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Energy savings for a wood based modular pre-fabricated façade refurbishment system compared to other measures

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Abstract

There is a need to focus on energy efficiency for the existing buildings, especially buildings erected before the energy crises in the seventies, as these buildings provide a massive potential for improvements in energy performance. The facades of these buildings are also facing an increased need for a face-lift. There are a large number of such facades in all these countries. One problem is that these buildings must be refurbished at low costs and with limited disturbance to the users/tenants. In this study we have investigated the energy efficiency of a modular pre-fabricated façade refurbishment system based on wood and compared it to two existing systems for on-site mounting of additional insulation. These existing alternatives require a lot of on-site works. Hence pre-fabricated solutions would, of course, offer advantages. There have been several attempts to develop such solutions in recent years but so far none of them have provided an acceptable solution. This approach is based on an alternative with small scale prefab elements with a simple assembly process. The energy analyses concentrate on thermal bridges and U-values, relating it to the total energy performance and compared to the current situation and comparable refurbishment methods. We have mainly focused on the wall structures but as a comparison also other energy saving measures has been investigated shortly. For the very common reference building the pre-fabricated solution is the third most effective energy measure. We have also conducted a study of the energy efficiency regulations in different Nordic countries in order to see what the current legal framework is, and tried to sort out how far it is possible to improve energy efficiency by means of improving the U-value of the exterior walls. The outcome is a verification of the energy efficiency of the chosen prefab structure as a solution for refurbishment. The advantages are to be found in the dry production process combined with a simple and fast assembly on site. Similarly there are advantages in the reduced number of thermal bridges and in the potential for the use of recyclable materials. Another advantage is that it has an integrated air tightness that is mounted on the outside of the existing wall. This is part of a larger research project aiming at cost efficient and sustainable solutions for refurbishment of facades in a Nordic context. In the larger research project we have also

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conducted a cost-benefit analyses and studied moisture conditions in order to see how far this solution might be feasible. The ultimate aim is to test a product and compare the findings from demo projects in the three countries Norway, Sweden and Finland.

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Keywords: pre-fabricated, refurbishment, wood, facade element, energy saving, thermal bridge

1. Introduction

There is a need to focus on energy efficiency for the existing buildings, especially buildings erected before the energy crises in the seventies, as these buildings provide a massive potential for improvements in energy performance. The facades of these buildings are also facing an increased need for a face-lift. One problem is that these buildings must be refurbished at low costs and with limited disturbance to the users/tenants. In this study we have investigated the energy efficiency of a modular pre-fabricated façade renovation system based on wood and compared it to two existing systems for on-site mounting of additional insulation. These existing alternatives require a lot of on-site works. Hence pre-fabricated solutions would, of course, offer advantages.

The prefab element only consists of an inner and an outer laminated board with insulation in between, interconnected with thin wooden bars. The amount of insulation can be increased but this analysis is limited to 50-150mm of added insulation, as a complement to an estimate of 100mm in poorly insulated buildings from the sixties and the seventies. Thus it is estimated that one can reach current levels of U-values which is found feasible in recent research regarding larger housing blocks [1]. The most common façade refurbishment solution today, in the Nordic countries, is based on plastered insulation, which is not suited for wooden substructures as it poses a well-known risk of moisture damages. There are a large number of such facades in all these countries. The alternative would be on-site works, but prefabricated solutions would, of course, offer advantages. There have been several attempts to develop such solutions in recent years (TES [2], smartTES [3], etc.) but so far none of them, based on their market share, seem to have provided an acceptable solution. This approach is based on an alternative with small scale prefab elements with a simple assembly process.

The energy analyses concentrate on thermal bridges and U-values, relating it to the total energy performance and compared to the current situation and comparable refurbishment methods with wooden structures. We have mainly focused on the wall structures but as a comparison also other energy saving measures has been investigated shortly. We have also conducted a study of the energy efficiency regulations in different Nordic countries in order to see what the current legal framework is, and tried to sort out how far it is possible to improve energy efficiency by means of improving the U-value of the exterior walls. It seems that both the regulations and the researchers [1] have come to similar conclusions regarding a feasible U-value for façade refurbishment, i.e. a U-value around 0.17-0.18 W/m^2K.

The outcome is a verification of the energy efficiency of the chosen prefab structure as a solution for refurbishment. The advantages are to be found in the dry production process combined with a simple and fast assembly on site. Similarly there are advantages in the reduced number of thermal bridges and in the potential for the use of recyclable materials.

This study is part of a larger research project aiming at cost efficient and sustainable solutions for refurbishment of facades in a Nordic context. In the larger research project we have also conducted a cost-benefit analyses and studied moisture conditions in order to see how far this solution might be feasible. The ultimate aim is to test a product and compare the findings from demo projects in the three countries Norway, Sweden and Finland.

Nomenclature

A_{om}	Total surface area of the building envelope facing the heated indoor air (m^2). The building envelope refers to the structural element that separates heated parts of dwellings or non-residential premises from the outdoor, the ground or partially heated spaces.
A_{temp}	The area enclosed by the inside of the building envelope of all storeys (m^2), including cellars and attics for temperature-controlled spaces, intended to be heated to more than 10 ºC. The area occupied by interior walls, openings for stairs, shafts, etc., are included.
E_{spec}	The building's specific energy use (kWh/m^2a) is the building's energy use divided by A_{temp}. Household electricity is not included.
U_m	The average thermal transmittance (W/m^2K) for the building envelope including thermal bridges.
U	Thermal transmittance (W/m^2K) for a part of the building envelope.
q_{n50}	The air tightness (l/sm^2) is the air leakage through the building envelope at 50 Pa pressure difference divided by A_{om}.
ΔE_{spec}	The specific energy saving (kWh/m^2a) compared to a reference case.
Ψ	Thermal transmittance (W/mK) for a linear thermal bridge.

2. Purpose

The purpose of this study is to evaluate the energy savings of a wooden prefab facade element compared to two different conventional on-site façade refurbishment solutions, but also to compare the energy savings with other types of refurbishment options, i.e. new windows, additional insulation of attic floor, ventilation heat recovery, etc. Another objective has been to study the influence of thermal bridges around the window fastenings.

3. Method

A typical low rise multi-family building from the period 1965 to 1975 is chosen as a reference building. It is a two story high building with 12 apartments. It has a concrete frame with infill walls (wooden studs and insulation) on the long sides. The windowless short sides consist of concrete, insulation and bricks. The windows, the wooden paneling on the sides and the bricks on the short sides are in poor condition and in need of replacement. The building has exhaust ventilation without heat recovery and the airtightness of the building envelope is poor. There are more than a million apartments in the Nordic countries built in a similar manner and in need of refurbishment.

Fig. 1. The model of the reference building used in the energy calculation program.

The reference building has been modeled in an energy calculation program and the specific energy use calculated. The influence on the specific energy use for three different façade refurbishment systems has been calculated:

- 50 mm thermal-bridge-breaking on-site mounted additional isolation (total U-value 0.26 W/m^{2}K)
- 100+50 mm on-site mounted additional insulation (total U-value 0.18 W/m^{2}K)
- A modular pre-fabricated façade renovation system (total U-value 0.18 W/m^{2}K)

The first system is the simplest but it does not meet the recommended U-value for refurbishment in the Nordic countries. Both the second and the third system meet the recommended U-value for refurbishment according to the Swedish building code [2]. For all three systems two different thermal bridge values has been used, corresponding to a good and a less good mounting of the window frames. For the second and the third system detailed calculations of the linear thermal bridges has been performed. For the 50 mm system the thermal bridge values has been estimated from values given in the literature. The same applies to all other thermal bridge values used in the calculations.

The influence of other types of refurbishment options, i.e. new windows, additional insulation of attic floor, ventilation heat recovery and building envelope air tightness, has also been calculated. Recommended U-values for refurbishment according to the Swedish building code [2] has been used for new windows and additional insulation of attic floor.

Energy calculations for the three façade refurbishment systems together with different thermal bridges around the windows has been performed for the reference building both for a case where no other refurbishment options are implemented and for a case where all the other refurbishment options are implemented. In this way one can estimate the maximum sensitivity of the calculated energy savings of the façade systems depending on other energy saving measures.

4. Results

4.1. Calculation of the reference case

Total surface area of the reference building's envelope facing the heated indoor air (A_{om}) is 2092 m^2 and the floor area for temperature-controlled spaces enclosed by the inside of the building envelope of all storeys (A_{temp}) is 1196 m^2. The total floor area of the 18 apartments is 1080 m^2. The remaining 116 m^2 consists of stairways and partition walls. The air tightness (q_{n50}) of the reference building is assumed to be 0.8 l/s and m^2 A_{om} at 50 Pa pressure difference.

The original reference building, Grindstugan, is situated in Vörå in Finland. However, in the calculations climatic data for Umeå in Sweden has been used, having a mean outdoor temperature of +4°C. For initial more detailed calculations the program IDA ICE version 4.7 has been used. To shorten down the calculation time a more simple calculation tool has been used for most of the calculations. It is a beta-version of TMF Energi[†] for calculation of specific energy use in multi-family houses. It has been verified that TMF Energi gives almost the same energy savings for the same energy saving measures as IDA ICE, especially when considering the façade refurbishment systems. All calculations are made assuming the building is either heated with district heating or direct electric heating as these are the most common heating solutions for this type of buildings.

[†] TMF Energi is a calculation tool developed by SP for TMF, the national trade and employers' association of the wood processing and furniture industry in Sweden, for calculation of specific energy use in single family buildings according to the energy requirement in the Swedish building regulations. It has been used for nearly ten years and with good correlation with measured values.

The U-values for the different parts of the building envelope of the reference case are given in table 1 and the Ψ-values (thermal bridges) are given in table 2.

Table 1. U-values for the different parts of the building envelope of the reference case.

	A (m^2)	U (W/K m^2)	UA (W/K)	UA/$(UA+\Psi L)_{total}$ (%)
Roof/attic floor	628.5	0.27	169.7	12.9
Long side walls	474.6	0.50	237.3	18.0
Short side walls	153.4	0.31	47.5	3.6
Windows	181.3	2.80	507.7	38.5
Doors	34.5	2.00	69.1	5.2
Bottom floor	619.3	0.30	185.8	14.1

Table 2. Ψ-values for the different parts of the building envelope of the reference case.

	L (m)	Ψ (W/mK)	ΨL (W/K)	$\Psi L/(UA+\Psi L)_{total}$ (%)
Window	422.7	0.050	21.1	1.6
Doors	109.0	0.050	5.5	0.4
Wall corners	25.3	0.050	1.3	0.1
Wall-Roof	128.0	0.050	6.4	0.5
Wall-Bottom floor	134.5	0.100	13.4	1.0
Wall-Middle floor	262.4	0.200	52.5	4.0

This gives an average thermal transmittance (U_m) of 0.630 W/m^2K and a specific energy use (E_{spec}) of 231.1 kWh/m^2a. Operational electricity is 8.8 kWh/m^2a and district heating is 222.3 kWh/m^2a. The latter consists of 7.3 kWh/m^2a hot water circulation losses, 25.0 kWh/m^2a use of hot tap water and 190.0 kWh/m^2a space heating. Hot water circulation losses and use of hot tap water is assumed to be the same in all the following calculations. The use of household electricity, not included in the specific energy use but part of the energy balance, is in all calculations assumed to be 30 kWh/m^2a. The energy use for hot tap water and household electricity are values for standardized use according to Sveby[‡]. As the building envelope of the reference case is rather poorly insulated the thermal bridges stands for less than 8% of the total U_m-value.

4.2. Calculation of thermal bridges

For all three renovation systems two different linear thermal bridge values has been used around the windows, corresponding to a good and a less good mounting of the window frames. For the 100+50 mm on-site mounted system and the modular pre-fabricated façade refurbishment system detailed calculations have been made in Comsol Multiphysics for the thermal transmittance of linear thermal bridges around the windows. For the 50 mm system the linear thermal bridge values has been estimated from values given in the literature. The same applies to all other thermal bridge values used in the calculations. The thermal transmittance for point shaped thermal bridges has been neglected in the current study. The linear thermal bridges around the windows used in the calculations are given in table 3.

Table 3. Linear thermal bridges around the windows used in the calculations (W/mK).

	Less good	Good
50 mm thermal-bridge-breaking system	0.08	0.05
100+50 mm on-site mounted system	0.076	0.041
Modular pre-fabricated system	0.066	0.036

‡ SVEBY program is the Swedish construction and property sector's interpretation and clarification of the functional requirements on energy set by the National Board of Housing, Building and Planning. Within the program the sector has established standardized user behaviour related input data for energy calculations.

As can be seen in table 3 the windows can be mounted with rather small thermal bridges in all the systems. However, if one is not attentive and careful the thermal bridges may more than double. Figure 2 shows an example of a mounting giving a small thermal bridge in the modular pre-fabricated system.

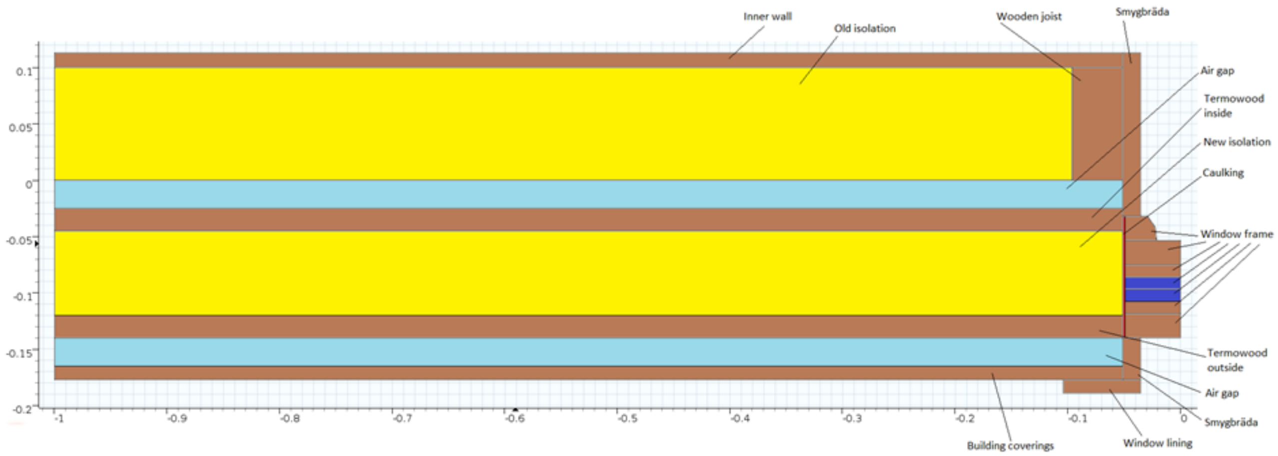

Fig. 2. Example of window mounting in the modular pre-fabricated system with low thermal bridges.

4.3. Calculation for the façade refurbishment systems as the only energy saving measure

For the 50 mm thermal-bridge-breaking system it is assumed that it is only of interest to refurbish the long side walls. The U-values for the different parts of the building envelope are given in table 4 and the Ψ-values (thermal bridges) are given in table 5. This gives an average thermal transmittance (U_m) of 0.575 – 0.581 W/m^{2}K and a specific energy use (E_{spec}) of 215.9 – 217.6 kWh/m^{2}a depending on the thermal bridges around the windows.

Table 4. U-values for the different parts of the building envelope of the 50 mm thermal-bridge-breaking system.

	A (m^2)	U (W/K m^2)	UA (W/K)	$UA/(UA+\Psi L)_{total}$ (%)
Roof/attic floor	628.5	0.27	169.7	14.1-14.0
Long side walls	474.6	0.27	128.2	10.7-10.5
Short side walls	153.4	0.31	47.5	4.0-3.9
Windows	181.3	2.80	507.7	42.2-41.8
Doors	34.5	2.00	69.1	5.7
Bottom floor	619.3	0.30	185.8	15.5-15.3

Table 5. Ψ-values for the different parts of the building envelope of the 50 mm thermal-bridge-breaking system.

	L (m)	Ψ (W/mK)	ΨL (W/K)	$\Psi L/(UA+\Psi L)_{total}$ (%)
Window	422.7	0.05-0.08	21.1-33.8	1.8-2.8
Doors	109.0	0.050	5.5	0.5-0.4
Wall corners	25.3	0.070	1.8	0.1
Wall-Roof	128.0	0.070	9.0	0.7
Wall-Bottom floor	134.5	0.130	17.5	1.5-1.4
Wall-Middle floor	262.4	0.150	39.4	3.3-3.2

For the 100+50 mm on-site mounted system also the short side walls are refurbished. The U-values for the different parts of the building envelope are given in table 6 and the Ψ-values (thermal bridges) are given in table 7. This gives an average thermal transmittance (U_m) of 0.543 – 0.550 W/m^{2}K and a specific energy use (E_{spec}) of 207.4 – 209.3 kWh/m^{2}a depending on the thermal bridges around the windows.

Table 6. U-values for the different parts of the building envelope of the100+50 mm on-site mounted system.

	A (m^2)	U (W/K m^2)	UA (W/K)	UA/(UA+ΨL)$_{total}$ (%)
Roof/attic floor	628.5	0.27	169.7	14.9-14.7
Long side walls	474.6	0.18	85.4	7.5-7.4
Short side walls	153.4	0.18	27.6	2.4
Windows	181.3	2.80	507.7	44.7-44.1
Doors	34.5	2.00	69.1	6.1-6.1
Bottom floor	619.3	0.30	185.8	16.3-16.1

Table 7. Ψ-values for the different parts of the building envelope of the100+50 mm on-site mounted system.

	L (m)	Ψ (W/mK)	ΨL (W/K)	ΨL/(UA+ΨL)$_{total}$ (%)
Window	422.7	0.041-0.076	17.3-32.1	1.5-2.8
Doors	109.0	0.050	5.5	0.5
Wall corners	25.3	0.100	2.5	0.2
Wall-Roof	128.0	0.100	12.8	1.1
Wall-Bottom floor	134.5	0.200	26.9	2.4-2.4
Wall-Middle floor	262.4	0.100	26.2	2.3

Also for the modular pre-fabricated system both the long side walls and the short side walls are refurbished. The U-values for the different parts of the building envelope are given in table 8 and the Ψ-values (thermal bridges) are given in table 9. This gives an average thermal transmittance (U_m) of 0.542 – 0.548 W/m^{2}K and a specific energy use (E_{spec}) of 207.1 – 208.8 kWh/m^{2}a depending on the thermal bridges around the windows.

Table 8. U-values for the different parts of the building envelope of the modular pre-fabricated system.

	A (m^2)	U (W/K m^2)	UA (W/K)	UA/(UA+ΨL)$_{total}$ (%)
Roof/attic floor	628.5	0.27	169.7	15.0-14.8
Long side walls	474.6	0.18	85.4	7.5-7.4
Short side walls	153.4	0.18	27.6	2.4
Windows	181.3	2.80	507.7	44.8-44.3
Doors	34.5	2.00	69.1	6.1-6.0
Bottom floor	619.3	0.30	185.8	16.4-16.2

Table 9. Ψ-values for the different parts of the building envelope of the modular pre-fabricated system.

	L (m)	Ψ (W/mK)	ΨL (W/K)	ΨL/(UA+ΨL)$_{total}$ (%)
Window	422.7	0.036-0.066	15.2-27.9	1.3-2.4
Doors	109.0	0.050	5.5	0.5
Wall corners	25.3	0.100	2.5	0.2
Wall-Roof	128.0	0.100	12.8	1.1
Wall-Bottom floor	134.5	0.200	26.9	2.4-2.3
Wall-Middle floor	262.4	0.100	26.2	2.3

When only refurbishing the façade some thermal bridges are decreased and others are increased. For all the façade refurbishing systems the thermal bridges still stands for less than 10% of the total U_m-value.

The results of the calculations for the façade refurbishment systems only are summarized in tables 10-12.

Table 10. U_m-values for the different façade refurbishment systems as the only measure (W/m^2K).

	Less good	Good
50 mm thermal-bridge-breaking system	0.581	0.575
100+50 mm on-site mounted system	0.550	0.543
Modular pre-fabricated system	0.548	0.542

Table 11. E_{spec}-values for the different façade refurbishment systems as the only measure (kWh/m^2a).

	Less good	Good
50 mm thermal-bridge-breaking system	217.6	215.9
100+50 mm on-site mounted system	209.3	207.4
Modular pre-fabricated system	208.8	207.1

Table 12. Energy savings for the different façade refurbishment systems as the only measure (kWh/m^2a).

	Less good	Good
50 mm thermal-bridge-breaking system	13.5	15.2
100+50 mm on-site mounted system	21.8	23.7
Modular pre-fabricated system	22.3	24.0

If the reference building is moved from Umeå with a mean outdoor temperature of +4°C to the west coast of Sweden with a mean outdoor temperature of +8°C both the energy savings due to the façade renovation system as well as the total energy savings including all measure is decreased by 25%. For the modular prefabricated system this mean saving 18 kWh/m^2a instead of 24 kWh/m^2a.

4.4. Calculation for other types of refurbishment options

To compare the energy savings of the façade refurbishment systems with other energy saving measures the influence of some of the most common measures have also been calculated, each as a single measure. The results of the calculations are shown in table 13.

Table 13. Influence of other types of energy saving measures.

	Measure	U_m (W/m^2K)	E_{spec} (kWh/m^2a)	ΔE_{spec} (kWh/m^2a)
Windows	U-value 2.8 to 1.2 W/m^2K	0.491	193.1	38.0
Doors	U-value 2.0 to 1.2 W/m^2K	0.617	227.4	3.7
Roof/attic floor	U-value 0.27 to 0.13 W/m^2K	0.588	219.5	11.6
Air tightness	Q_{n50}-value 0.8 to 0.3 l/s m^2	0.630	226.9	4.2
Ventilation heat recovery	From 0 to 80/75 % recovery [§]	0.630	187.2	43.9

The most effective energy saving measures for the reference building is changing to new energy efficient windows and installation of ventilation heat recovery. But the third most effective measure is the façade

[§] 80% heat recovery at +2°C outdoor temperature and 75% heat recovery at -15°C outdoor temperature. The specific fan power is assumed to be the same for the old exhaust fan as for the new supply and exhaust air ventilation unit, i.e. 1.5 kW/(m^3/s).

refurbishment. Air tightening and changing to energy efficient door is the least effective single measures. However, if combined with balanced ventilation and heat recovery the air tightening will be twice as effective.

4.5. Calculation for the façade refurbishment systems including other options

To reach very low energy use the façade refurbishment systems should be combined with all the other energy saving measures.

For the 50 mm thermal-bridge-breaking system it is also now assumed that it is only of interest to refurbish the long side walls. The U-values for the different parts of the building envelope are given in table 14 and the Ψ-values (thermal bridges) are given in table 15. This gives an average thermal transmittance (U_m) of 0.383 – 0.389 W/m^{2}K and a specific energy use (E_{spec}) of 113.7 – 115.3 kWh/m^{2}a depending on the thermal bridges around the windows.

Table 14. U-values for the different parts of the building envelope of the 50 mm thermal-bridge-breaking system.

	A (m^2)	U (W/K m^2)	UA (W/K)	UA/(UA+ΨL)$_{total}$ (%)
Roof/attic floor	628.5	0.13	81.7	10.2-10.1
Long side walls	474.6	0.27	128.2	16.0-15.8
Short side walls	153.4	0.31	47.5	5.9-5.8
Windows	181.3	1.20	217.6	27.2-26.8
Doors	34.5	1.20	41.4	5.2-5.1
Bottom floor	619.3	0.30	185.8	23.2-22.9

Table 15. Ψ-values for the different parts of the building envelope of the 50 mm thermal-bridge-breaking system.

	L (m)	Ψ (W/mK)	ΨL (W/K)	ΨL/(UA+ΨL)$_{total}$ (%)
Window	422.7	0.050-0.080	21.1-33.8	2.6-4.2
Doors	109.0	0.050	5.5	0.7
Wall corners	25.3	0.070	1.8	0.2
Wall-Roof	128.0	0.100	12.8	1.6
Wall-Bottom floor	134.5	0.130	17.5	2.2
Wall-Middle floor	262.4	0.150	39.4	4.9-4.8

For the 100+50 mm on-site mounted system also now both the long side walls and the short side walls are refurbished. The U-values for the different parts of the building envelope are given in table 16 and the Ψ-values (thermal bridges) are given in table 17. This gives an average thermal transmittance (U_m) of 0.352 – 0.359 W/m^{2}K and a specific energy use (E_{spec}) of 105.9 – 107.7 kWh/m^{2}a depending on the thermal bridges around the windows.

Table 16. U-values for the different parts of the building envelope of the100+50 mm on-site mounted system.

	A (m^2)	U (W/K m^2)	UA (W/K)	UA/(UA+ΨL)$_{total}$ (%)
Roof/attic floor	628.5	0.13	81.7	11.1-10.9
Long side walls	474.6	0.18	85.4	11.6-11.4
Short side walls	153.4	0.18	27.6	3.8-3.7
Windows	181.3	1.20	217.6	29.6-29.0
Doors	34.5	1.20	41.4	5.6-5.5
Bottom floor	619.3	0.30	185.8	25.2-24.7

Table 17. Ψ-values for the different parts of the building envelope of the100+50 mm on-site mounted system.

	L (m)	Ψ (W/mK)	ΨL (W/K)	ΨL/(UA+ΨL)$_{total}$ (%)
Window	422.7	0.041-0.076	17.3-32.1	2.4-4.3
Doors	109.0	0.050	5.5	0.7
Wall corners	25.3	0.050	1.3	0.-
Wall-Roof	128.0	0.150	19.2	2.6
Wall-Bottom floor	134.5	0.200	26.9	3.7-3.6
Wall-Middle floor	262.4	0.100	26.2	3.6-3.5

Also for the modular pre-fabricated system both the long side walls and the short side walls are refurbished. The U-values for the different parts of the building envelope are given in table 18 and the Ψ-values (thermal bridges) are given in table 19. This gives an average thermal transmittance (U_m) of 0.351 – 0.357 W/m^{2}K and a specific energy use (E_{spec}) of 105.6 – 107.2 kWh/m^{2}a depending on the thermal bridges around the windows.

Table 18. U-values for the different parts of the building envelope of the modular pre-fabricated system.

	A (m^2)	U (W/K m^2)	UA (W/K)	UA/(UA+ΨL)$_{total}$ (%)
Roof/attic floor	628.5	0.13	81.7	11.1-10.9
Long side walls	474.6	0.18	85.4	11.6-11.4
Short side walls	153.4	0.18	27.6	3.8-3.7
Windows	181.3	1.20	217.6	29.7-29.1
Doors	34.5	1.20	41.4	5.6
Bottom floor	619.3	0.30	185.8	25.3-24.9

Table 19. Ψ-values for the different parts of the building envelope of the modular pre-fabricated system.

	L (m)	Ψ (W/mK)	ΨL (W/K)	ΨL/(UA+ΨL)$_{total}$ (%)
Window	422.7	0.036-0.066	15.2-27.9	2.1-3.7
Doors	109.0	0.050	5.5	0.7
Wall corners	25.3	0.050	1.3	0.2
Wall-Roof	128.0	0.150	19.2	2.6
Wall-Bottom floor	134.5	0.200	26.9	3.7-3.6
Wall-Middle floor	262.4	0.100	26.2	3.6-3.5

As the most of the surfaces of the building has been better insulated the thermal bridges now stand for up to 15% of the total U_m-value.

The results of the calculations for the façade refurbishment systems together with all other measures are summarized in tables 20-22.

Table 20. U_m-values for the different façade refurbishment systems and all other measures (W/m^{2}K).

	Less good	Good
50 mm thermal-bridge-breaking system	0.387	0.381
100+50 mm on-site mounted system	0.359	0.352
Modular pre-fabricated system	0.357	0.351

Table 21. E_{spec}-values for the different façade refurbishment systems and all other measures (kWh/m^{2}a).

	Less good	Good
50 mm thermal-bridge-breaking system	115.3	113.7
100+50 mm on-site mounted system	107.7	105.9
Modular pre-fabricated system	107.2	105.6

Table 22. Energy savings for the different façade refurbishment systems and all other measures (kWh/m^{2}a).

	Less good	Good
50 mm thermal-bridge-breaking system	115.8	117.4
100+50 mm on-site mounted system	123.4	125.2
Modular pre-fabricated system	123.9	125.5

When combined with all the other energy saving measures the energy saving due to the façade renovation systems are decreased by approximately 8%. For the modular prefabricated system this mean saving 22 kWh/m^2a instead of 24 kWh/m^2a. The reason is that the heating season is decreased due to the other energy saving measures.

5. Conclusion

The most effective energy savings measures for this typical multifamily building from the period 1965-1975 is changing to new energy efficient windows and installation of ventilation heat recovery. But the third most effective measure is the façade refurbishment. Insulation of the roof/attic floor is surprisingly only the fourth most effective measure. Air tightening and changing to energy efficient door is the least effective single measures. However, if combined with balanced ventilation and heat recovery the air tightening will be twice as effective.

If one wants to reach really good energy performance, i.e. comparable to new buildings, then also the walls need additional insulation. Sometimes 50 mm addition insulation is enough to reach the requirements on energy and thermal comfort. The advantage of much more insulation is however that the required air tight layer then can be place on the outside of the existing wall. The studied prefabricated wood based refurbishment system has an integrated air tight layer for that purpose. Even 50 mm of additional insulation may require better air tightness of the building envelope to avoid condensation and moisture in the outer parts of the wall. But only 50 mm additional insulation requires the air tight layer to be placed on the inside of the existing wall which is much more difficult and would mean major disruptions for the residents. A good air tightness of the building envelope is also required if one wants to reach the full potential of installing a ventilation heat recovery system.

The length of the thermal bridge around the windows is by far the longest of all the thermal bridges in this type of building and as the insulation of the wall is increased the Ψ-value of this thermal bridge also tend to increase. If one is not attentive and careful the thermal bridges may more than double, leading to a significant and unnecessary heat loss. But as shown in this study it is also possible to mount the windows in a way that keeps the thermal bridges at a reasonably low level..

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