Re/genT Note[1]:15423 / CE15 / V2	Technical Note
Project	Ecodesign & Labelling Review Household Refrigeration, preparatory/review study
Subject	CECED Comments to Interim report (14.11.2015); Topic: technical model chapter 9
Date	7-12-2015
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To	CECED WG Cold and VHK

1. Introduction

1.1. Document revision history

Release date	***Author***	***Version***	***Remark / document change***
5/12/2015	MJ	D1	First draft for internal discussion with ad-hoc group
7/12/2015	MJ	V1	Update after comments from ad-hoc group
8/12/2015	MJ	V2	Update on appendix 1 for the combi heat load calculations with respect to the distribution of wall thicknesses between fridge and freezer part.

1.2. General

The EU commission, DG Energy has ordered a review study of current eco-design requirements (regulation 643/2009) and labelling (delegated regulation 1060/2010) for cold appliances. A study team lead by VHK, the Netherlands, has presented a second interim report (dated 14-11-2015) which is to be discussed in a second stakeholder meeting, planned to be held in Brussels, 14-12-2015.

This notes collects observations from CECED, based on an analysis performed on the technical model used in chapter 9 of the report and discussions in a WG Cold meeting, Milan, 3-12-2015.

The method of choosing a technical model in combination with statistical methods rather than just statistical data for setting new reference lines is welcomed by CECED. There is indeed significant bias in current product data as appliances have been optimised towards existing reference lines and energy classes.

From an analysis of the technical model, following observations are made, which are further discussed in this note:

a) The basis of the technical model is correct, though it is recognised that due to its simplifications, it may not always respond properly to input changes.

[1] *The last digits refer to the version number of this note*

b) A few errors were found in the volume and area calculation for which corrections are listed in this note.
c) Specifically for the combi products, the technical model does not address properly the heat exchanger temperatures.
d) The proposed reference line in the report does fit with the technical model results for category 1 (fridge) and category 8 (freezer) but not for the combi.

2. Issues with the technical model

2.1. Appliance volume and area

The original formula's are:

$$V_{rf} = (w-2t)\cdot(d-2t)\cdot(h-a-2t) - b^2\cdot w$$

$$A_{rf} = 2\cdot(w-t)\cdot(d-t) + 2\cdot[(h-t-a)\cdot(d-t)-(b+0.5t)^2] + 2\cdot(w-t)\cdot(h-t-a)$$

Which needs correction to:

$$V_{rf} = (w-2t)\cdot(d-2t)\cdot(h-a-2t) - b^2\cdot(w-2t)$$

$$A_{rf} = 2\cdot(w-t)\cdot(d-t) + 2\cdot[(h-t-a)\cdot(d-t) - b^2] + 2\cdot(w-t)\cdot(h-t-a)$$

Both are relatively small corrections.

A larger error is found for the combi appliance where the surface area calculated is too large (it seems that two times the separator wall area seems to be included, while the separator should be entirely excluded)[2]. This results in too high heat losses of the combi.

Further the method for using an average temperature for a combi based on volume ratio's is not so accurate. There are two issues here:

a) The heat load is proportional to the surface area ratio rather than volume ratio.
b) In praxis fresh food compartments are less insulated than frozen food compartments[3].

The model is extended by calculating the fresh food and frozen food compartment surface areas separately. Further a ratio has been defined between the wall thicknesses of the fresh food compartment and the average wall thickness[4]. The equations are given in appendix 1.

2.2. Wall thickness

The wall thicknesses in the model have been taken from the data base analysis presented in chapter 10 where wall thicknesses have been reconstructed from

[2] In principle the surface area for the combi should be the same as for the single door appliance with the same height, width, depth and wall thickness.
[3] For a combi, it is possible to optimise the foam given a certain foam quantity. This results in thicker insulation at the coldest compartments.
[4] This ratio can be optimised with the model itself. If this is done for an appliance with 73 % fresh food volume, a thickness ratio of 0.84 has been found.

appliance properties present in the CECED data base[5]. In the technical model not the average values have been used but roughly the higher end values found (from 10 to 20 mm more wall thickness depending on the product). This is not wrong, but means that the model represents already well insulated products.

There are a number of issues to consider:

a) Especially for larger appliances, often elements are included which reduce the net storage volume (e.g. door features, ice makers, etc.) which may get translated into wall thickness by the method used.
b) Appliance production is mostly based on platforms where products with different volumes only have different heights (so shelves, baskets, etc. can be shared) and maintain the same thickness.
c) For built-in the option to increase wall thickness with volume increase is much more limited.
d) The fact that larger appliances are on average more insulated is indeed partly due to the fact that more space is available (as listed in the report) but partly also due to current regulations, so in fact some of the bias present in the market is then copied back into the model.

The fact that the input of the model uses an increasing wall thickness at increasing volumes rather than a constant wall thickness, means that products at different sizes are not compared any more at equivalent technology levels, i.e. one of the obvious energy saving options (increase in foam) has then already been used for the larger sized appliances. To use a wall thickness as a function of volume is on itself not wrong; it just needs recognition of the above considerations and that it is actually more a policy parameter than a technical parameter.

In some of the calculations, the wall thickness of the largest appliances was set too high. This can also be shown by calculating the optimal wall thickness which is the point where any further increase in wall thickness reduces the volume more than the reduction in heat loss. The parameter to minimize is then the specific heat loss[6] in W/dm^3. In general, the wall thickness should be kept smaller than this minimum value as increasing it to the exact minimum is inefficient in terms of material use.

A further constraint for wall thicknesses is the foaming process where any thickness larger than 100 mm is difficult to handle (process itself and duration).

2.3. General

This note is accompanied with a spreadsheet model, which contains the model as proposed in the report together with the proposed modifications.

3. Category 1

The following modifications are suggested to the model:

a) Correction of area and volume

[5] Note that the CECED database does not contain wall thickness as a parameter, the reconstruction is based on comparing external volume (can be defined by height, width and depth properties) and net storage volume. The accuracy of this method is limited.

[6] This can easily be done with the technical model using the excel solver, select the specific heat loss as the parameter to minimise and the wall thickness as the parameter to vary.

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b) The wall thickness of appliance 4 has been reduced from 70 to 65 mm. The spreadsheet contains the 70 mm data as well (Column 4A) which has 4.9 % less volume and 5.9 % more consumption. (The specific heat loss is practically the same). Column 4B has been added using the optimal wall thickness, being 82 mm in this case. For similar reasons the wall thickness for appliance 3 has been reduced from 53 mm to 50 mm.

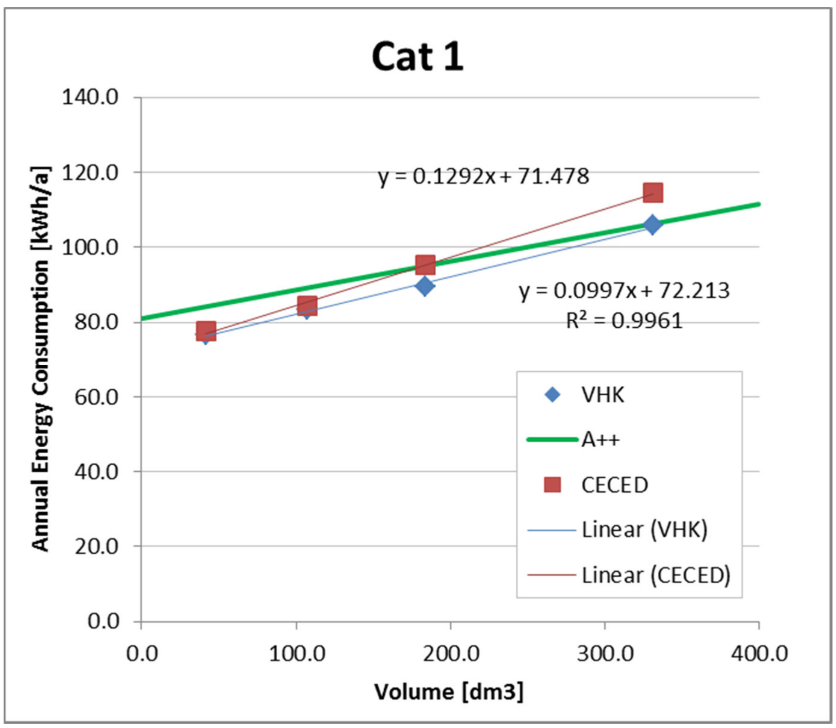
c) Nominal cooling capacity has been made a function of product size. All these products should have to match highest ambient spec. which requires different capacities for each.

Other remarks (issues noted, but left unchanged):

a) Nominal COP values have been kept the same, though typically the smaller appliances would have a lower COP value.

b) Evaporation temperatures, especially for the large size are quite ambitious and are certainly only present on high efficient appliances.

Next figure shows the report data ("VHK") and the results using the modifications ("CECED"). The effect is a small change in the reference line. For comparison the A++ line is drawn, showing that the evaluation has led to products more or less on the A++ line. The increased inclination compared to the A++ line is very realistic as today reference line is unrealistically flat for refrigerators.



4. Category 8

The following modifications are suggested to the model:

a) Correction of area and volume

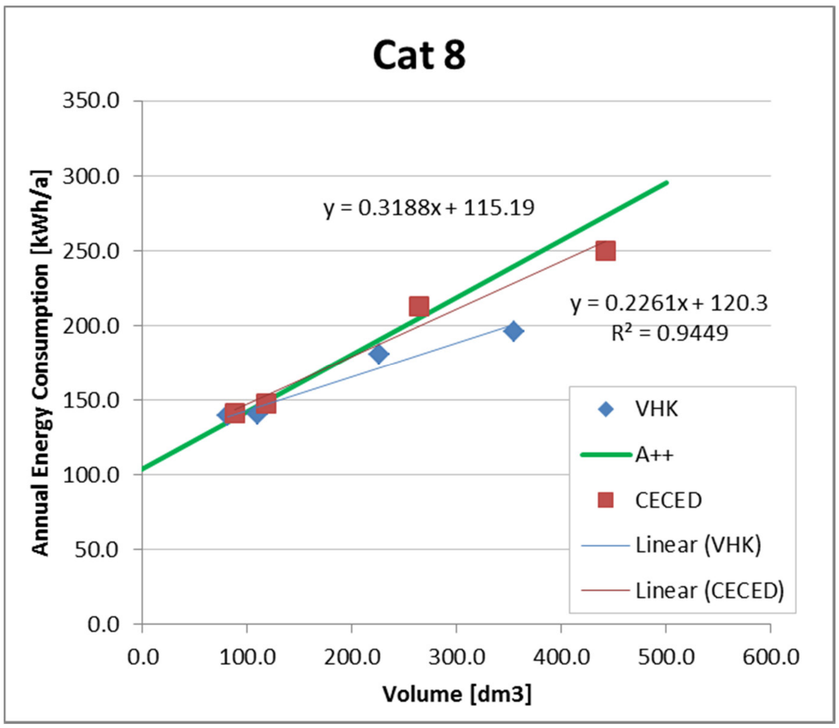
b) The wall thickness of appliance 3 and 4 has been limited to 100 mm. For reference a column 4A has been added with 120 mm. This wall thickness results in more volume loss than input power reduction. The optimal wall thickness has also been calculated here (111 mm) and is shown in column 4B.

c) The condensation temperature differences have been increased except for appliance 1. The original values ranged from 11 to 6 K. At such low values the heat transfer for natural convection reduces considerably. Forced convection for this type of appliance and of this efficiency level (A++) is not common. The proposed values are from 11 to 9 K, which still must be considered highly efficient condensers.

Other remarks (issues noted, but left unchanged):

a) Nominal COP values have been unchanged, but note that for appliance 4 a very high efficient compressor has been used (COP=1.9).

Again, a figure is shown with the report data and the results using the modifications. Compared to the VHK data the modifications result in a steeper curve, which is believed to be more realistic. Compared to the current A++ line the curve is somewhat more flat.



5. Category 7

The more problematic category is formed by the combinations. These cannot be seen as simple additions of separate appliances as properly discussed on page 98 and page 99 of the report where the synergy effects are correctly listed and a number of possible benefits are explained. As mentioned for type I products (single control) the synergy effects are limited and proper operation over a wide ambient range requires additional elements such as a heater. For type II products (double control) it is mentioned that there are different options:

1. Two compressor systems: the report correctly mentions that these have the drawback of lower compressor efficiency at the low capacity levels.
2. Compressor + solenoid system: here it needs mentioning that, in contrast to the report, these are not typically using "consecutive regulation" of the compartments. Typically the solenoid valve swaps the system between running through fresh food and frozen food evaporator (in series) or only through the frozen food evaporator (using a cap tube which bypasses the fresh food evaporator). The reason for this are twofold:
    a. The refrigerant charge: if the system would run only on the fresh food evaporator the required refrigerant charge would be typically very different from the charge needed to run only the freezer, resulting in inefficient operation. A second complication is that liquid refrigerant would migrate to the freezer evaporator during fresh food mode operation.
    b. The compressor capacity would be much too large to run only the fresh food, resulting in inefficient operation.
3. As a consequence of this, these systems operate with an evaporation temperature always below the freezer compartment temperature, also during what is called the "fresh food" mode operation[7].
4. Using a variable speed compressor in a solenoid system does not solve the principle problem of the refrigerant charge, so most systems with variable speed compressor operate in the same way (so either fresh food + freezer or only freezer).

In the technical model discussion on page 100 it is mentioned that simplified modelling of a combi appliance is the most difficult, which is confirmed. The first approach has been to assume that the system can be presented by a single compartment appliance operating at an intermediate temperature level (e.g. -1 C for a product with 75 %/25% volume share of fresh food and frozen food respectively). Due to the reasons listed before, this will predict evaporator temperatures above freezer compartment temperatures and thus unrealistic low energy consumption values. The second alternative is to calculate the energy consumption of fresh food and frozen food as if it were separate products and use a multiplication factor of 0.8. Also here, the same problem arises as the fresh food compartment would operate with higher evaporation temperature in the model than in praxis achievable.

Here following modifications are suggested to the model:

a) Correction of area and volume
b) The wall thickness of appliance 4 has been reduced from 85 to 70 mm. 85 mm on average for a combi is too close to the optimum or even above it. Due to this reduction, appliance 4 became uncommonly large in volume. Therefore, the width and depth have been reduced from 800 to 700 mm. The wall thickness of appliance 2 has been changed from 65 mm to 60 mm. This has only been done as the 60 mm fits better between appliance 1 and 3 (the volume of 2 is namely close to the volume of 1).
c) In the model in the report, the compartment temperature has been volume rated using -20 C en +4 C as target (which differs from the other categories).

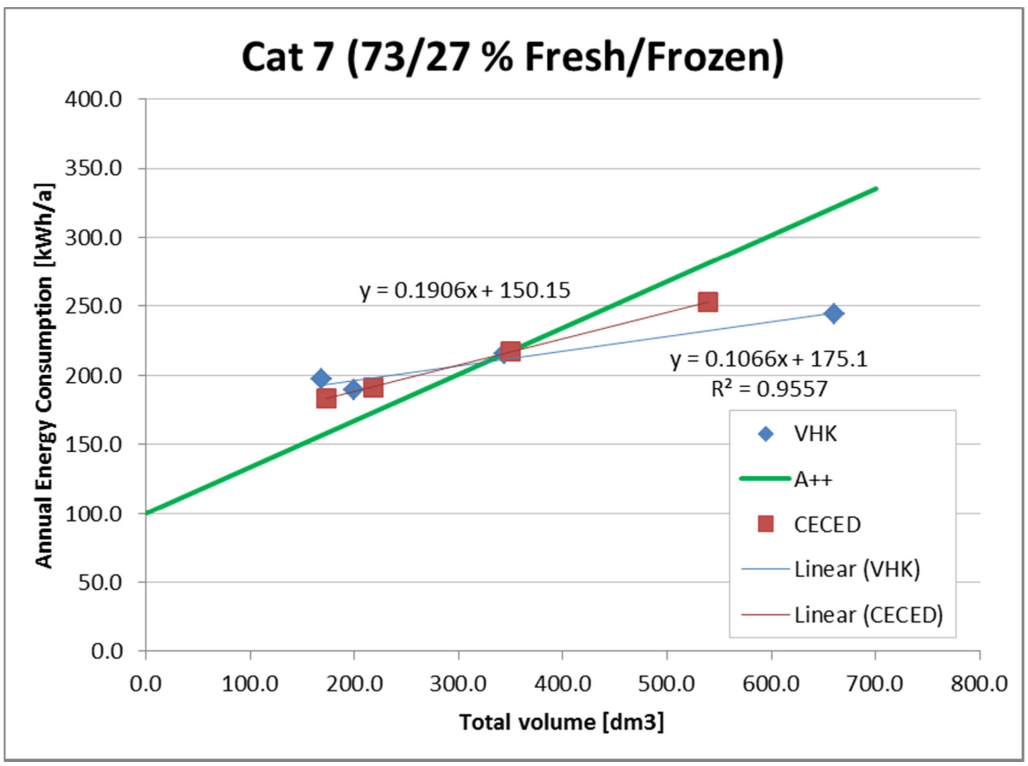
[7] The term "fresh food mode" is somewhat misleading for these appliances as in this mode both the fresh food and frozen food compartment are being cooled. However, depending on refrigerant charge/ evaporator design, the largest fraction of the cooling power may go to the fridge during this mode.

The average compartment temperature is then used for the heat loss calculation. In chapter 2.2 it has been mentioned that this may not be accurate and a model modification is suggested which takes into account the different areas of the compartments and their different wall thicknesses.

d) The evaporation temperatures have been set directly. The average temperature difference in the model is difficult to handle as neither compartment evaporators operate at this temperature difference. This becomes very clear when e.g. the fresh food volume ratio is changed to e.g. 50 %. The model in the report would reduce the evaporation temperature significantly, while in praxis similar evaporation temperature prevail on a product with 50 % fridge as with 80 %. The evaporation temperatures have now been set from -26 to -23 C, the reason for this temperature level has been explained before.

e) The condenser temperature difference was also scaled in the model, but here this temperature difference is only influenced by the heat the condenser has to reject. Temperature differences of 13 to 10 K have been used which are lower than in the model in the report and more in line with the other categories.

Next figure shows the report data (“VHK”) and the results using the modifications (“CECED”):



Compared to the VHK data the curve is now more steep, bit still significantly flatter than the current A++ curve, so larger appliances are penalised compared to today.

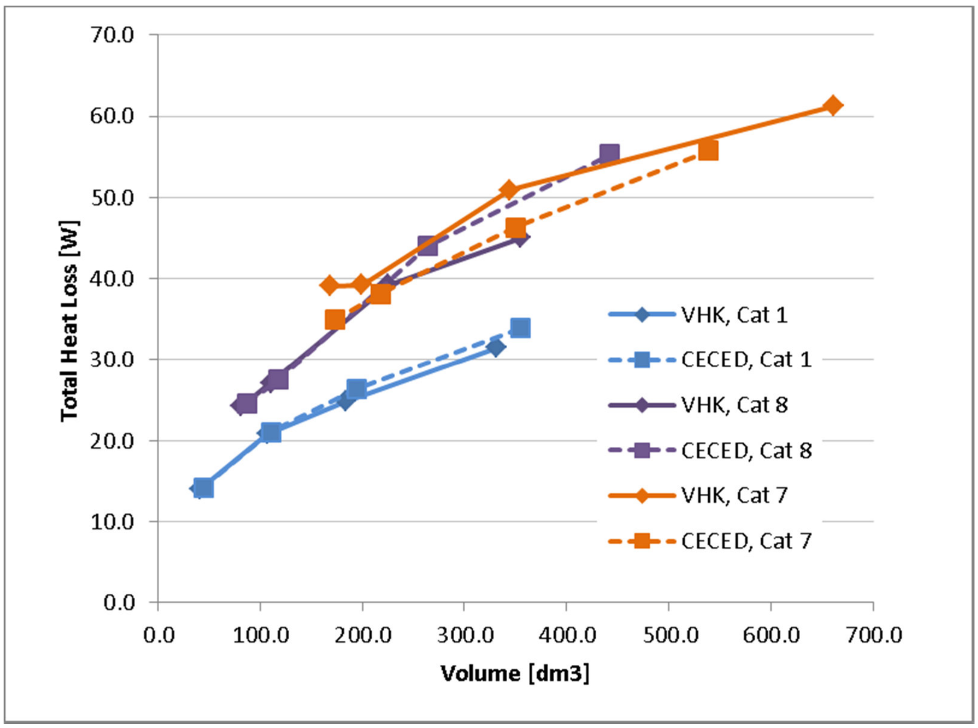
6. Considerations on heat loss and wall thicknesses

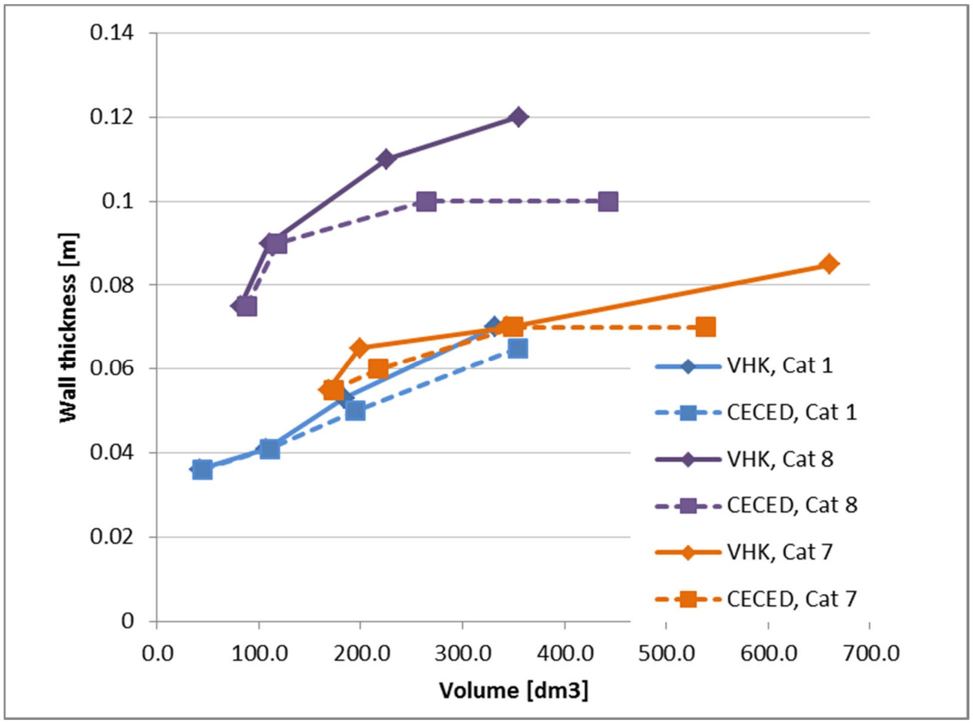
The next figure below shows all heat losses calculated for the model in the report (“VHK”-solid lines) and for the modified model (“CECED”-dashed lines) as a function of total volume. A second figure shows the wall thickness used.

From the heat loss the VHK model showed a higher heat loss for the combi product than a freezer at the same volume. This is for the larger part due to the error in the area calculation of the combi.

In the CECED model data the combi product is more in between the freezer and fridge. The values are still high and for the smaller volumes even close to the freezer data. This is mainly due to the following points:

a) The combi has more external surface area (e.g. needs to be higher than a freezer with the same internal volume due to the separator).
b) Perimeter losses increase due to the two doors.





The chart above shows the wall thicknesses as applied in the model, it needs mentioning that the values given here are typical for free standing appliances but difficult to meet for built-in.

7. Reference line

In the report regressions are made for category 1 and 8 which are subsequently used in a common reference line. Also regressions are made for category 7 but these are not used in the reference line, as category 7 should be based on coefficients for fresh food and freezers plus a correction for the combination.

Here the model presented in the report is unclear as has been communicated earlier. The model presented also does not fit to the technical data, at least not for category 7.

The basis of the reference line as presented in the report is that it can be composed from a summation over the different compartments and a correction factor for combi's. In standard energy form this is straightforward:

$$SAE = D\sum_{c=1}^{n} A_c B_c C_1 (r_c M_c V_c + N_c)$$

Note that the coefficient C_1 should not correct for volumes as the net volume of each compartment is already implemented in the formula.

A formulation in terms of q is also feasible but note that adding compartments means that the individual q terms must be multiplied by the individual volumes, then summed and then divided by the total volume.

From the SAE equation, it is possible to make a formula in q form by dividing through *V*:

$$q_{ref} = D \sum_{c=1}^{n} A_c B_c C_1 \left(\frac{N_c}{V} + r_c M_c \frac{V_c}{V} \right)$$

The combi factor can also be expressed with a volume fraction inside by using:

$$C_c = C_1 \frac{V_c}{V}$$

The q-ref formula then becomes:

$$q_{ref} = D \sum_{c=1}^{n} A_c B_c C_c \left(\frac{N_c}{V_c} + r_c M_c \right)$$

Which is very close to the formula in the report, except for the division by V_c rather than *V*.

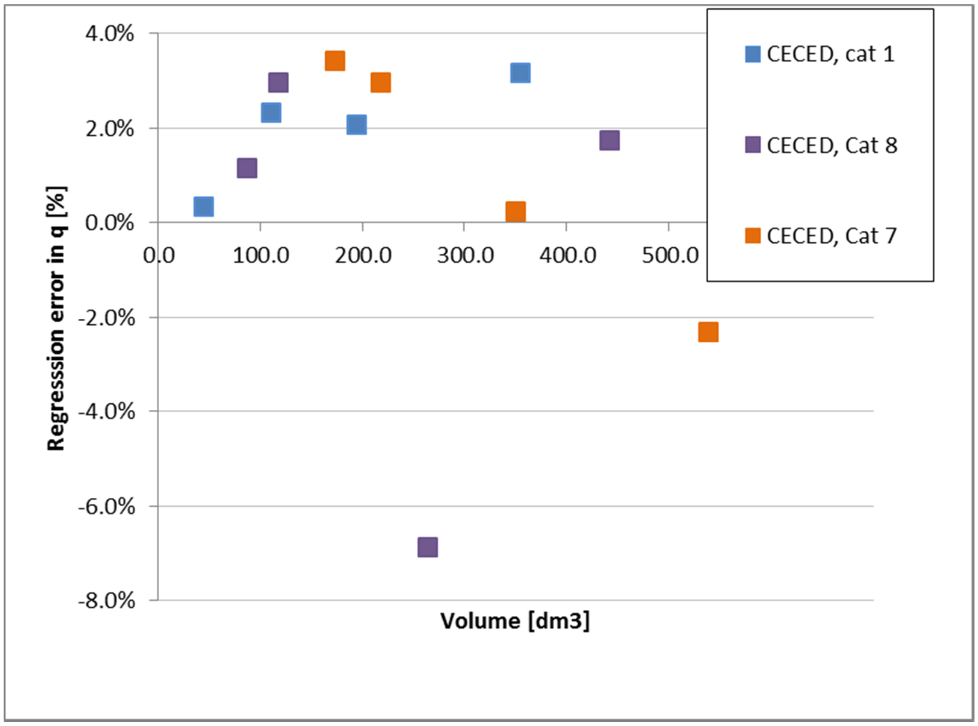
As q-ref shows better the effect that the larger appliances need to be significantly more efficient per litre than smaller ones, it is agreed to use this formula.

8. Regression of the reference line

If the reference formula of the previous chapter is used in combination with the suggested model modifications discussed earlier then the parameters M and N can be taken from the regression of the technical model for category 1 and 8. This gives the following coefficients:

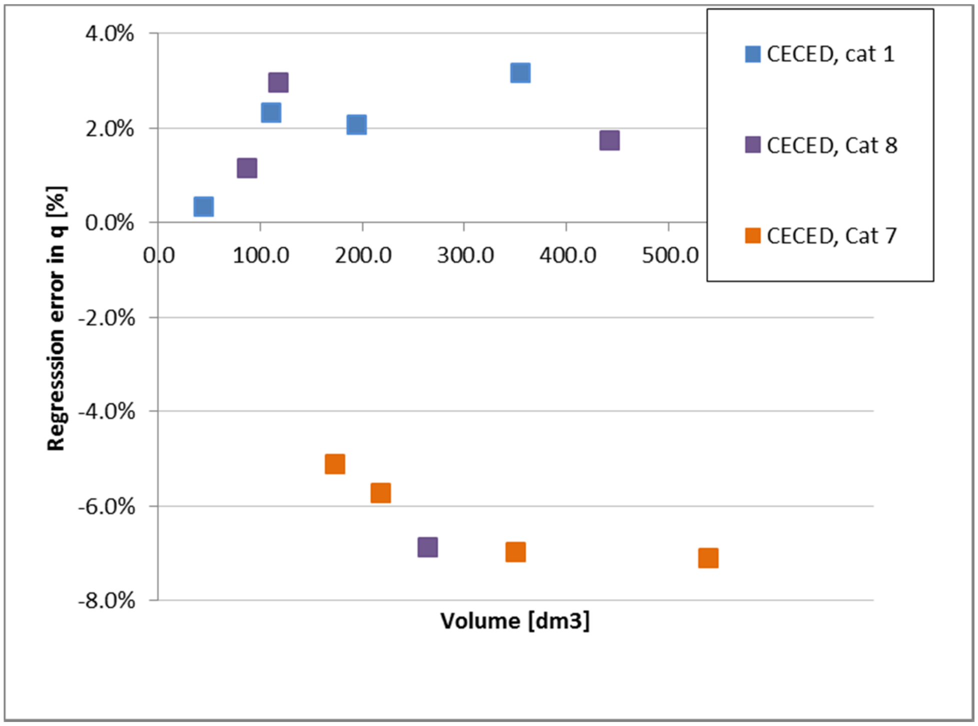
M fresh	0.13
Nfresh	72
Mfrozen	0.150 (obtained from 0.32/2.15)
Nfrozen	115

Then a fitting is also needed for the combi-factor. Here a value of 0.87 was used for C_1. This resulted in the following error diagram:



Note that this regression is then done for a product range with 73% fresh food volume fraction.

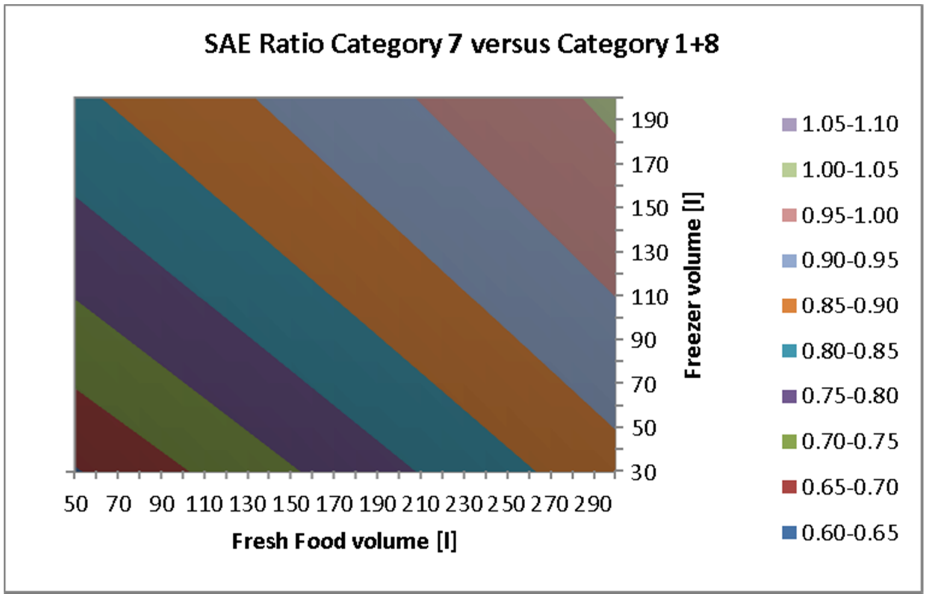
For other volume ratio's the model can be applied and compared to the regression. E.g. when this is done for a product range with 50 % fresh food volume (which is probably an extreme case already), the following diagram results:



This shows that for such products the reference curve predicts 6 to 7 % lower consumption values than the model, or in other words, such products need to be 7 % more efficient to obtain the same efficiency class. The opposite is the case for products having a higher fresh food fraction than 73 %.

In fact the issue above shows that the temperature correction factor used in the formula is an approximation only of the processes involved.

On itself this issue above is of concern, but also today the reference formula gives quite different results if the SAE is evaluated for separate fridges and freezers and compared with a combi appliance having the same volumes as shown in the following diagram:



A second shortcoming results if other compartment temperatures are used then fresh foods or freezers. An extreme case is when a combi with two fresh food compartments or with two frozen food compartments four star are calculated. In principle the ratio between the combi reference line and two separate ones would simply be the coefficient C_1. Such product would therefore have to consume 13 % less to get similar efficiency rating, which is probably still realistic due to the reduction in heat loss and the increase in available surface area for the heat exchangers.

The other extreme is to combine e.g. a pantry with a freezer. Model calculations have been performed which are included in the workbook with exactly the same appliance as for the combi fresh food/freezer. The only difference is that the wall thickness ratio of pantry compartment versus the average has been set to 0.68 which delivered the minimum heat load. The model then predicts roughly 30 % reduction in consumption compared to the combi with fresh food. This corresponds largely to the reduction in heat loss.

The reference line changes only very little (from 5 to 10 %) between the combi with fresh food and the one with pantry. This is caused by the fact that M and N values are used of the fresh food compartment and the temperature correction factor is not able to compensate fully for the pantry temperature. This effect can more easily be seen for a single door product. E.g. for a fresh food appliance of 200 litre the SAE value is 1*0.13*200+72 = 98 kWh/y. For a pantry this would be 0.35*13*200+72= 81 kWh/y, so approximately 20 % less, while the heat load is 60 % less than for the fresh food appliance. Note that this effect is also present in today standard annual energy equations.

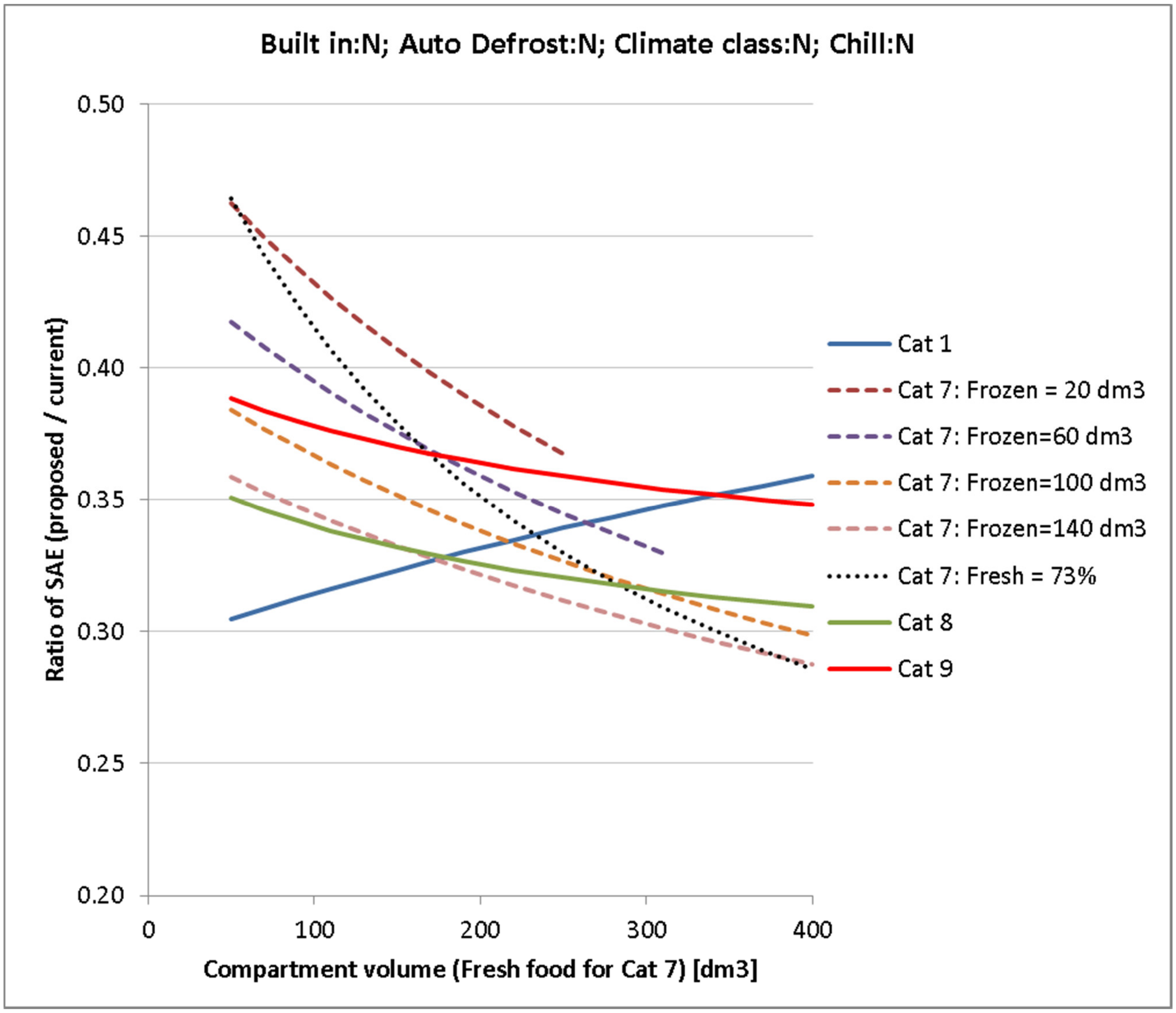
With respect to the reference line, some further work is needed:

a) The reference line does not fit well to other volume ratios than the one used for the regression.

b) The reference line does not compensate for other temperatures levels. Note that this may not be an issue only for combination appliances, but also for single door products.
c) Some more evaluations are needed on combination appliances with 3 or more compartments.

9. Comparison of proposed reference line with actual reference line

It is possible to evaluate the new reference line with current references. This is done for all categories in the next figure:



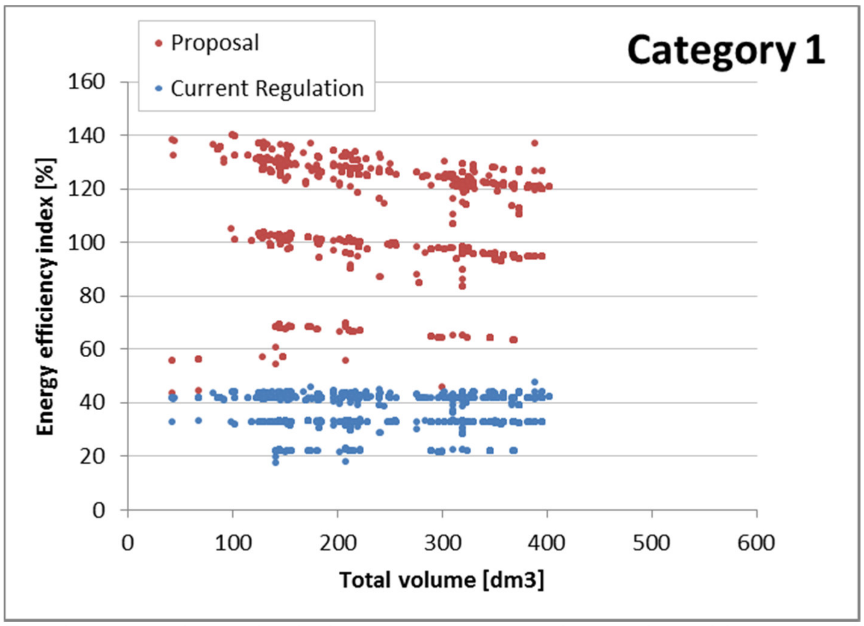
Taking the current A++ level as reference (ratio = 0.33), one can conclude the following:

a) Some relaxation for larger fridges, which is realistic given the much too low inclination of the reference line today. In fact, the technical model demonstrates this.
b) Somewhat more stringent requirements for large freezers.

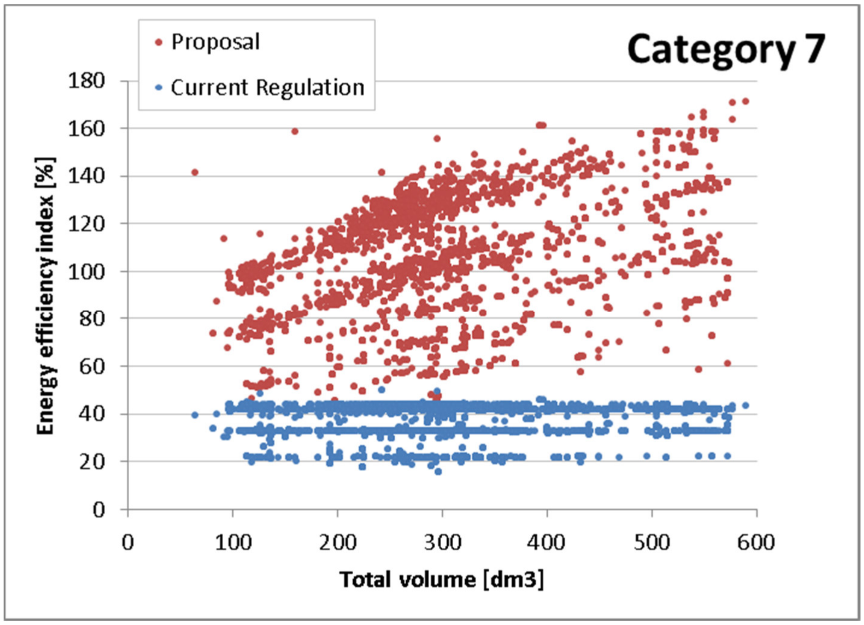
c) Chest freezers are relaxed compared to upright freezers, which is realistic given their lower energy consumption.
d) The large combi appliances will have much more stringent requirement compared to the small ones, though less than in the original analysis presented in the report.

10. Consequence on actual appliances

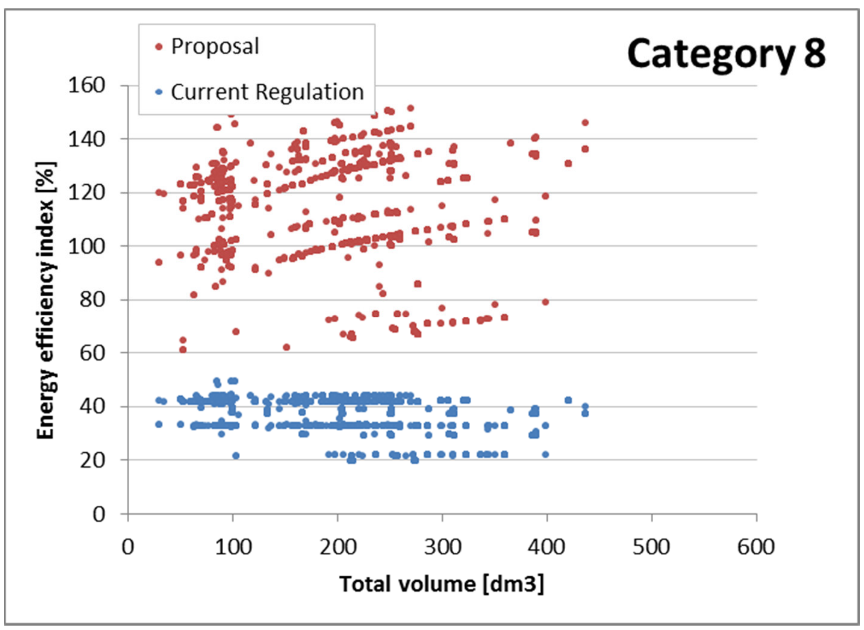
Using the above definition of the reference line it is possible to plot the energy efficiency index as a function of total volume and compare this to the actual energy efficiency indices. This is done using the CECED database 2015 (listed as database 2014 within CECED). Separate figures are made for cat 1, 7, 8 and 9. In all cases the compensations as listed in the report have been applied (note that this means that no compensation is made for chill compartment or climate class). Further the energy consumption has not yet been corrected for the new global standard.

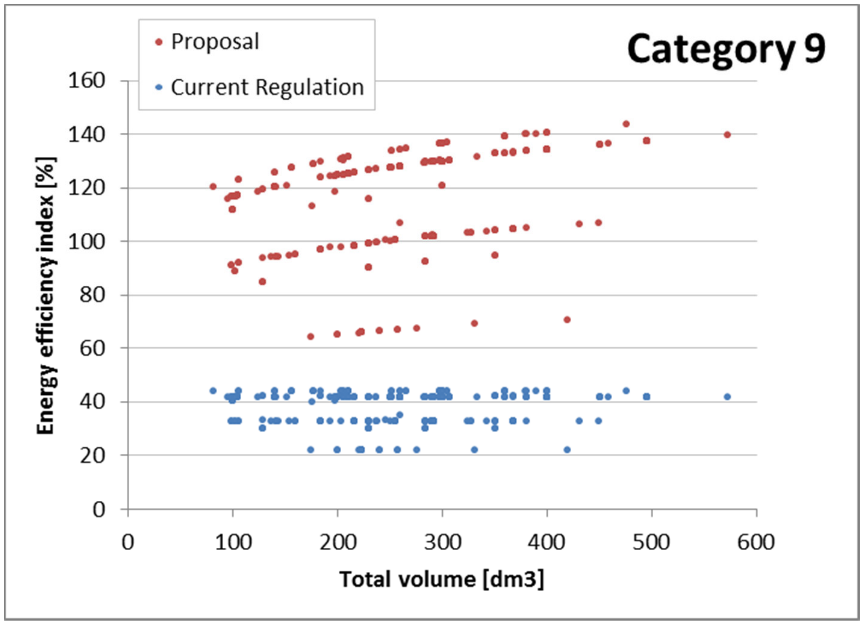


For these products the index 100 corresponds roughly with current A++ appliances. However, using the new standard the consumption will increase.



The final result on category 7 show a steep increase as function of the volume. A limit at index 100 would cancel out all current A++ appliances with a total volume larger than app. 250 litre (uncorrected for the global standard).





So also for category 8 and 9 the larger appliances will move more up in index than the smaller ones.

Appendix 1: Heat load model for combinations

To calculate the volumes and areas for a combi with a fresh food on top and a frozen food at the bottom, the following formulas have been applied:

$$V_s = (w-2t)(d-2t)t$$
$$V_{FF} = (w-2t)(d-2t)(h-t-h_s) - 0.5V_s$$
$$V_{FR} = (w-2t)(d-2t)(h_s-a-t) - b^2(w-2t) - 0.5V_s$$
$$A_{FF} = (w-t)(d-t) + 2(h-0.5t-h_s)(d-t) + 2(w-t)(h-0.5t-h_s)$$
$$A_{FR} = (w-t)(d-t) + 2[(h_s-0.5t-a)(d-t)-b^2] + 2(w-t)(h_s-0.5t-a)$$

Where V_s is the separator volume and h_s is the height at the separator position (average height measured from the floor). FF = fresh food and FR= frozen food.

To calculate the heat loss, it has further been assumed that the fresh food compartment is less insulated than the frozen food. Here the following formula is applied:

$$t_{FF} = 0.84t$$

The resulting frozen food average wall thickness can then be found from the following equation which assumes that the total foam volume is the total surface area multiplied by the average wall thickness.

$$At = A_{FF}t_{FF} + A_{FR}t_{FR}$$

With the model it is then actually possible to optimize the foam distribution between fresh food and frozen food. From this optimisation the value of 0.84 has been found, which resulted in the minimum heat load for a combi fresh food plus frozen food with a split of 73%/27%. Note that this parameter changes for other volumes and for other temperatures than fresh food / freezer combinations. This requires some further work.

The total heat load is then calculated as follows:

$$Q = \frac{k}{t_{FF}} A_{FF}(T_{amb-}T_{FF}) + \frac{k}{t_{FR}} A_{FR}(T_{amb-}T_{FR})$$