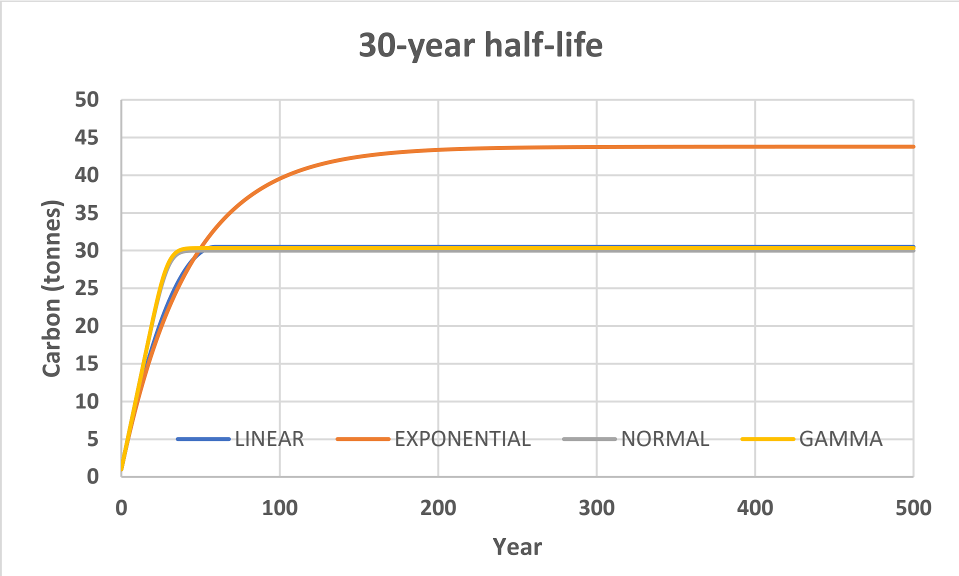

Figure 18: Comparison of the carbon storage dynamics of the four decay functions for a 30-year half-life

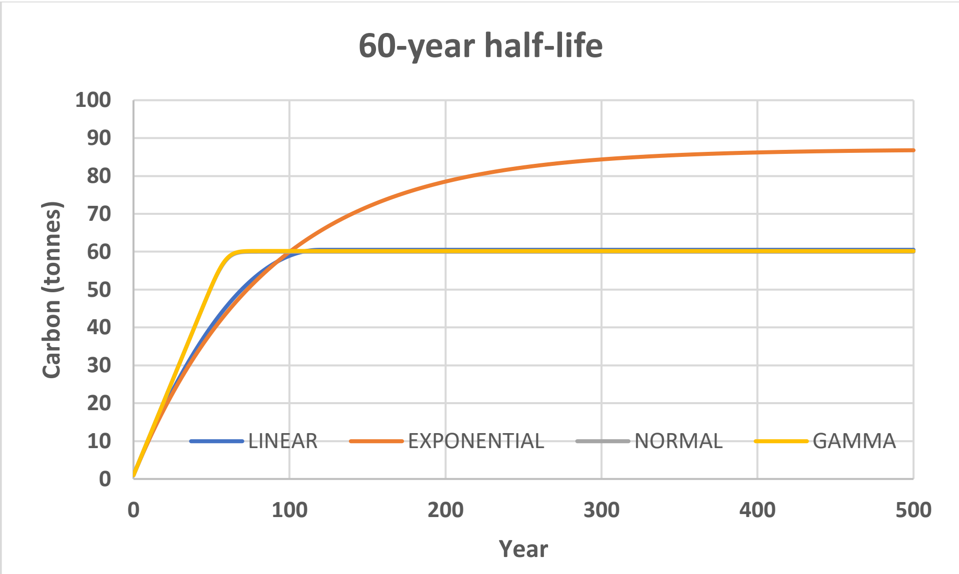

Figure 19: Comparison of the carbon storage dynamics of the four decay functions for a 60-year half-life

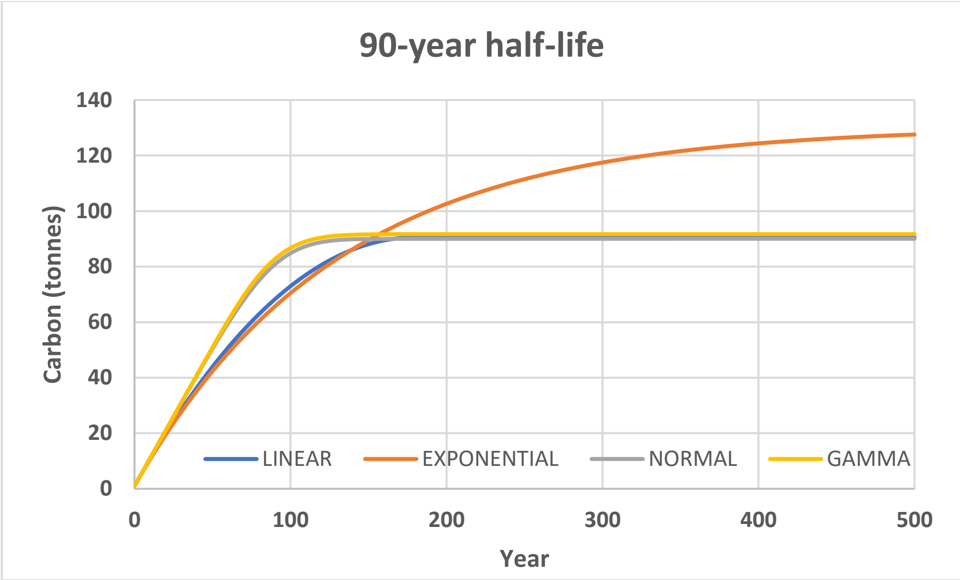

Figure 20: Comparison of the carbon storage dynamics of the four decay functions for a 90-year half-life

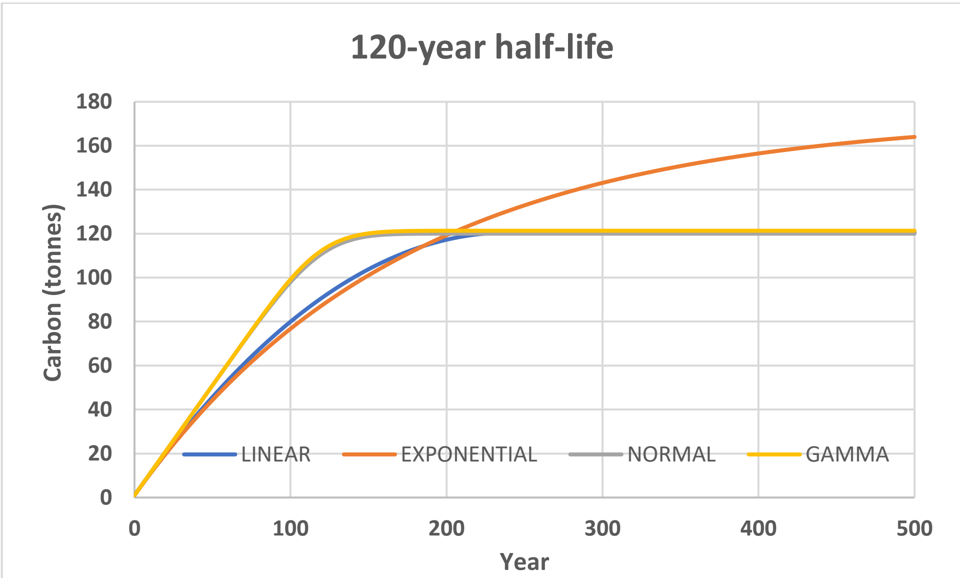

Figure 21: Comparison of the carbon storage dynamics of the four decay functions for a 120-year half-life

These plots clearly show that there is little difference in behaviour between the normal distribution and the gamma function, but that the use of exponential function results in lower carbon storage at lower time periods and higher carbon storage for longer time periods. The linear function closely follows the exponential function at low time periods and then the normal/gamma function behaviour at longer time periods. It is also clearly illustrated how extended lifetimes for the products result in greater amounts of atmospheric carbon storage in the HWP pool and a longer time to reach the equilibrium point. The behaviour observed with the exponential decay function is an exception in that the equilibrium point is never reached (although it is approached asymptotically) due to the shape of the decay function.

The conclusion from this part of the study is that it is only necessary to use two decay functions to explore the effect of cascading on the carbon dynamics:

- Exponential decay, because this is the default decay function
- Normal distribution, as the simplest function that is more representative of reality

Ford-Robertson (2003) compared linear and exponential decay functions to fluctuating inputs and concluded that there was little difference in the results that they produced for carbon stocks.

MODELLING – cascading

The spreadsheet model has the possibility of including two, separate, parallel, cascades, which are both derived from material leaving the HWP cycle 1 pool (Fig. 22).

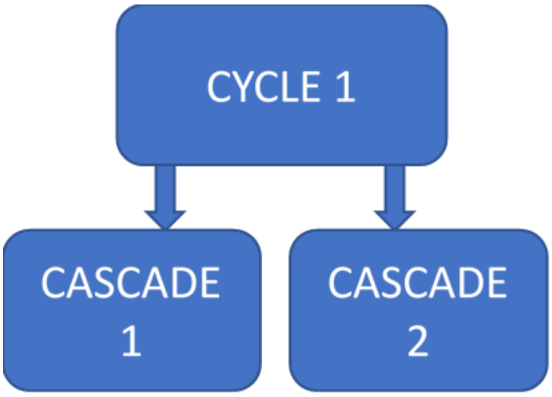

Figure 22: Diagram of the modelled cascade cycles

The effect of serial cascades was not modelled.

This section discusses the effect of using one cascade only, with different proportions of material being cascaded and the use of different product lifetimes in the cascade (30, 60, 90 ,120 years). Exponential and normal distribution decay functions were used in the models.

The first section explores the consequences of different quantities of material being cascaded with a fixed decay time for the cascaded material (chosen as a half-life of 30 years). The next section describes the effect of different product lifetimes, with a fixed amount of material cascaded. Finally, the difference in results between the exponential decay and normal distribution decay functions is presented.

Cascading – the consequences of re-using different proportions of material

The normal distribution decay function was used with a half-life of 30+/-10 years. The amount of material cascaded was 20, 40, 60% of the carbon leaving the HWP pool in cycle 1. The mean lifetime for cycle 1 was fixed at 90+/-30 years (note: this is not one standard deviation, but the 95%-ile = 2 SD). Results are shown in Table 5 and Fig. 23.

Table 5: The total quantity of carbon stored at equilibrium with different proportions cascaded and fixed product lifetime.

Proportion cascaded (%)	Half-life (years)		Carbon stored (tonnes)
	Cycle 1	Cascade	
0	90+/-30	30+/-10	90.00
20	90+/-30	30+/-10	96.00
40	90+/-30	30+/-10	102.00
60	90+/-30	30+/-10	108.00

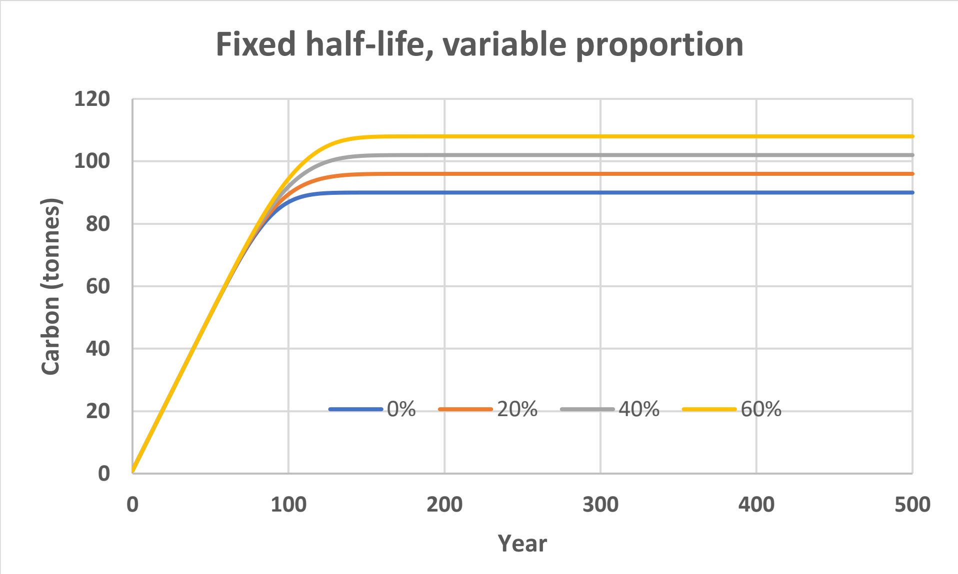

Figure 23: Carbon dynamics for cascade of different quantities with cascade mean lifetime of 30+/-10 years and cycle 1 lifetime of 90+/-30 years.

The effect of different product lifetimes in the cascade is shown in Table 6 and Figure 24, where 40% of the cycle 1 carbon is used in the cascade and cascade mean lifetimes (+/- 2 SD) of 30+/-10, 60+/-10, 90+/-30 and 120+/-30 years are used.

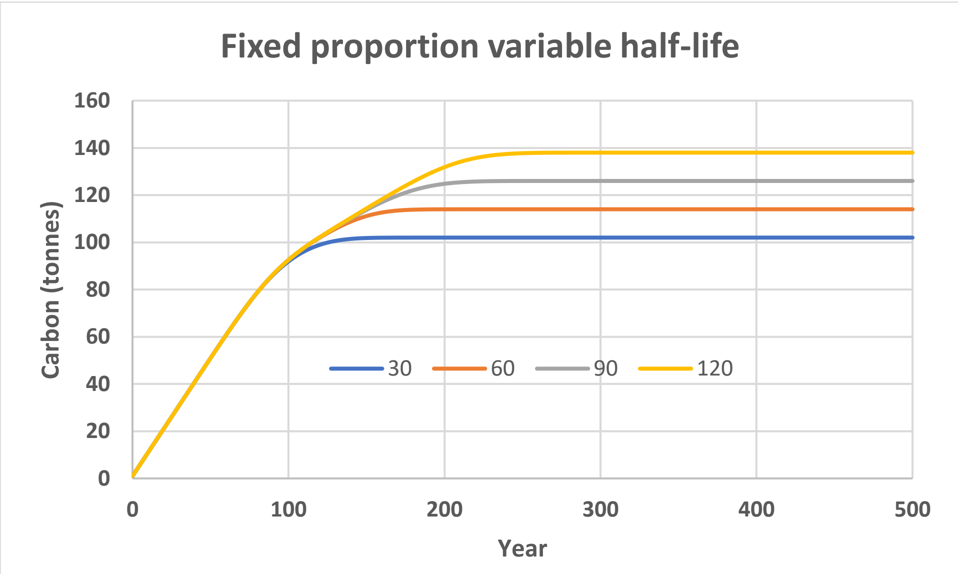

Figure 24: Carbon dynamics for cascade of 40% with cascade lifetime of 30+/-10, 60+/-10, 90+/-30, 120+/-30 years and cycle 1 lifetime of 90+/-30 years.

Table 6: The total quantity of carbon stored at equilibrium with a proportion cascaded and different product lifetimes.

Proportion cascaded (%)	Half-life (years)		Carbon stored (tonnes)
	Cycle 1	Cascade	
40	90+/-30	30+/-10	102.00
40	90+/-30	60+/-10	114.00
40	90+/-30	90+/-30	126.00
40	90+/-30	120+/-30	138.00

Extending product lifetime has a greater effect upon total carbon stored and time to equilibrium than increasing the proportion cascaded.

The IPCC recommends the use of exponential decay curves in its methodology. It has already been demonstrated that this results in an under-reporting of stored carbon in the early stages and an over-reporting at later stages. However, due to the widespread use of exponential decay, it is necessary to show how this function affects the results of the cascading study.

For the first study, the half-life for cycle 1 was fixed at 90 years and for the cascaded product at 30 years, to represent solid timber in houses and cascading to particleboard for use in construction. Different proportions of material from cycle 1 were cascaded (0, 20, 40, 60%).

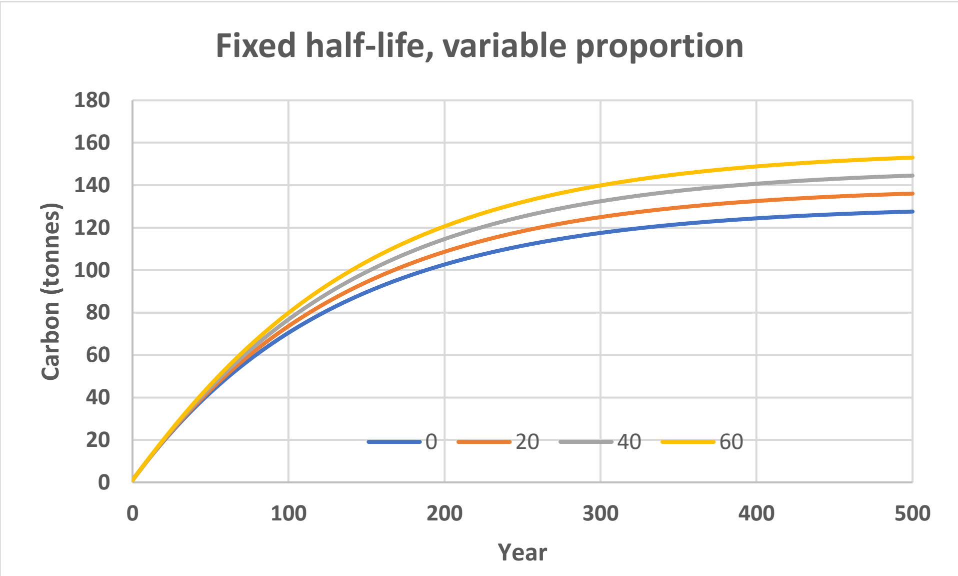

Figure 25: Carbon dynamics for cascade of different quantities with cascade half-life of 30 years and cycle 1 half-life of 90 years.

Table 7: The total quantity of carbon stored at equilibrium with different proportions cascaded and fixed product half-life.

Proportion cascaded (%)	Half-life (years)		Carbon stored (tonnes)
	Cycle 1	Cascade	
0	90	30	127.58
20	90	30	136.05
40	90	30	144.53
60	90	30	153.00

The effect of different product lifetimes in the cascade is shown in Table 8 and Figure 26, where 40% of the cycle 1 carbon is used in the cascade and cascade half-lives of 30, 60, 90 and 120 years are used.

Table 8: The total quantity of carbon stored at equilibrium with different proportions cascaded and fixed product half-life.

Proportion cascaded (%)	Half-life (years)		Carbon stored (tonnes)
	Cycle 1	Cascade	
40	90	30	144.53
40	90	60	160.40
40	90	90	174.35
40	90	120	186.01

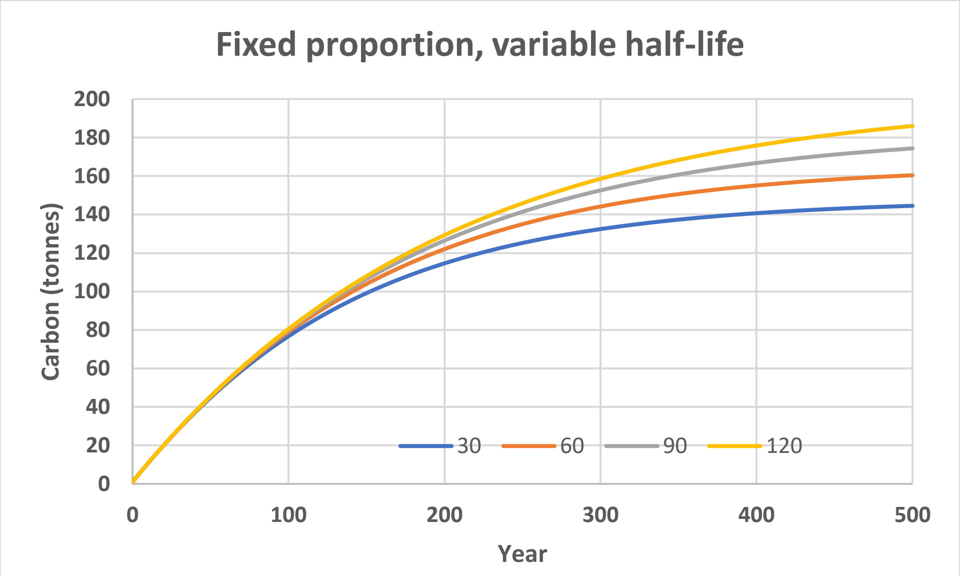

Figure 26: Carbon dynamics for cascade of 40% of cycle 1 carbon with cascade half-lives of 30, 60, 90 and 120 years and cycle 1 half-life of 90 years.

The use of the exponential decay function results in an overestimation of carbon stored at long time periods and equilibrium not being established within the time period of the study.

MODELLING – using housing statistics

Based upon supplied data for timber use in housing in Finland (Table 9), the impact upon carbon storage was modelled using the normal distribution (90+/-30 years and 120+/-30 years). The first study was based upon the actual numbers supplied, with the data series starting in 1995 and finishing in 2019 (Fig. 27). Please note that the data in Figures 27-30 reports the stored carbon in tonnes atmospheric carbon dioxide equivalents.

Table 9: Wood use for new housing in Finland (1995-2019)

Year of completion	Wood used (tonnes)	Carbon (tonnes)	CO_2eq (tonnes)
1995	74,425	37213	136446
1996	69,231	34615	126923
1997	82,601	41300	151435
1998	93,885	46943	172123
1999	99,215	49607	181894
2000	102,341	51170	187625
2001	96,801	48400	177468
2002	93,926	46963	172197
2003	99,706	49853	182794
2004	115,676	57838	212073
2005	122,546	61273	224668
2006	128,269	64134	235159
2007	131,222	65611	240574
2008	114,900	57450	210650
2009	86,538	43269	158653
2010	87,124	43562	159728
2011	98,842	49421	181210
2012	91,915	45958	168512
2013	81,878	40939	150110
2014	71,275	35638	130671
2015	60,982	30491	111800
2016	60,428	30214	110784
2017	60,311	30156	110570
2018	61,423	30711	112608
2019	60,382	30191	110700

The graph in Figure 27 takes no account of atmospheric carbon that is stored in the Finnish built environment and no account of future inputs into the built environment. The assumed lifetime for the timber is 90+/-30 years, where +/-30 represents two standard deviations. The annual input of timber (in tonnes CO_2 equivalents) is also shown. The plot shows that approximately 50% of the stored carbon remains in the built environment pool after 100 years. Figure 28 shows the effect of introducing cascading at a rate of 40% of the timber leaving the built environment carbon pool and using a product lifetime of 90+/-30 years. This represents a design for disassembly scenario, where there are high recovery rates of good quality timber products that are re-used in their current form for an equivalent function. The extension of carbon storage time as a result of introducing one cascade cycle is very clearly seen.

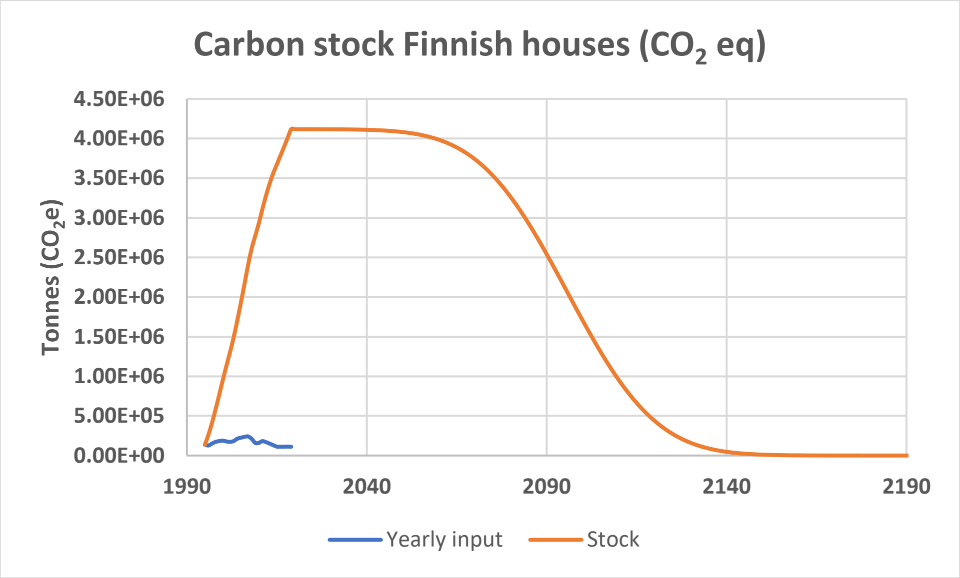

Figure 27: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30) years, mean (2 SD).

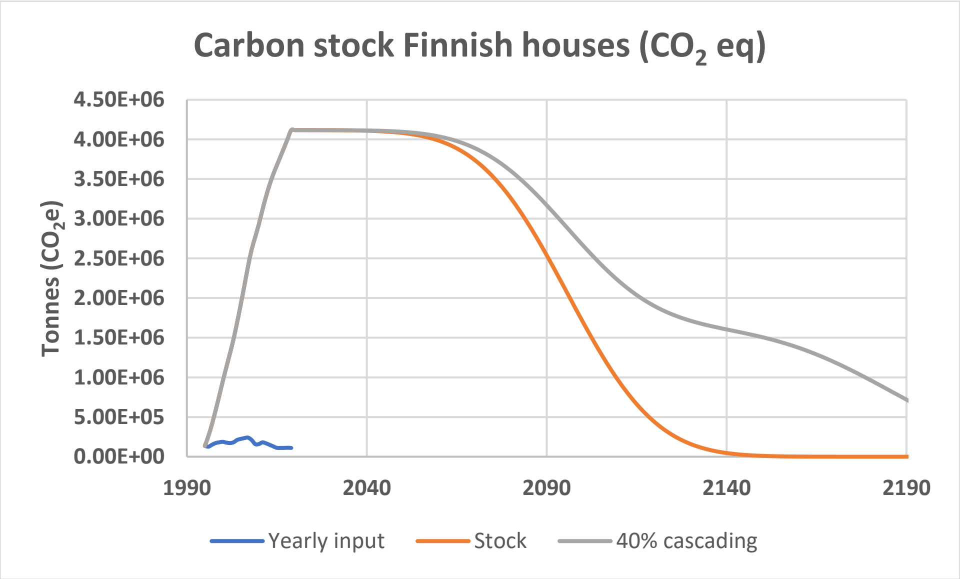

Figure 28: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30) years, mean (2 SD). A cascade of 40% has been introduced with the same lifetime as in cycle 1.

The effect of introducing a 40% cascade, but with a product lifetime of 30+/-10 years is shown in Figure 29. Although there is some extension of storage time, this is not so significant as that observed with cascade product lifetime of 90+/-30 years. By increasing the lifetime of products in cycle 1 from 90+/-30 to 120+/-30 years, a much greater influence upon the carbon storage profile is observed (Fig. 30).

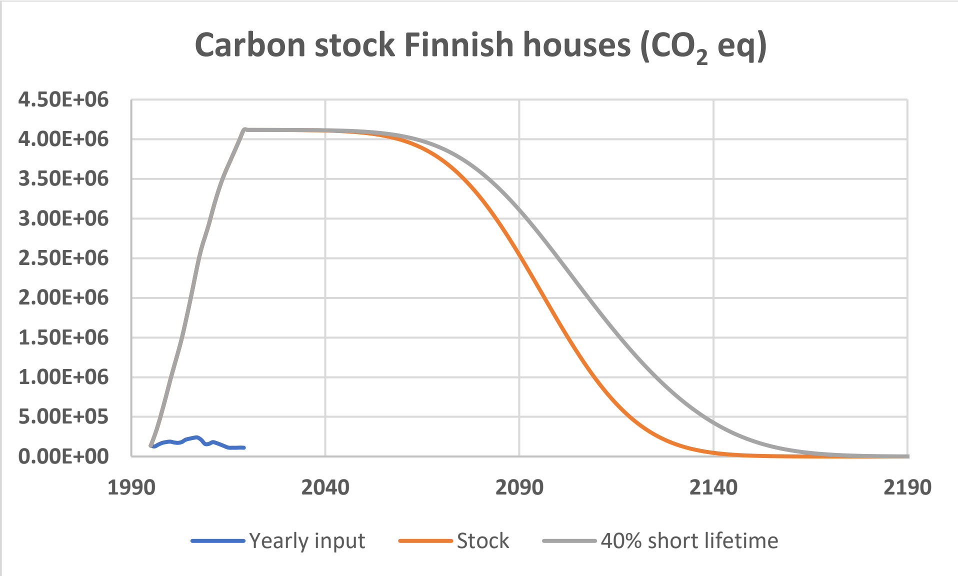

Figure 29: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30) years, mean (2 SD). A cascade of 40% has been introduced with a product lifetime of 30+/10 years.

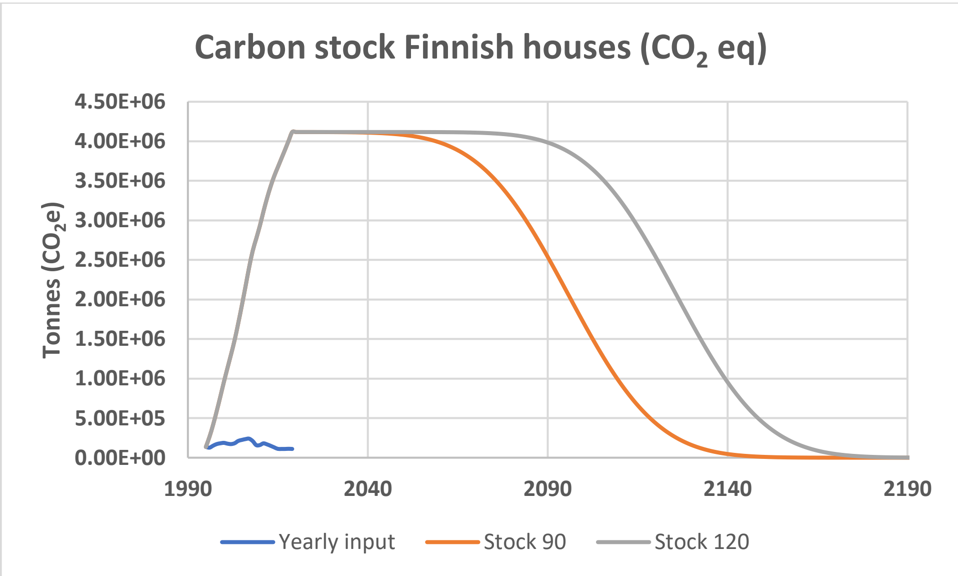

Figure 30: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30 and 120(+/-30) years, mean (2 SD). No cascade.

In all cases, the total carbon stored is the same, irrespective of the product lifetime, which appears contradictory, given the results presented earlier. Furthermore, there is a sharp transition from the phase where the carbon stored is increasing to where it flattens off. The reason for this behaviour is that the time series used is not long enough for a condition of equilibrium to be established.

An additional model was created using the yearly input data series and then a constant use of timber based upon the last time record (2019).

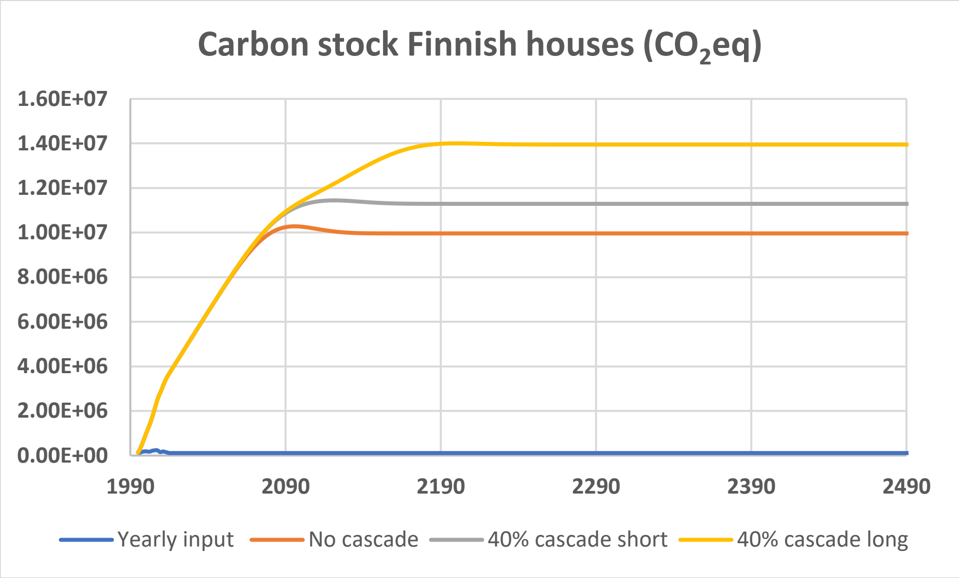

Figure 31: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019, then a constant input after 2019. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30) years, mean (2 SD). The cascade lifetime is 30(+/-10) years (short) and 90(+/-30) years (long).

The total amount of carbon stored reported as carbon dioxide equivalents in the housing pool at equilibrium is 9.96 million tonnes with no cascading, 11.29 million tonnes for 40% cascading (short lifetime) and 13.95 million tonnes for 40% cascading (long lifetime).

A comparison between introducing a 40% cascade with a long life (90+/-30 years) and a changing the product lifetime from 90+/-30 to 120+/-30 years is shown in Figure 32.

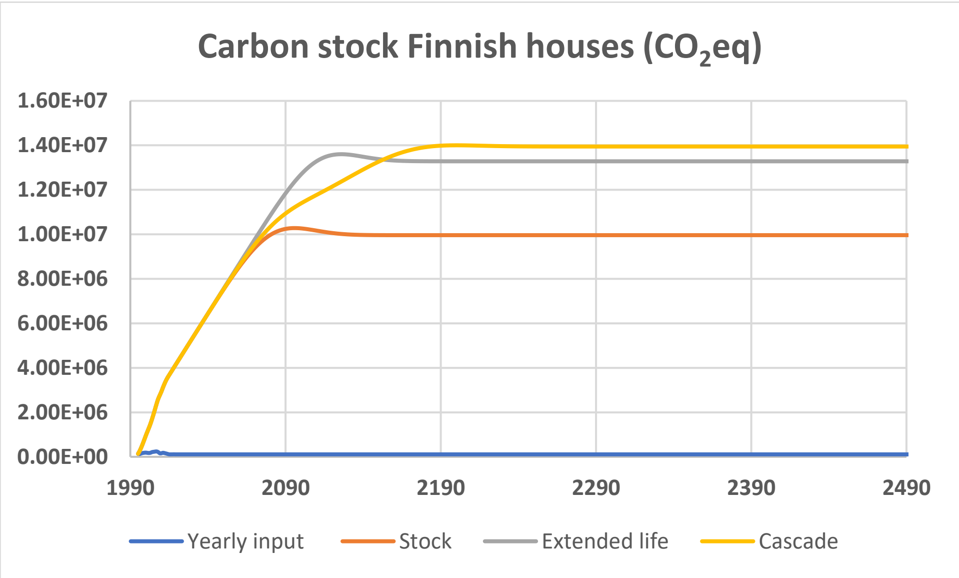

Figure 32: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019, then a constant input after 2019. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30) years and 120(+/-30) years, mean (2 SD). The cascade lifetime is 90(+/-30) years.

Cascading using a recovery level and a product lifetime of 90+/-30 years ultimately results in more carbon being stored in the pool (13.95 million tonnes CO_2eq), compared to an extension of the product lifetime from 90+/-30 (9.96 million tonnes) to 120+/-30 years (13.28 million tonnes), with no cascading.

Finally, a model was introduced in which the input for year 2019 was increased in a linear manner at 1% per year until the year 2119 (double the 2019 input in 100 years).

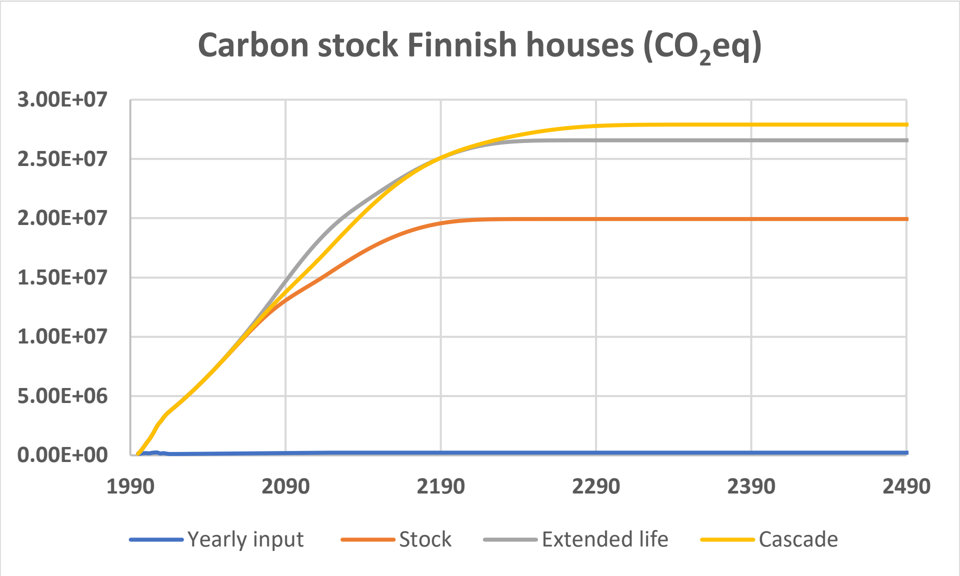

Figure 32: Carbon storage profile for Finnish housing stock with timber use data from 1995 to 2019 then a linear increase of 1% for 100 years from 2019 to 2119, then a constant input after 2119. The lifetime of the annual inputs is represented by a normal distribution of 90(+/-30) years and 120(+/-30) years, mean (2 SD). The cascade lifetime is 90(+/-30) years.

As with the previous model, cascading using a recovery level and a product lifetime of 90+/-30 years ultimately results in more carbon being stored in the pool (27.89 million tonnes CO_2eq), compared to an extension of the product lifetime from 90+/-30 (19.93 million tonnes) to 120+/-30 years (26.57 million tonnes), with no cascading.

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APPENDIX 1: ESTIMATED SERVICE LIVES AND HALF LIVES (IPCC 2019)

HWP commodity classes	Markets	Market share	Estimated service life	Obsolescence factor	ESL for commodity class	Half-life
Sawn wood	construction	60%	70	0.9	41.0	28.4
	furniture	10%	45	0.6		
	packaging	30%	6	0.3		
	paper	0%	-	-		
Wood-based panels	construction	50%	60	0.7	30.5	21.2
	furniture	45%	35	0.6		
	packaging	5%	6	0.3		
	paper	0%	-	-		
Paper and paperboard	construction	0%	-	-	1.5	1
	furniture	0%	-	-		
	packaging	50%	3	0.3		
	paper	50%	10*	2		

*presumably this is a misprint in the IPCC Table 12.4

APPENDIX 2: GAMMA DISTRIBUTION PARAMETERS USED BY MARLAND et al. (2010) (Table 1) AND GAMMA PARAMETERS USED IN THE CURRENT STUDY (Table 2)

Table 1

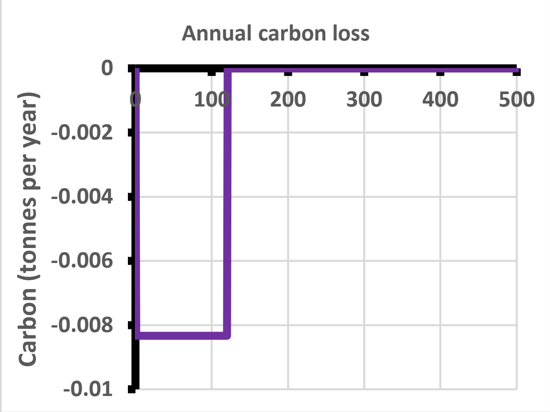
Product	Year of maximum decay	95% decay period (years)	α	β
Waste, bark, fuel	2	18	1.305	4.918
Pulpwood	1	5	1.418	1.196
Particleboard	15	40	3.676	5.419
Pallet, packaging	2	5	3.196	0.683
Fencing	40	80	6.662	6.976
Construction	150	300	6.740	26.045
Mining	40	1000	1.128	308.594

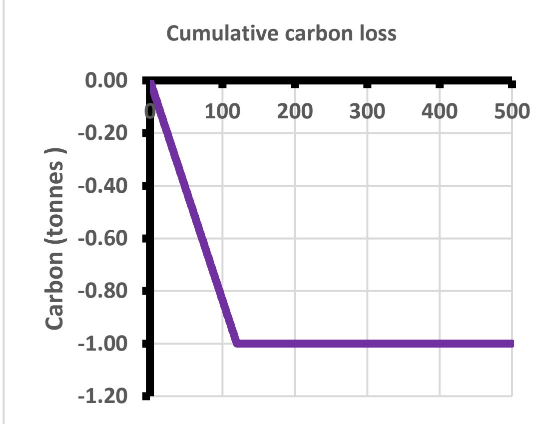
Table 2

Product	50%-ile (years)	95%-ile (years)	α	β
Particleboard	30.00	40.00	29.964	1. 0126
Particleboard (long)	60.00	70.00	108.450	0.555
Construction	90.00	120.00	29.929	3.041
Construction (long)	120.00	150.00	50.650	2.3848

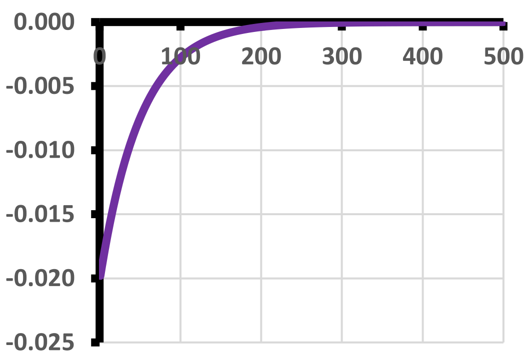
APPENDIX 3: DECAY FUNCTIONS USED FOR THE CARBON MODEL

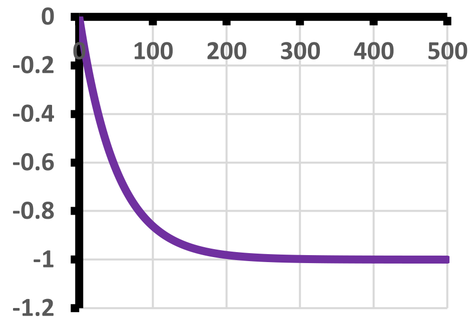
Linear decay



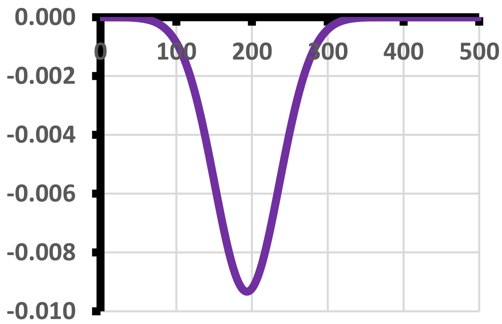


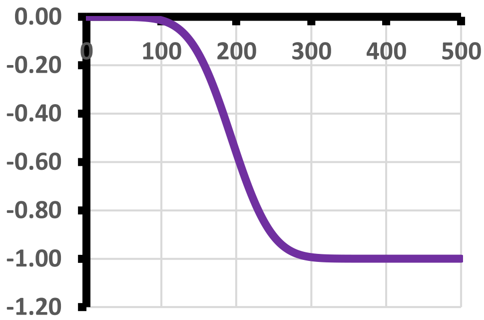
Exponential decay





Normal distribution





Gamma function