Assessment of Dan-iso A/S insulation

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Abstract:

This report investigates the two methods of mechanical recycling of Rigid Polyurethane (PUR) developed by Dan-iso A/S, which are not used by any other company at the moment. Today, PUR insulation at the end of its life is transported to communal waste processing facilities, where it is incinerated for energy recovery. Dan-iso A/S seeing this empty segment of the market developed two recycling methods, where not only their own production waste can be recycled, but also PUR from other sources such as construction waste can be turned into the circular economy model. Recycled materials are different in material properties from virgin PUR. This study analysed these possible changes. The influencing factors were determined and evaluated through several laboratory measurements. Both mechanical recycling methods were considered feasible within the selected market environment. Also while the environmental impact of the material is decreased in comparison to the virgin PUR, the material production price decreased as well, making the product more affordable which can create a more appealing option. The calculation, where a case building was used, showed the comparison between the other renovation options for an external wall scenario.

Foreword

This section serves a purpose of a navigation tool.

Reading instruction:

Sections C, D, E, F and G are related to the material properties and in the H section, it is applied in a building case and compared with other products.

Article

Section A: Introduction In this section, the reader is enlightened with information about the PUR material itself, and with the company.

Section B: Problem formulation The section defines the specific problem being addressed throughout the study.

Section C: Introduction to laboratory measurements In this section, the reader is introduced to the recycling methods of the PUR.

Section D: Laboratory experiments - Thermal conductivity This section is about thermal conductivity measurements. At the end of the section, the results and conclusion explain the observed results of the measurements.

Section E: Laboratory experiments - Structural properties Material structural changes are evaluated with a stereo microscope in this section. The samples have their structure assessed.

Section F: Laboratory experiments - Compressing strength properties Material strength measurements were made in Dan-iso A/S internal laboratory, where the compressive strength was evaluated for both fine and coarse granulated samples. At the end of the section, samples were chosen according to certain factors, which are further evaluated in the thesis.

Section G: Life cycle assessment - LCA This section includes the LCA calculation of the recycled PUR, which was chosen according to the previous laboratory measurements.

Section H: Renovation of the case building Case building was utilised to evaluate the material at the building level and compare it with different options on the current market in terms of LCA and LCC.

Section I: Discussion

The discussion covers the key findings, and limitations, and offers recommendations for future research.

Appendix

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Appendix K: Thermal conductivity measurements
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Contents

Part I
Article

Assessment of Dan-iso A/S insulation

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Abstract—This report investigates the two methods of mechanical recycling of Rigid Polyurethane (PUR) developed by Dan-iso A/S, which are not used by any other company at the moment. Today, PUR insulation at the end of its life is transported to communal waste processing facilities, where it is incinerated for energy recovery. Dan-iso A/S seeing this empty segment of the market developed two recycling methods, where not only their own production waste can be recycled, but also PUR from other sources such as construction waste can be turned into the circular economy model. Recycled materials are different in material properties from virgin PUR. This study analysed these possible changes. The influencing factors were determined and evaluated through several laboratory measurements. Both mechanical recycling methods were considered feasible within the selected market environment. Also while the environmental impact of the material is decreased in comparison to the virgin PUR, the material production price decreased as well, making the product more affordable which can create a more appealing option. The calculation, where a case building was used, showed the comparison between the other renovation options for an external wall scenario.

Keywords—Mechanical recycling of PUR, Life cycle assessment, life cycle cost, laboratory measurements, thermal conductivity, thermal transmittance, compressive strength, sustainability of PUR

1. Introduction

Ensuring sustainable development is one of the important parts of this project, but what does that mean?
The Brundtland report [1] defines sustainable development as:
"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This means the need for recycling is an important factor in the development of new materials.
According to EU statistics [2] more than one-third of all the waste comes from construction and demolition. Throughout time the amount of insulation in the waste is also increasing as stated in the waste statistics [3] due to the trend of higher use of insulation in general. Therefore, the need for better inclusion of insulation materials in the circular economy is rising.

In the Environmental Product Declarations (EPD) documentation of other commonly used insulation materials [4] can be found that for Rockwool, 90,4 % of the material ends as a landfill with the remaining 9,6 % recycled. It is important to create new materials as well as new recycling methods to move forward within the sustainable industry.

This thesis contains research in collaboration with the company Dan-iso A/S, which produces PUR and PIR insulation. The investigation will focus on testing their new methods of recycling the PUR material in terms of thermal conductivity as well as an LCA comparison of their new insulation components with the current standard on the market from the competitors. The amount of the material recycled (up to 45%) was not achieved yet in other recycling studies of PUR material [5], where the recycling is less than 10 % by weight.

The insulation properties might change based on the recycling percentage and recycling method. Therefore, the goal is to create and measure samples of various percentages over the span of the possibility in order to create an overview of the properties of the percentages. The overview contributes to finding the optimal solution (heat transfer) for the percentage amount over the possible recycling percentages, which is then compared to other insulation materials on the market.

The material is then also simulated with life cycle cost and life cycle analysis to other insulation types such as EPS, mineral wool or blown-in insulation. If the new product will be a viable opponent for the materials currently used on the market, the company can consider expanding their field of insulation products production.

The PUR is tested as a material for the properties and then it is also simulated in an example case building for the visualisation of the effect it has on the LCC and LCA of the case building, where the applicability can be compared with the tools such as SimaPro and LCAbyg.

The LCC is one of the most important parts of the analysis since the main drawback of the PUR is that it is more expensive than other materials with worse thermal quality. The analysis of the cost efficiency utilises the software LCCbyg to define the possible economical benefit of renovation with this insulation instead of other options.

The material is investigated for applicability using the renovation of an old multi-storey residential building as a case. The different results will result in a comparison of different renovation options within the LCA and LCC.

Research questions:

- Is there a difference in the thermal conductivity of PUR with different recycling percentages?
- Is there a difference in the compressive strength and structure of PUR with different recycling percentages?
- What is the comparison between the new material and the other insulation products in different places in terms of LCC, LCA and applicability?

All those questions will be answered throughout the report and supported with documentation.

The current approach for the end of life of the PUR is municipality incineration for energy recovery, but with an achieved recycling method the end of life of the PUR can mean the reuse in the production. This would help to reduce production waste as well as waste from the building industry.

The final step of the thesis is to apply the measured results in a renovation case for a case building and investigate whether the PUR is a feasible solution in comparison with other options for insulation materials on the current market.

1.1. PUR vs PIR

Polyurethane [6] was created in Germany in 1937 by Otto Bayer and his colleagues. In 1954 PUR (Rigid Polyurethane) was created by the accidental introduction of water to polyurethane resulting in rigid foam insulation.

In 1967 PUR's thermal stability and flame resistance were improved by the creation of the PIR foam (Polyisocyanurate). To create this new formulation, the scientist included an extra chemical reaction at high temperatures.

PUR [7] foams are made by reacting "polyol" and "isocyanate" elements in which the OH_2 (Hydroxide) of the polyol elements chemical balance the NCO (an isocyanate chemical group) isocyanate components creates urethane linkage as can be seen in the figure 1.

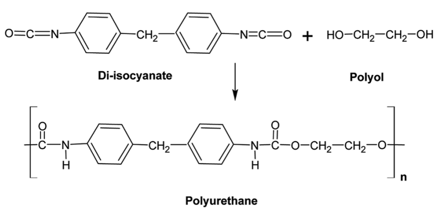

Fig. 1: PUR chemical synthesis [7]

In PIR [8] foams the "isocyanate" elements react with each other in a trimerization reaction to establish isocyanurates. Excess "isocyanide" reacts with a polyol to establish urethane linkage as well. (See figure 2)

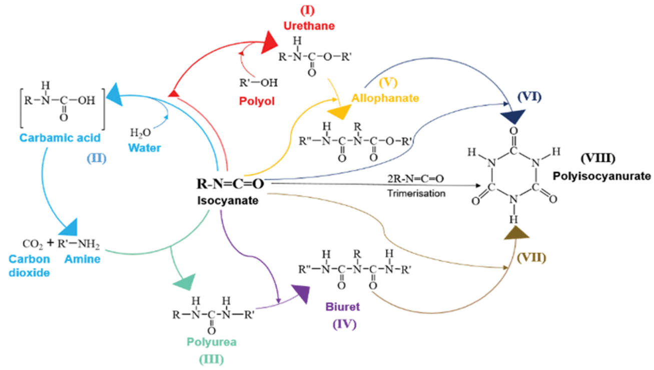

Fig. 2: PIR chemical synthesis [8]

PUR and PIR have the same unique property as they are highly water and moisture-resistant making them suitable for usage in flood-prone areas.

The downside in the case of injection is there can be damage caused by not following specific instructions of the application. Additionally, in Denmark, there are restrictions to the spraying of chemicals that prevent the widespread use of spray PUR.

PIR differs from PUR in the flame and smoke-resistant properties of the material. PIR has the unique ability to slow down the flame spreading and reduces the emitted smoke from the fire comparison.

1.2. Dan-iso A/S

Dan-iso A/S is a PUR and PIR insulation producer company, that is capable to supply these high-performance materials to customers from a wide range of industrial sectors. Dan-iso A/S can supply their product in every needed shape thanks to their highly precise Computer Numerical Control (CNC) machine. However, CNC is used mainly for prototypes, as CNC-made insulation is too expensive for most requirements.

Dan-iso A/S was established in 1986 in an old diary building in Aars by Finn and Ebba Pedersen. At the time they had only a few employees whose high quality of work paid out, as the company started to grow at high speed.

The main speciality of the company is the more complicated smaller size components, which are declined by the competitors. There is no limit in shape for their CNC machine to produce the material for the components. The customers usually come from the sectors of Marine, Industry, Oil and gas or Energy. The demand is usually for insulation for pipes and other special systems dealing with hot or cold temperatures.

Due to the ambition of lowering their product's carbon footprint, Dan-iso A/S has decided to devote substantial resources to the development of methods that allow for the recycling of the material waste from their production line.

Dan-iso A/S is capable to serve a wide range of needs from their customers in high-quality certificates such as EN-253 (district heating) and in the near future also the EN-14308 (thermal insulation products for building equipment and industrial installations).

1.3. Introduction to laboratory measurements

The recycling of demolished building materials is an important task, to reduce the overall environmental footprint of a renovation. The demolished PUR is not used currently to reduce the environmental footprint of the newly produced PUR, which can change now. Recycled particles can influence material properties such as thermal conductivity, strength and structural integrity.

1.4. Recyclated PUR

There is a possibility to recycle PUR chemically [9] and mechanically. This thesis is focused on mechanical recyclation with two different methods. The recyclate taken into consideration is from demolished buildings and or production waste with a density variation of $55kg \pm 8kg$. The first method is fine granulated where the particle size is under a millimetre and the second is coarse granulated with particles larger than a centimetre.

1.5. Tested samples

There was a limitation of prototype production in terms of density and recycled percentage. The aim of the used percentage of recycled particles was to evaluate the material properties changes by producing prototypes for every 5 % of the increased amount of recycled particles. This issue was especially complicated for the coarse granulated recycling method because of the density of the recyclate parts. In the table 1 below, There is a set of measured samples from both fine and coarse granulated recycling methods.

TABLE 1: NUMBER OF SAMPLES DURING THE LABORATORY EXPERIMENTS

Method	Recycled %	Amount of prototypes
Virgin PUR		3
Fine granulated	15 %	3
	20 %	3
	25 %	1
	27 %	1
	35 %	2
	44 %	1
Subtotal:		**11**
Coarse granulated	15 %	2
	16 %	3
	25 %	3
	35 %	2
	37 %	1
	42 %	1
	43 %	2
	45 %	3
Subtotal:		**17**
In total:		**31**

2. METHODOLOGY FOR THE THERMAL CONDUCTIVITY

A building element is consisting of several different building materials. These materials are having various thermal conductivity values. To evaluate the building elements' final thermal transmittance, calculations are needed.

The equation 1 explains the calculation method of the uncorrected thermal transmission for a building element. After the calculation, other correction aspects (described in DS418 [10]) must be considered to calculate the thermal coefficient.

$$\frac{1}{U'} = R_{si} + R_{se} + \sum_{i=1}^{n} R_i \qquad (1)$$

U' - Uncorrected thermal transmission coefficient $[W/m^2K]$
R_{si} - Surface resistance at the inner surface $[m^2K/W]$
R_{se} - Surface resistance at the outer surface $[m^2K/W]$
R_i - Thermal resistance for each material layer $[m^2K/W]$
n - Number of layers

The R_{si} and R_{se} can be found in the DS418 while the R is calculated with equation 2.

$$R = \frac{d}{\lambda} \qquad (2)$$

R - Thermal resistance $[m^2K/W]$
d - Thickness of the material layer$[m]$
λ - Thermal conductivity of material $[W/mK]$

Therefore this thesis focuses on measuring the thermal conductivity of the samples prototypes to determine thermal properties.

2.1. Measurements - Thermal conductivity

The additionally added recycled particles are capable to influence the thermal conductivity. To evaluate these changes measurements are needed. For the measurement, the Guarded Hot Plate Apparatus EP500 from Lambda-Messtechnik Gmbh was used.

2.1.1. General information about the Hot Plate Apparatus

The description of the Guarded Hot Plate Method for Thermal Conductivity Measurement guides the execution of the thermal conductivity measurement. The used Guarded Hot Plate Apparatus EP500 from Lambda-Messtechnik GmbH is capable of accurately measuring the steady-state thermal conductivity of insulation materials. The range of measured thermal conductivities is from 0,005 W/mK to 2 W/mK. The available temperature difference between the upper and lower plate ranges from 10°C to 40°C. with the difference being between 5 K to 15 K. The vertical pressure ranges from 500 Pa to 2500 Pa on the tested specimen. The final controlled pressure depends on its hardness [11].

The PUR prototypes are not available in the required dimension with a base size of 500 x 500 *mm*. There is a solution available, which is a smaller sample base size of 150 x 150 *mm* with a thermal protection shield around the prototype.

The target is to maintain a one-dimensional temperature gradient and heat flux between the plates. As the temperature on the cold guarded plate could get lower than the dew point and it could compromise the measurement. The testing zone is protected by a double coil protection ring. This ring prevents any external humidity penetration towards the testing zone.

The measurement is completed once the stability criteria are met when the difference between the maximum and minimum thermal conductivity number is not more than 1 % over 500 minutes of time [11].

The temperature condition of testing was defined with the guidance of ISO 8302 [12], including the accuracy and the time length of accuracy.

The different average temperatures can result in different thermal conductivity due to the various performances of the materials, therefore the tested PUR has selected a temperature close to usage for building insulation. Guidance in ISO 8302 [12] only explains the set of average temperatures has to be considered according to the final place of usage of the tested specimen. The lowest available average temperature between the upper and lower plate was chosen, which is 10°C. Condensation can occur due to the used temperature set because the hot side of the plate is chosen to be 17,5°C and 2,5°C on the cold side during the measurement. The temperature goes under the dew point creating unwanted condensation. Rigid Polyurethane foam has very little absorption of water and rather acts as a repellent, this is because of its closed-cell structure and hydrophobic nature. Water resistance of rigid polyurethane study [13] shows that small-scale tests in the laboratory described a water absorption below 2 %.

2.1.2. Sample dimension

To execute a measurement, an accurate dimension of samples is required. The measured samples are cut with the precise machine to the base size of 150 x 150 *mm*. The pieces were surrounded by a heat shield as figure 3 represents.

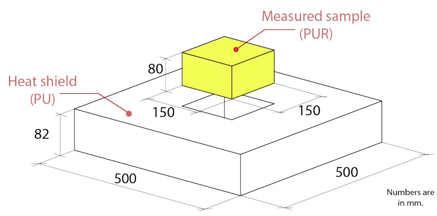

Fig. 3: Dimension of PUR sample and heat shield

After weighing the prototype, it is placed into the PU heat shield, which can be only a few millimetres higher than the sample thickness. The following step is to place the heat shield with the sample in the middle of the test area and the hot side of the plate can be lowered. When the set pressure is applied for the sample, the displayed thickness must be below the thickness of the sample, since if it would be above, a slight air gap can occur, which can highly compromise the measurement. For rigid products, 1000 Pa pressure is set in order not to damage the surface.

3. Methodology for the structural properties

A Carl Zeiss discovery v8 stereo microscope was utilised to evaluate the structural changes in the PUR. Thanks to its stereo lens system, the microscope can examine the sample in a 3D view.

Both fine and coarse granulated samples were inspected for structural pore system change in relation to the added amount of recycled particles and density. The lens zoom was used on 1x to 2,5x magnification since the maximum magnification of 8x could not give more value to this evaluation. Lighting from below could highlight the structural pore system of the samples.

Before the evaluation, the examined samples were sliced up into 3 *mm* thick on their X or Y axis, as figure 4 explains. Only in cases of structural deformity could be seen.

Microscopic evaluation was made mainly on the Y-axis surface. Due to this reason, structural differences were the most visible from the axis. In case of visible structural deformation, X-axis was tested too.

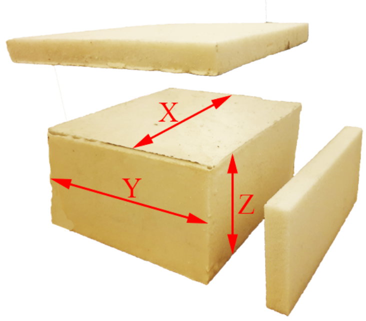

Fig. 4: Examined samples XYZ axis orientation

All the samples went through a visual observation, where assumptions could be made according to the level of structural uniformity or non-uniformity and the quality of their pore system.

4. Methodology for the Compressive strength

ISO 844 [14] states that the thickness of the specimen must be usually 50±1 *mm*. But for the purposes of these prototypes, the minimum requirement for the thickness is to be thicker than 10 *mm*, and the maximum thickness is not greater than the width and length.

All the surfaces of the sample must be parallel to the opposite side by the maximum 1 % of tolerance.

The temperature and the relative humidity of the specimen must be in the range of 23±2 °C and 50±10 % respectively.

The samples were sliced up for the test into three 30 x 30 x 30 *mm* blocks, coded to A-B-C and tested separately to validate the results of the test. Measuring the specimens on their X, Y and Z axis according to ISO 1923 [15] is the first step. Then the specimen is placed in between the two parallel plates of the compression-test machine. Increase the pressure of the plates on the specimen at a rate of 10 % of the specimen height. Continue this until the thickness is reduced to 85 % of the initial thickness. Then note the maximum force during the reduction of the thickness. Repeat this on all three samples, as differences can occur due to the production technology of the product.

5. Methodology for the Life cycle analysis

The life cycle assessment (LCA) is the best-known quantitative analysis of the environmental aspects of a product over its entire life cycle. The LCA is a systematic tool for analysing the environmental burdens of the product over its life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to the use and end-of-life treatment and disposal.

The reason for the calculation of the life cycle assessment is to reduce impact due to raising awareness about the building industry contributing highly to the production of greenhouse gasses. The carbon dioxide from the building represents nearly 40% of annual global emissions, where approximately 28% comes from operations of the building and 12% comes from building materials and construction. Therefore, to reduce the impact, it should be traced. Danish Government had embraced a Climate Act [16], which goal is to reduce the emission of CO_2 by 70% by 2030 [16]. New regulation planned in 2025, requires all new buildings to perform LCA analysis with a limit value to carbon dioxide emission from the building.

The ISO 14040 [17] standard method describes the LCA and also how to identify individual processes. There are four phases in LCA, goal and scope definition, inventory analysis, impact assessment and interpretation. These are described in the following sections. The main focus will be an evaluation of the environmental impact of recycled PUR, which can be compared with mineral wool, extruded polystyrene and blow-in cellulose as an option for the renovation of the external wall. The assessment also follows EN 15804 [18] Sustainability of construction works - environmental product declarations (EPD).

5.1. Goal and scope

The goal of the LCA of the PUR is to create an environmental impact table which can be compared with EPD results for LCA documentation of the mineral wool, extruded polystyrene and cellulose. The selected standard parameters according to The ISO 14040 [17] can be found in the table 2. The functional unit for the results is one *kg* of the PUR.

Table 2: Parameters according to the ISO 14040 [17]

Parameter	Environmental indicator	Abbreviation
Global warming potential	$kg\ \mathrm{CO_2} - eq$	GWP
Depletion potential of the stratospheric ozone layer	$kg\ CFC11 - eq$	ODP
Acidification potential of land and water	$kg\ \mathrm{SO_2} - eq$	AP
Eutrophication potential	$kg\ (\mathrm{PO_4})^3 - eq$	EP
Formation potential of tropospheric ozone photochemical oxidants	$kg\ ethene - eq$	POCP
Abiotic depletion potential for non-fossil resources	$kg\ \mathrm{Sb} - eq$	ADPE
Abiotic depletion potential for fossil resources	MJ	ADPF

The parameters will be calculated for each version of the material recycling as can be seen in the table 3.

5.2 Life cycle inventory analysis - LCI

TABLE 3: SAMPLES FOR SIMAPRO MODELLING

Recyclation method	**Recyclate [%]**
Fine granulated	15
Fine granulated	20
Fine granulated	25
Coarse granulated	15
Coarse granulated	25
Coarse granulated	35
Coarse granulated	45

The following table in figure 5 summarises the system boundary as described in EN 15804 [18]. The X means it is included in the LCA and the MND stands for Module not declared.

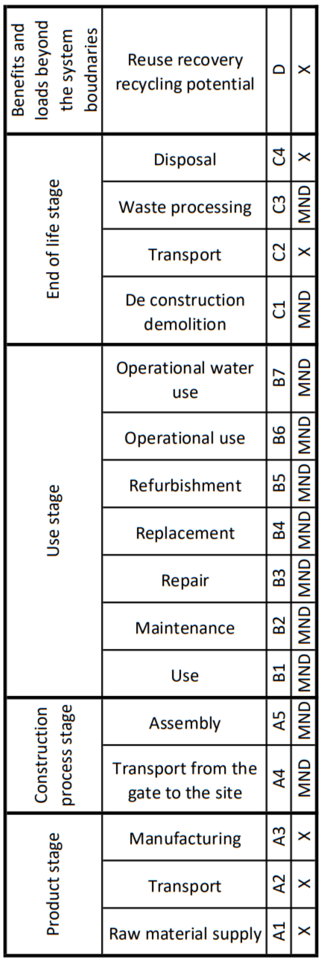

Fig. 5: Description of the system boundary (Visible version of this figure can be found in the section G1 of the report)

The included modules are:

- Product stage (A1) Raw material supply
- Product stage (A2) Transportation to the manufacturer
- Product stage (A3) Manufacturing
- End of life stage (C2) Transport to waste processing
- End of life stage (C4) Waste disposal
- Benefits and loads beyond the system boundary (D) Reuse, recovery and/or recycling potential

The used allocation method for recycling is the Cut-off method. This method works with the basic assumption that all inputs and outputs of the product system throughout the entire life cycle are the responsibility of the product system. This means that recycling is not included and instead the recycled amount is included in the production stage. The amount of raw material is then proportionally subtracted based on the amount of recyclate included. Then the total load of the disposal material is proportional to the amount of waste after recycling the specific amount.

5.2. Life cycle inventory analysis - LCI

This section includes the collection of data regarding all the materials and energy used during the stages of the product. There are two major components, Polyol and Diisocyanate, that need to be produced and transported to the factory. The two main components are mixed together and the other two components (a release agent and a cleaning agent) are used for the treatment of the machinery. The visualisation of the processes in each module for the recycled sample of PUR is shown in figure 6.

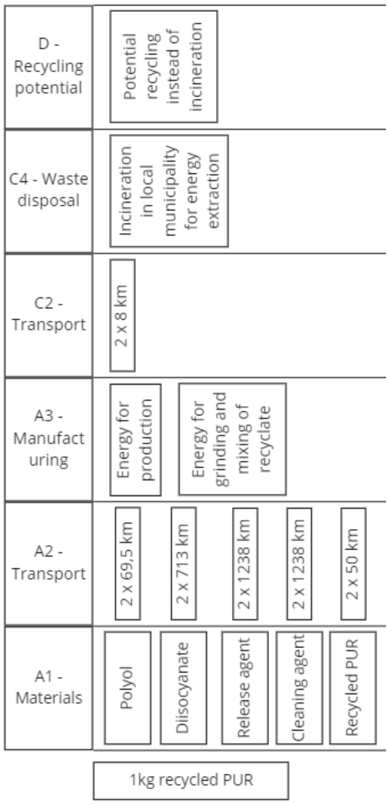

Fig. 6: Process map of the recycled PUR production

The main components are:

- Diisocyanate (Demsodur 44 v29L) [19]
- Polyol (Polyol RF2100PT8) [20]
- Release agent (PU-6222L) [21]
- Cleaning agent (Gamma-butyrolactone) [22]
- PUR recyclate

These components are consisting of several chemical parts described in table G.3 from the report. Each of the chemicals is also listed with their Chemical Abstracts Service (CAS) which helps to specify the chemical with the unique registration number that can be found. CAS contains most substances from 1957 to the present, with the addition of some substances from the early 1900s.

The estimation of the energy needed for the production of 1 kg of the PUR is 0,549 kWh/kg for the complete process.

Additional energy is needed for recycled material to be ground and mixed into the substance. For fine granulated recyclate, it is 0,253 kWh per kg of recyclate and for coarse granulate, it is 0,188 kWh per kg of recyclate.

5.2.1. Calculation model

The SimaPro software offers a broad selection of options for the selection of processes involved, but it does not contain all the chemicals and their specific parts therefore the components were simplified into the data that is shown in the table 4. The methylene diphenyl diisocyanate and polyol are modelled already in the SimaPro as a full substance on the other hand the Release agent had to simplify from the hydrotreated heavy paraffinic and hydrotreated heavy naphnetic into the petroleum and paraffine from which they are derived. The RER stands for the European modelled process, NO for the Norwegian and the DK stands for the Danish modelled process. The distances for transport were given by the Dan-iso A/S from the distributor to the factory.

TABLE 4: PROCESSES SIMULATED IN SIMAPRO

Material	**Weight** [g]	**Transport** [km]
Methylene diphenyl diisocyanate RER	606,3	713
Polyol RER	393,7	69,5
Petroleum NO	6,44	1238
Paraffin RER	4,76	1238
Butane - 1,4 diol RER	0,6	1238

Since polyol and methylene diphenyl diisocyanate are two main components, their weight needed for production is lowered with the increased percentage of recycling. The other chemicals are used for treatment of the equipment for each process without any regard for the materials used. The final amount of the chemicals used can be seen in table 5.

TABLE 5: RECYCLATION AND PRODUCTS WEIGHTS IN THE VARIOUS CASES

Recyclate [g]	**Methylene diphenyl diisocyanate** [g]	**Polyol** [g]
0 (0%)	606,30	393,70
150 (15%)	515,36	334,65
200 (20%)	485,04	314,96
250 (25%)	454,73	295,28
350 (35%)	394,10	255,91
450 (45%)	333,47	216,54

For modules C2 transport and C4 waste disposal, there is only one process for each. The C4 waste disposal has the process of municipal incineration. The amount of the waste simulated for incineration is equal to 1 kg with subtracted the recycled amount according to the recyclation of each sample. The C2 transport is from the factory to the municipal incineration facility located 8,4 km away.

Module D is the potential of the material for 100 % recyclation, therefore it is the value of C2 and C4 subtracted, therefore a negative value.

6. METHODOLOGY FOR THE RENOVATION OF CASE BUILDING

In the thesis, the PUR with different percentages of recyclate is tested for its properties such as thermal conductivity and strength. There was also a life cycle analysis of the material, but how do the samples compare to other insulation materials?

For the purpose of visualisation and taking the results into context, there is a need for an example such as a renovation of a case building. The goal of the renovation is to compare the insulation material in the cavity brick wall. The cavity has limited space between the bricks therefore the thickness for all the insulation is 90 mm. The materials chosen for the comparison are Rockwool Murbatts 34, JACKON EPS S150 and ISODAN Warmfiber Papirisolering. The result is calculated as the change of the heating demand in kWh/m^2year. It is not a realistic expectation for a renovation, because it expects to exchange only the external wall insulation and normal renovation would take care of all the problematic parts of the building. This serves only as a direct comparison of one option.

Figure 7 visualises the thermal conductivity changes between the materials.

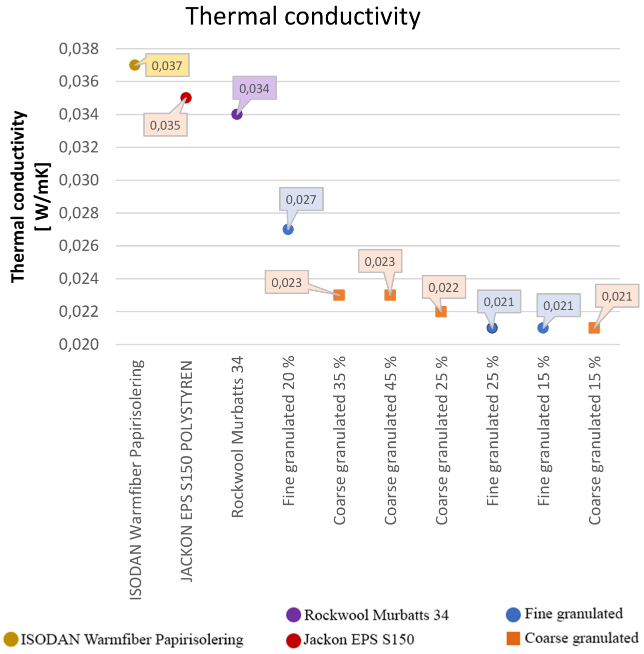

Fig. 7: Thermal conductivity of materials in the case building

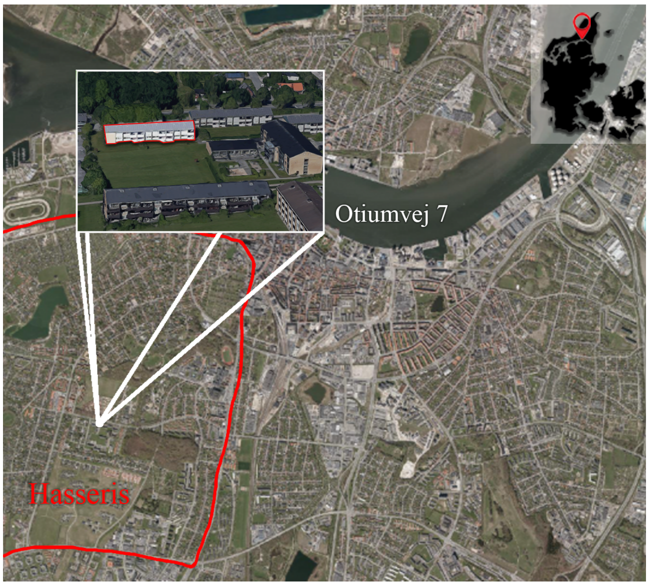

Fig. 8: Location of Otiumvej 7

There are no specific requirements for the strength of the insulation materials if they are not used as a load-bearing element.

The comparison focuses on life cycle analysis (LCA) and life cycle cost (LCC). The LCC includes the cost of renovation as well as the operation cost changes for the building which includes the heating demand (influenced by the thermal conductivity of insulation).

6.1. Case building

The first step for choosing a relevant case building was to analyse the amount of built multi-storey buildings in Denmark in different year periods. The amounts were from Dansk Statistik [23]. The periods were formed according to the Tabula web tool [24], buildings typology references the years, which represents the different danish standards used in the building industry.

The case building from the year 1964 was selected to represent the building type from the largest era. The standards and the reality does not match, therefore the thermal transmittance were recalculated according to the case building instead of taking the required value from the standards.

6.2. Building information

The construction was finished in 1964 and the location is in Aalborg in the Hasseris district 8.

The building is a 2-storey building complex serving the purpose of an elderly home. Figure 9 shows the northern facade, which describes a typical yellow brick building from this age.

Figure 9 shows the northern facade.

Fig. 9: South facade

In most cases, buildings are partially renovated every 20 years and deeply refurbished after every 40 years to complete the modern requirements. There is although in this case it was not followed and the refurbishment is delayed due to financial or other reasons. The floor area is two times 720.5 m^2 and figure 10 shows the floor plan.

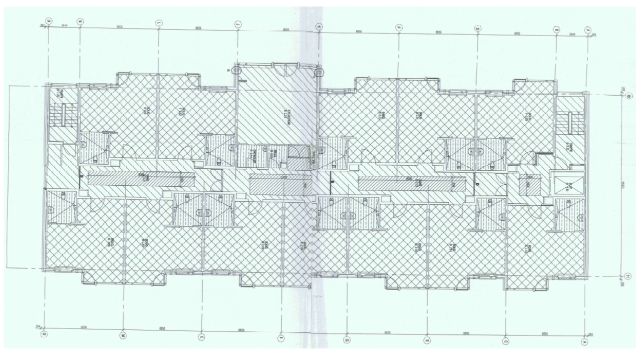

Fig. 10: 1st floor plan

The information about the construction elements was taken from the tabula webtool [24] and the thermal transmittance coefficient was calculated according to the DS 418 [10] with the thermal conductivity numbers for the bricks taken from SBI 5 - Varmeisolering [25] to ensure the calculation is with the older version of materials. The results can be found in the table 6.

TABLE 6: THE CASE BUILDING ENVELOPE ELEMENTS AND THEIR PARAMETERS

Element	**Area** $[m^2]$	**Thermal transmittance coefficient** $[W/m^2K]$
External wall	462,1	1,64
Ground floor slab	720,7	1,11
Roof	720,7	0.34
Windows	294,7	2.7
Doors	14,3	3

6.3. External wall renovation

The construction of the building is following the classical danish building structures as the load and non-load-bearing walls are from bricks (dimension: 228 x 108 x 54 *mm*) and in between the inner and outer leaf, there is an empty wall cavity of 90 *mm*. The existing building and the proposed renovation can be seen in figure 11.

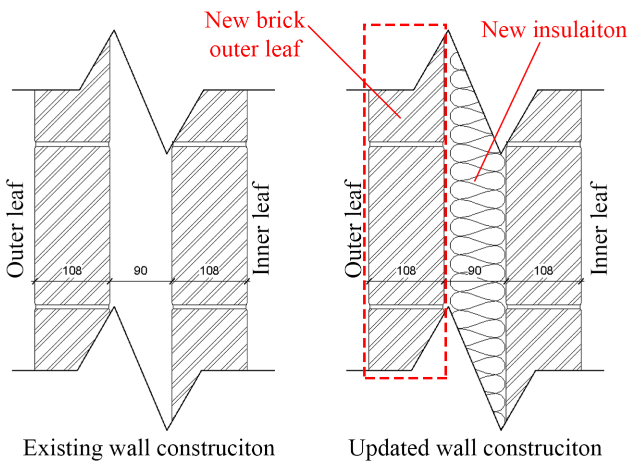

Fig. 11: Wall structure before and after the renovation

6.4. Heating demand

The case building was modelled using the software BE18 which included all the building elements of the envelope. The other parameters such as heat from the building occupants or the natural ventilation remained the same for all the cases. All the construction sizes as well as the window placement with shadings are also defined the same to compare with the result only the differences in the energy demand between the external wall materials. All the linear losses are also identically calculated according to the DS 418 and all of them are the same for all the different materials.

6.5. Life cycle analysis Case building

The comparison of the insulation materials' environmental impacts is focusing on comparing the calculated parameters (according to ISO 14040 [17]) and the LCA parameters declared for the Rockwool Murbatts 34 [26], Jackon EPS 150 polystyrene [27] and ISODAN Warmfiber papirisolering [28] in their respective EPD documents.

Only modules A1, A2, A3 and D (Production stage and Benefits and loads beyond the system boundaries) were included since the EPDs of the materials do not declare values. The life cycle assessment of the case building renovation is calculated using LCAbyg which is a tool that helps analyse the environmental profile and consumption of resources. It has a broad database with elements commonly used in the building industry. It has usually only LCA modules A1, A2 and A3 included in the database, which is the production stage. The results from LCAbyg should be added for the case building where the external wall is removed and remade.

6.6. Life cycle cost calculation

Life cycle cost (LCC) investigates the costs related to the lifetime of a component and it is a decision-making process with a long-term approach. Life cycle cost broadens the perspective from focusing on acquisition costs to also including the costs that arise during the operation and use of the building. The study of LCC is crucial if the project involves multiple options because LCC allows seeing the full picture of the benefits and losses occurring during different stages of the building's lifetime. The life cycle cost assessment of the building was calculated using LCCByg, which is the Danish tool that helps to evaluate the life cycle costs for the entire building or single components. In this case, the building's external walls scenario is compared.

The calculation usually takes into consideration the price for construction, operation, maintenance, cost of supply and utility as well as the cleaning. But in this case, the cleaning and utility costs are neglected due to reason the building insulation options carry the same cost as the non-insulated building. In this project, the software was used to calculate the net present value of the existing building component cost over the period of 50 years and then it is compared with the renovation option scenarios as well as the option for no renovation at all.
Prices and additional costs were used from Molio Prisdata [29], which is the most comprehensive tool for price calculation in the construction industry.
The assumptions for the price development are taken from the DGNB certification suggestions where the discount rate is determined nominally and prices are stated in current prices over the entire calculation period.

6.6.1. Supply cost

As the current building is connected already to the Aalborg Fjernvarme A/S system the price of the meters is neglected. Additionally, even if a refurbishment happens or not the monthly subscription fee is added to the tenant's A-conto contribution meaning, this cost is also neglected.

Prices of the district heating is varying yearly, however, due to global conflicts prices are still increasing. The cost of 1 kWh energy from the district heating plant in Aalborg increased by 1,5 % from 2021 to 2022 and 17 % to 2023 [30]. This means the price now is standing currently at 0,684 DKK/kWh.

6.6.2. Insulation material prices

For the PUR, according to the Dan-iso A/S, the price of one m^2 of the product with a thickness of 90 mm is 283 DKK. The internal calculation on savings is that the cost of the raw materials is reduced by the amount of recycling. However, the recycling process of grinding and mixing also has its price and on the other hand, the company will not have to pay for the removal of the product waste during production. An estimate is the savings from recycling are 80 % of the raw material savings. The material cost for each percentage of recyclation can be seen in table 7.

TABLE 7: PUR PRICES CHANGES

Sample	Recycled percentage	Price [DKK/m^2]
Virgin PUR		283
Fine granulated	15 %	249
	20 %	238
	25 %	226
Coarse granulated	15 %	249
	25 %	226
	35 %	204
	45 %	181

The table 8 shows the prices for the other considered materials per m^2 with the same thickness as PUR of 90 mm.

TABLE 8: PRICES OF OTHER INSULATIONS

Materials	Price [DKK/m^2]
ISODAN Warmfiber Papirisolering [31]	67
JACKON EPS 150 POLYSTYREN [32]	114
Rockwool Murbatts 34 [33]	125

6.6.3. Application of insulation

Application of blown-in insulation takes fewer labour hours (according to Molio) and needs organisation for construction. All the included costs are listed in table 9 are taken from element Hulmursisolering in Molio.

TABLE 9: USED COST FOR BLOWN-IN INSULATION

Item	Unit	Quantity	Unit cost
Labour and machinery	hours/m^2	0,2793	455,10 DKK
Total cost	m^2	1	127,11 DKK

The application of rigid board insulation materials is including the demolition of the external leaf, removal of existing insulation, and application and cost of new wall and new insulation material. Prices for the renovation can be seen in table 10, which is including work tasks from Molio.

TABLE 10: COST FOR APPLICATION OF THE PUR, EPS AND MINERAL WOOL INSULATION AS WELL AS THE NEW WALL

Item	Unit	Quantity	Unit cost
Demolition of brick external leaf	m^2	1	66,55 DKK
Application of new insulation	hours/m^2	0,1278	455,1 DKK
Building the new external leaf	m^2	1	1032,23 DKK
Total cost	m^2	1	1156,94 DKK

7. RESULTS

The results are divided intoseveral categories:
- Results for thermal conductivity, - compressive strength and structure review measuring
- Results for LCA of recyled PUR
- Results for Case building

7.1. Results for thermal conductivity

Most of the findings helped to improve the material properties to develop a material with better thermal conductivity.

Figure 12 visualises the correlation between the density and the value of thermal conductivity. In the figure, the 44% fine granulated sample was neglected due to structural integrity issues.

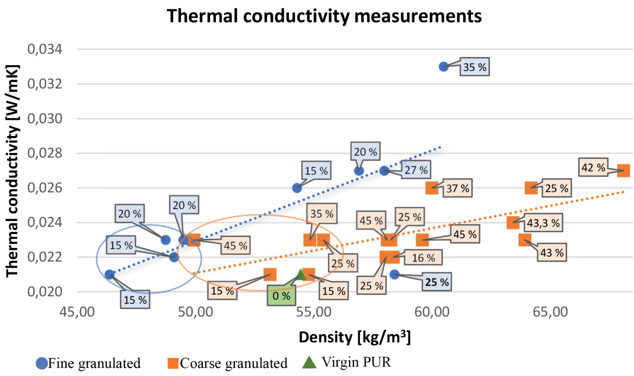

Fig. 12: Thermal conductivity results of fine and coarse granulated recycled samples

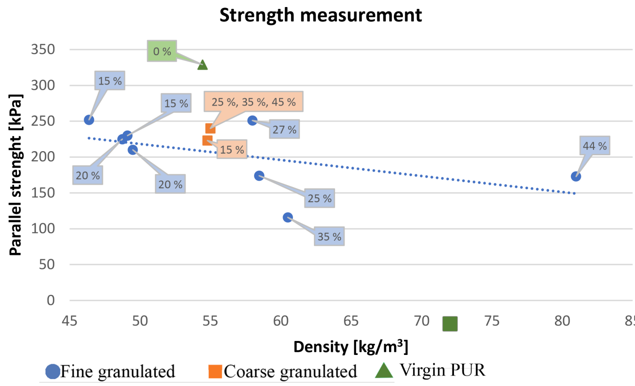

Fig. 13: Results of strength measurements for fine granulated samples

Observation of the received results from figure 12 describes a clear pattern. The samples have the lower thermal conductivity the lower their density is. Samples inside the blue circle visualise the best fine granulated samples. It shows that the lowest thermal conductivity between 0,021 and 0,023 W/mK, can be reached within the range of 48 kg/m^3±3 kg of density.

The coarse granulated samples showed a different tendency for lower thermal conductivity values. Samples included in the orange circled zone displays the lowest measured thermal conductivity between 0,021 and 0,023 W/mK, within the density range of 55 kg/m^3 ±3 kg.

For the last measurement, a new 25% sample was created with a different mixing machine, which measured the thermal conductivity number closest to the virgin PUR. The injected PUR was mixed more evenly, therefore increased density was possible without the loss of the expansion energy through the particles. With more prototypes with this machine, there are possible changes in the case of lower density that can be done for further product development.

The coarse granulated samples have mostly lower thermal conductivity than the fine granulated particles. But the limitation of the coarse granulated method is that there is already a variable density of the recycled coarse granulated pieces. In conclusion, the recycled amount of particles of the prototypes did not correlate with the measured thermal conductivity. The thermal conductivity was more dependent on the density of the samples, but the recyclate amount influences the possibility of the creation of specific density prototypes since the recyclate is taking out the energy needed for the expansion of the PUR foam.

7.2. Results for Compressive strength

Figure 13 shows the relation between the strength and density for fine granulated samples.

Table that contains all the parallel and perpendicular strength tests can be found in the report section F.2.1, however, the common industry practice only takes into account the parallel results which are shown in the figure 13.

The compressive strength of coarse granulated samples is similar to the virgin PUR. Due to the fact that the foam contains only virgin PUR and coarse granulated recyclate, which are not influencing the overall compressive strength. This means that the coarse granulated samples' strengths according to internal measuring showed that the measured values are similar in the interval of 216 N ± 15 N for the Force and 240 kPa ± 17 kPa for the strength.

Evaluation of the measured strengths properties for the recycled products with fine granulated particles allows the observation of above 58 kg/m^3 of density the strength begins to decrease by approximately 80 kPa. However, the strength of the fine granulated 25% and fine granulated 44% is similar. This observation also allows the conclusion that the amount of the added recyclate to the PUR mix does not influence the strength linearly through the percentage.

Products with recycled coarse granulated pieces allow the conclusion of the strength was diminished, but for all the percentages of recycling by the same amount.

According to internal strength measurement, it was observed, that in the case of lower density than 40 kg/m^3 the strength of the materials exponentially decreased. As a consequence of the smaller content of injected mixed PUR have more space to expand, as a result creating larger air bubbles, weakening the overall structure.

The strength is decreased to 116 kPa, but in comparison to other materials on the market for example Jackson EPS S150 has a 150 kPa and Rockwool Hardrock Energy roof and ceiling insulation 30 kPa [34] of compressive strength. Meaning the compressive strength of the PUR makes it capable of multiple areas of use, for example unlike the Rockwool as it cannot have any load-bearing capacity. In most cases, the building insulation material does not require to have a minimum compressive strength as it is not a load-bearing element.

7.3. Results for Life cycle analysis

The significance of potential environmental impacts of a product system based on life cycle inventory results is evaluated by using life cycle inventory assessment.

The graph 14 visualise the results for a clear understanding of the differences. The reference material that stands for the 0 % in the graph stands for the virgin PUR.

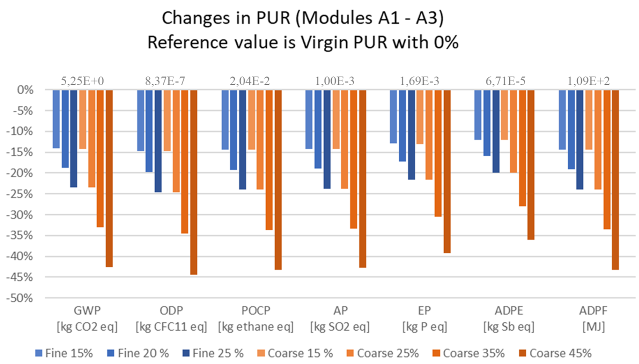

Fig. 14: Changes in PUR (Modules A1 - A3)

The waste transport C2 and waste disposal C4 are tight with the amount of recyclation since it is the remaining amount. The most important change is that recycling can in theory reduce waste disposal even to non-existent incineration for energy recovery.

Interpretation of the results can be based on the contribution of materials to the environmental impact as shown in figure 15. In the comparison is the virgin PUR with the coarse granulated sample. The sample impact as can be seen in figure 14 is approximately 35 to 45 % of the virgin PUR, while the contribution of the specific production materials in the final product to the impact is relatively similar.

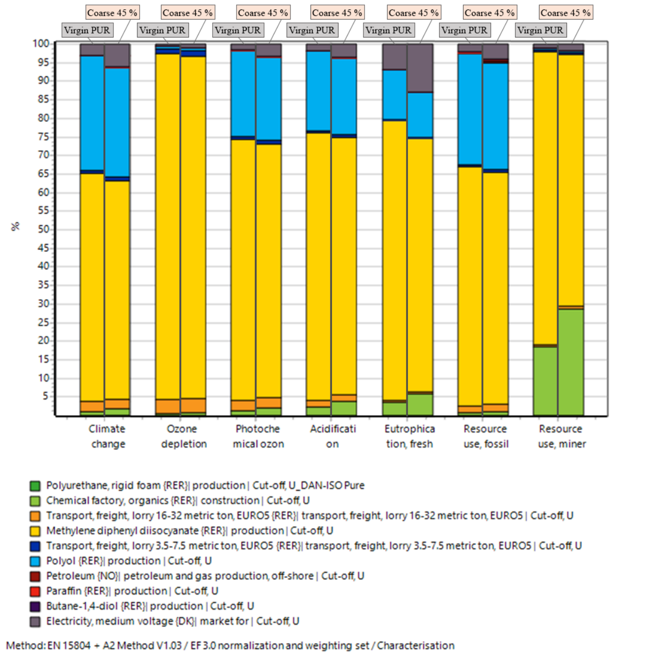

Fig. 15: Contribution (Modules A1 - A3)

From this can be concluded that the main driving force of the differing impact is the reduction in the number of main production elements such as diisocyanate and polyol.
The difference between the recycling methods (coarse granulated and fine granulated) is almost not relevant as it is close to 0,000 %.

This small difference between the methods is caused by the fact that the only variable between the methods is the energy use during production and it has a significantly lower environmental impact than other sources.

The possibility for lowering the total environmental impact of the material is in further progression with the reduction of the amount of the main components polyol and diisocyanate.

Overall the recycling of the product significantly improves the environmental impact of the PUR in all categories.

7.4. Results for Renovation of case building

Figure 16 visualises the calculated thermal transmittance of the external wall element options.

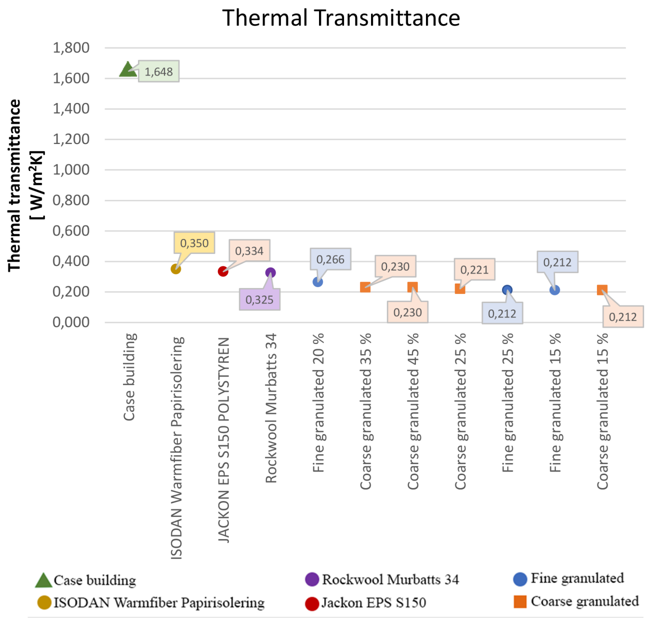

Fig. 16: Thermal transmittance of the wall element options in the case building

The differences between the thermal transmittance values for the materials used are not large as can be seen in the thermal conductivity graph. This is caused by the fact that the bricks which are two times 108 *mm* are the same for all the options and the insulation is only 90 *mm*.

The heating demand results have similar view as the thermal transmittance changes, the resulting values can be seen in figure 17.

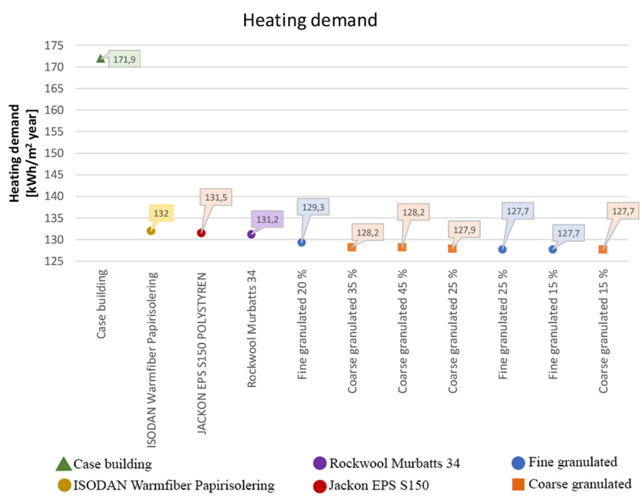

Fig. 17: Thermal transmittance of the wall element options in the case building

The span of the heating demand between the lowest and highest value for the renovation options is from 127,7 to 132 kWh/m^2year.

7.4.1. Results for LCC

The full graph of the result can be found in the Appendix L of the report. The figure 18 shows the initial cost of the investment.

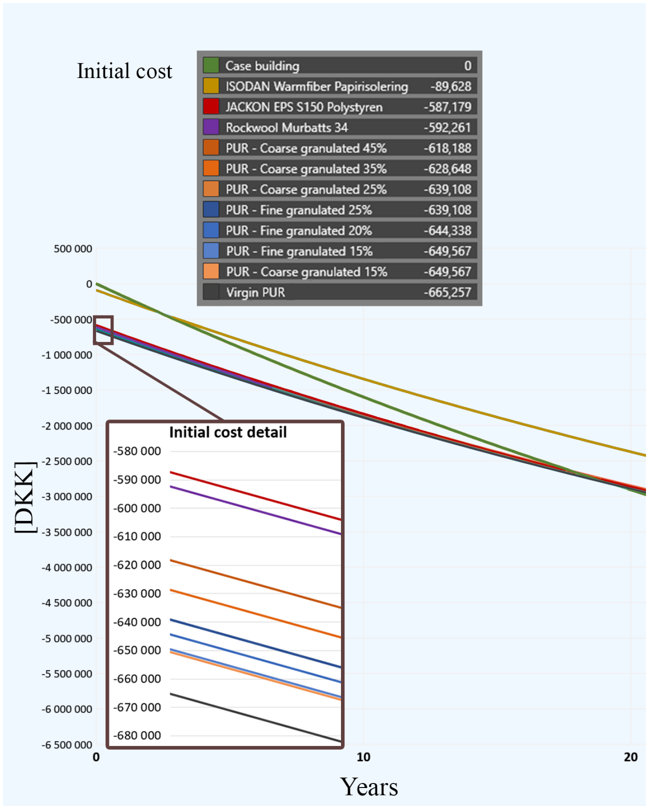

Fig. 18: Results of LCC over the period of 1 - 20 years

Figure 19 shows the total cost caused by the building element from 30 to 50 years period.

7.4 Results for Renovation of case building

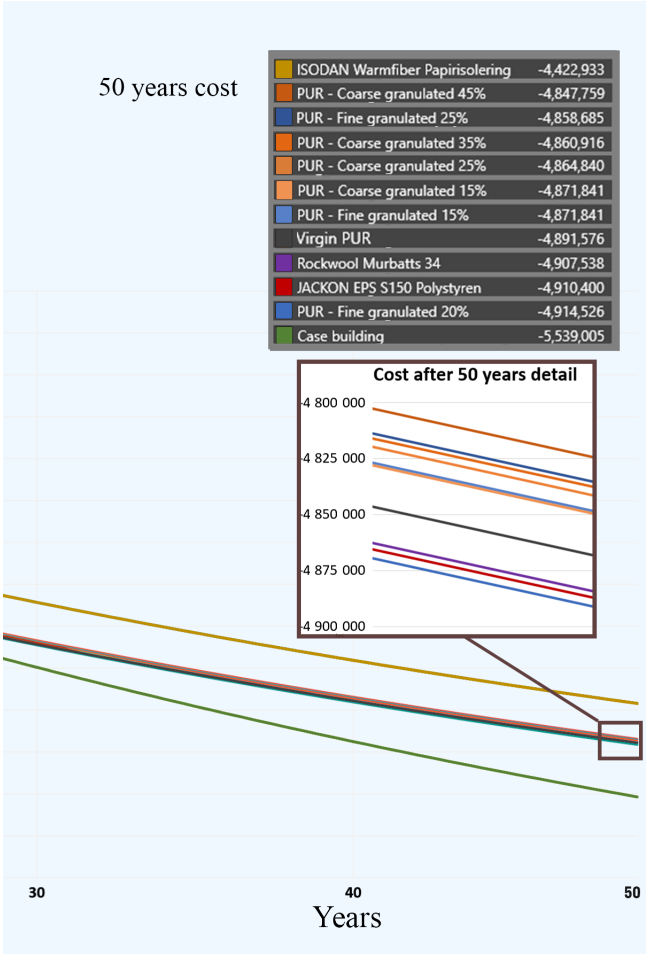

Fig. 19: Results of LCC over the period of 30 - 50 years

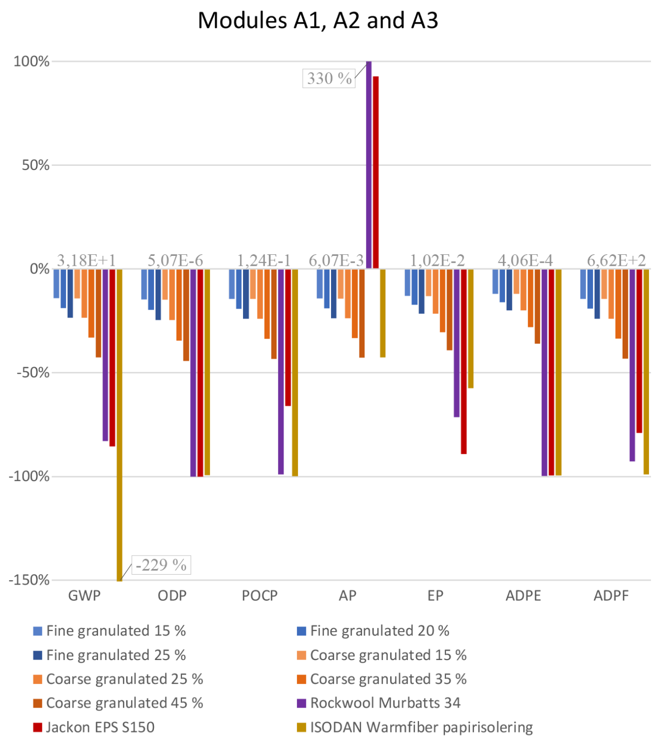

Fig. 20: Differences between the insulation materials LCA (Modules A1,A2 and A3)

In conclusion, the cheapest for the acquisition cost as well as the cost after 50 years is the ISODAN warmfiber papirisolering. But the cellulose has many problems with the containment of the particles and also cellulose is highly vulnerable to moisture. Another problem is that the cellulose can not be used in many other places such as the insulation of pipes and ducts in the building. Or can not be used as external insulation on the walls.

As for the other materials the initial cost of the EPS and Rockwool is lower than the recycled PUR, but after the span of 50 years, the Virgin PUR and also the tested samples show better performance in comparison.

7.4.2. Results for LCA

The changes are represented as a percentage change from the reference material which is for the graphs 20 and 21 the virgin PUR.

From the graph 20 is apparent that the PUR has a lower impact only in the parameter Acidification potential of land and water. These findings are highlighted even more in the graph 21 where the Rockwool Murbatts 34 has 362 % greater environmental impact compared to the virgin PUR.

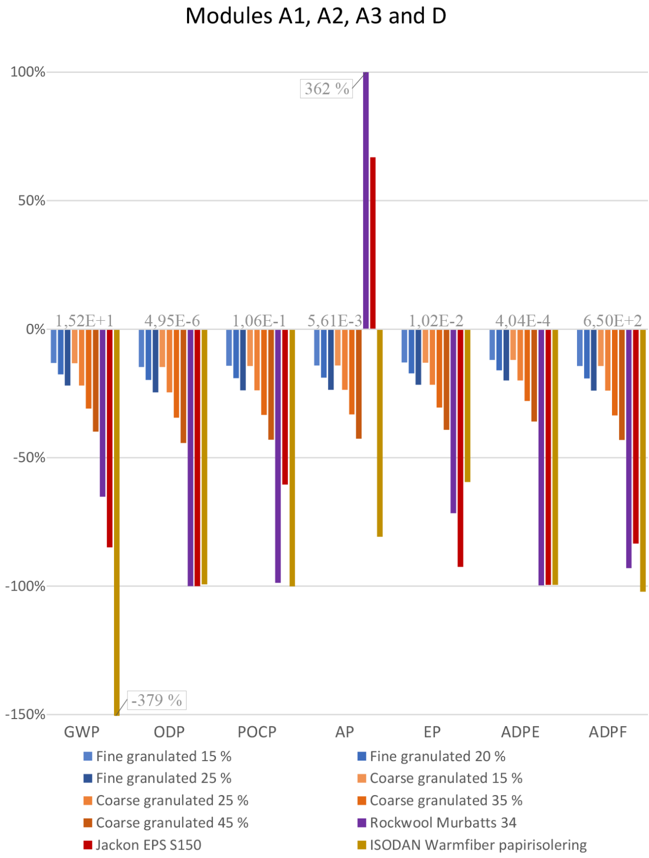

Fig. 21: Differences between the insulation materials LCA (Modules A1, A2, A3 and D

For the understanding of the environmental impact of the renovation of the external wall, not only insulation material is compared. Unlike other materials in this study, cellulose does not require the demolition and building of a new outer layer from bricks.

The results from the LCAbyg are in the table 11. It is per m^2 of the external wall from bricks. It is a sum of the impact of the bricks, lime plaster and finishing layer.

TABLE 11: THE RESULTS FOR THE BRICK WALL

Cat.	Environmental indicator %	External wall
GWP	$kg\ CO_2 - eq$	6,67E+1
ODP	$kg\ CFC11 - eq$	2,03E-2
AP	$kg\ SO_2 - eq$	5,75E-2
EP	$kg\ (PO_4)^3 - eq$	1,14E-2
POCP	$kg\ ethene - eq$	8,45E-3
ADPE	$kg\ Sb - eq$	3,22E-5
ADPF	MJ	8,91E+2

Since the cellulose was already best performing in many categories and since these environmental burdens are added only for the other insulation options it would be considered the best. The problem with cellulose is the limited amount of recycled paper from which the cellulose is created and the most problematic part is the fact that It can not be used in many places because it does not hold its form.

7.4.3. Conclusion of the external wall renovation

Chosen recycled PUR was compared with other insulation materials from the market and applied to a building renovation. This practical evaluation could give a clear image of the properties on the building scale. The analysis of the environmental impact shows that the PUR is not as good as the other materials, but as can be seen from the end-of-life cost, the energy requirement for the building decreased. The LCA analysis does not cover the modules for the operational use environmental burdens, which would be in favour of the PUR since the energy needed for heating is lower than that of its competitors.

The return of the investment for the wall renovation as can be seen in figure 18 and on the full figure located in the appendix L, is apparent that the cellulose has investment returns already after around 3 years while all the other materials have the return of the investment in around 18 years.

8. CONCLUSION

The tested 31 fine and coarse granulated samples delivered the following result. The content of recyclate in the recycled PUR influences the density of the sample and the thermal conductivity is highly dependent on the density. Furthermore, the material structural integrity was influenced by the percentage of recyclate in the fine granulated samples. Fine granulated samples limit, as neither the samples with 35 % nor 44 % of recyclate had their structure feasible with the intended use. The fine granulated recyclate takes a high amount of heat away from the PUR chemicals during the expansion process and restricts the curing. This can be clearly seen in the microscopic pictures of 35% and 44% fine granulated samples, where a lack of pore structure could be identified. Coarse granulated samples on the other hand reached the highest amount of recyclate content reached with 45 %, whereas the sample with 46% suffered from structural integrity deformation.

The compressive strength of the coarse granulated samples was similar to that of a virgin PUR in an interval of ±17 *kPa*. On the other hand, fine granulated samples' strengths vary, which was influenced by the use of fine granulated particles. As the particles cannot bind with the virgin PUR on a high level to create a durable material structure. There is no specific requirement for the strength of the insulation material but all of the PUR samples have a strength much higher than commonly used mineral wool.

New simulations showed that the usage of fewer raw materials for PUR production can improve the environmental properties. The environmental impact could be reduced by around 40 % for the 45% coarse granulated samples. This improvement could move the product closer to Rockwool and Jackon EPS products. However, this does not describe the whole environmental impact of modules that were not declared in the competitors' EPD documentation to compare the full LCA.

In comparison with the other materials, cellulose was a clear winner in terms of the LCA and the return on investment from the LCC. But cellulose runs often into many problems. The cellulose has a limited amount of recycled paper from which the cellulose is created and the most problematic part is the fact that it can not be used in many components because it does not hold its form. For example external insulation on the wall or insulation around pipes or also insulation for some types of roofs and ceilings.

The initial cost of recycled PUR decreased and with the 38 % lower thermal conductivity compared to other insulation materials the return on the investment time of the recycled samples is lower by several years in comparison with the virgin PUR, after the calculation of LCC.

For the summary, it is very feasible solution for the PUR to be recycled, since it reduces the environmental impact and also the cost of the final product, while keeping similar properties.

9. Further research

In this study, all of the samples were recycled prototypes, where few modifications of material properties could result in large changes. This was especially valid for the fine granulated 25 % sample. The change in the mixing machine (due to the malfunction of the old one), the material significantly improved its thermal conductivity to reach the level of virgin PUR. However, only one produced sample with this new method was tested therefore for the final evaluation it could not be validated. Since it showed a new path for improvement for the fine granulated recycling method the mixing should be further researched. According to Dan-iso A/S internal material development, the fine granulated method has a maximum between 20-27 % where the material structure is still uniform, but can this new mixing technology increase the stability of the sample reaches a higher amount of recyclate?

Further research can be made on another type of case building. Since there is a number of buildings which require high insulation (passive houses), where the high difference in thermal conductivity between the PUR, Rockwool and EPS could create varying results. The result of this study can decrease the initial cost of construction and decrease future property tax payments too. Because if the property tax is paid based on the external floor area (including the wall thickness) and therefore with PUR the building can reach the same thermal transmittance with a smaller thickness of the insulation than for example Rockwool.

The PUR can be precisely shaped and serve as insulation of pipes for the installations in the building. Further research is needed on the recycling ability of these smaller elements with presented recycling methods.

Further research can be made with the full LCA comparison including all the modules, for example, module B6 Operational use can be in favour of the PUR since it has a better thermal conductivity in comparison to the other materials.

The repeatability of recycling is another part that can be investigated. How many times can the PUR be recycled before it loses its value in thermal conductivity strength and pore structure?

10. Acknowledgment

This report and the research behind it would not have been possible without the exceptional support of Herluf Ubaldo Montes Schütte from Dan-iso A/S and the supervisors from AAU, Michal Zbigniew Pomianowski and Endrit Hoxha. Their enthusiasm, knowledge and exacting attention to detail have been an inspiration and kept the work on track. Their unconditional support made access to the university laboratory devices quick and easy nevertheless their comments and ideas increased the value of this study.

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Part II

Master thesis

Introduction A

Ensuring sustainable development is one of the important parts of this project, but what does that mean?
The Brundtland Report [1] defines sustainable development as:
“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” This means the need for recycling is an important factor in the development of new materials.
According to EU statistics [2] more than one-third of all the waste comes from construction and demolition. Throughout time the amount of insulation in the waste is also increasing as stated in the waste statistics [3] due to the trend of higher use of insulation in general. Therefore, the need for better inclusion of insulation materials in the circular economy is rising.

In the Environmental Product Declarations (EPD) documentation of other commonly used insulation materials [4] can be found that for Rockwool, 90,4 % of the material ends as a landfill with the remaining 9,6 % recycled. It is important to create new materials as well as new recycling methods to move forward within the sustainable industry.

This thesis contains research in collaboration with the company Dan-iso A/S, which produces PUR and PIR insulation. The main focus is on testing the two new methods for recycling their insulation material. The properties might change with the percentage of recycling and it is important to investigate how and why they could vary. The study focuses on testing the thermal conductivity and strength of the material as well as the environmental impact.

The current approach for the end of life of the PUR is municipality incineration for energy recovery, but with an achieved recycling method the end of life of the PUR can mean the reuse in the production. This would help to reduce production waste as well as waste from the building industry.

The final step of the thesis is to apply the measured results in a renovation case for a case building and investigate whether the PUR is a feasible solution in comparison with other options for insulation materials on the current market.

A.1 PUR vs PIR

Polyurethane [5] was created in Germany in 1937 by Otto Bayer and his colleagues. In 1954 PUR (Rigid Polyurethane) was created by the accidental introduction of water to polyurethane resulting in rigid foam insulation.

In 1967 PUR's thermal stability and flame resistance were improved by the creation of the PIR foam (Polyisocyanurate). To create this new formulation, the scientist included an extra chemical reaction at high temperatures.

A.1.1 Differences between PUR and PIR

It can be confusing for the general public to understand the difference between PUR and PIR insulation. Both insulation materials bear low thermal conductivity properties, which makes them better than the other commonly used standard insulation.

PUR [6] foams are made by a reaction of "polyol" and "isocyanate" elements in which the OH_2 (Hydroxide) of the polyol elements chemical balance the NCO (an isocyanate chemical group) isocyanate components creates urethane linkage as can be seen in the figure A.1.

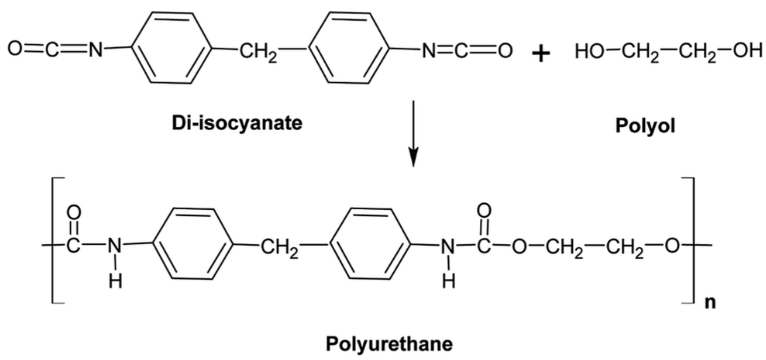

Figure A.1. PUR chemical synthesis [6]

In PIR [7] foams the "isocyanate" elements react with each other in a trimerization reaction to establish isocyanurates. Excess "isocyanide" reacts with a polyol to establish urethane linkage as well. (See figure A.2)

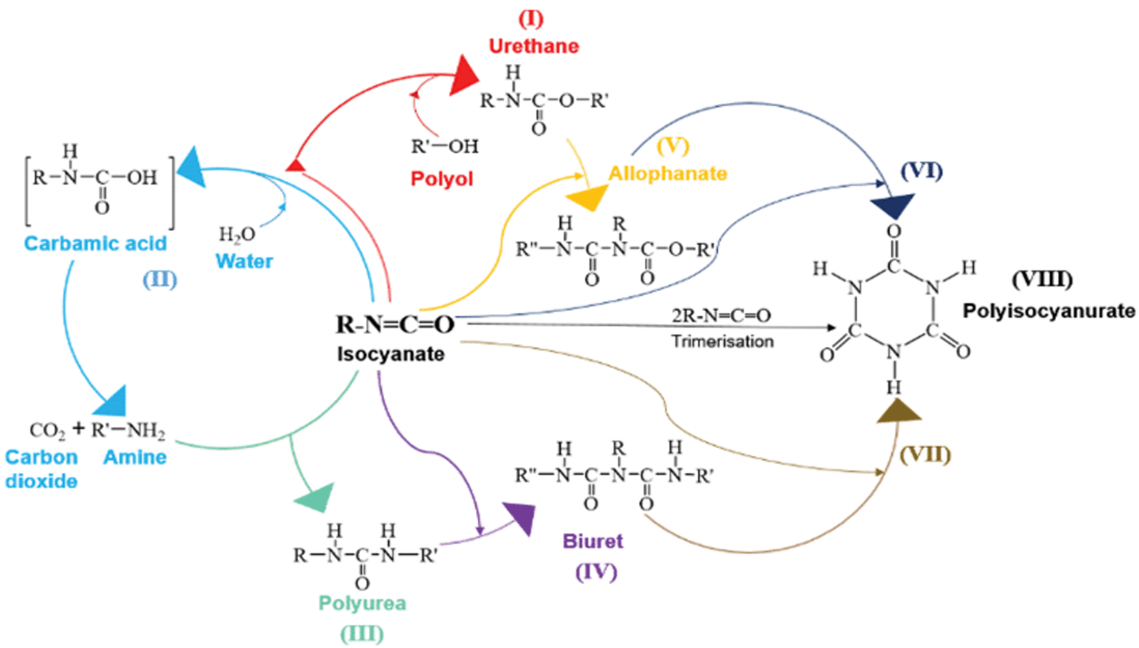

Figure A.2. PIR chemical synthesis [7]

A.1.2 Benefit of PUR foams

PUR is used as a sprayed insulation foam. This property gives a unique advantage compared to other standard insulation as it can be injected into any wall cavities where the smaller volume foam will expand and create an air-tight seal. The application of PUR foam has no limitation in the building industry on the surface where the material can be used. PUR and PIR have the same unique property as they are highly water and moisture-resistant making them suitable for usage in flood-prone areas.

The downside in the case of injection is there can be damage caused by not following specific instructions of the application. Additionally, in Denmark, there are restrictions to the spraying of chemicals that prevent the widespread use of spray PUR.

A.1.3 Benefit of PIR foams

PIR is used and sold typically in sliced boards. It is used for insulation of metal panels, wall cavities and as insulated plaster boards. PIR has such a high thermal conductivity that it can be used in a thinner thickness than other standard insulation to fulfil the needed thermal transmittance. It is useful insulation in case of space limitation for renovation.

PIR differs from PUR in the flame and smoke-resistant properties of the material. PIR has the unique ability to slow down the flame spreading and reduces the emitted smoke from the fire comparison.

A.2 Dan-iso A/S

Dan-iso A/S is a PUR and PIR insulation producer company, that is capable to supply these high-performance materials to customers from a wide range of industrial sectors. Dan-iso A/S can supply their product in every needed shape thanks to their highly precise Computer Numerical Control (CNC) machine. However, CNC is used mainly for prototypes, as CNC-made insulation is too expensive for most requirements.

Dan-iso A/S was established in 1986 in an old diary building in Aars by Finn and Ebba Pedersen. At the time they had only a few employees whose high quality of work paid out, as the company started to grow at high speed. In 1993 the company changed its title to the latest Dan-iso A/S.

In 1999 a second production hall was built to bear the high demand for production. In 2005 a generation change took place in the company and the so-called "management buy-in". At that time the original owners stepped down from the management and Fin Højgaard took it over and owned it until 2017.

In 2018 Erik H. Møller as the current owner took over the company and shaped the company into today's form. Dan-iso A/S is one of Europe's leading specialists in the technical insulation material of PUR. They also look towards future needs and criteria by taking high attention to their product's recycling capabilities.

The main speciality of the company is the more complicated smaller size components, which are declined by the competitors. There is no limit in shape for their CNC machine to produce the material for the components. The customers usually come from the sectors described in the table A.1:

Table A.1. Sectors of the usual customers.

Marine	Insulation of specialised bitumen tankers in extreme temperatures Insulation for cooling reefers
Industry	Steam systems Condensation pipes Ventilation systems in airports
Oil and gas	Insulation in risers from bed sea to platform Insulation of pipelines Insulation of LNG terminals
Energy	Buried pipe systems Insulation of river crosses Geothermal heating systems

Due to the ambition of lowering their product's carbon footprint, Dan-iso A/S has decided to devote substantial resources to the development of methods that allow for the recycling of the material waste from their production line.

Dan-iso A/S is capable to serve a wide range of needs from their customers in high-quality certificates such as EN-253 (district heating) and in the near future also the EN-14308 (thermal insulation products for building equipment and industrial installations).

Problem formulation B

This thesis contains research in collaboration with the company Dan-iso A/S, which produces PUR and PIR insulation. The investigation will focus on testing their new methods of recycling the PUR material in terms of thermal conductivity as well as an LCA comparison of their new insulation components with the current standard on the market from the competitors. The amount of the material recycled (up to 45%) was not achieved yet in other recycling studies of PUR material [8] , where the recycling is less than 10 % by weight.

The insulation properties might change based on the recycling percentage and recycling method. Therefore, the goal is to create and measure samples of various percentages over the span of the possibility in order to create an overview of the properties of the percentages. The overview contributes to finding the optimal solution (heat transfer) for the percentage amount over the possible recycling percentages, which is then compared to other insulation materials on the market.

The material is then also simulated with life cycle cost and life cycle analysis to other rigid insulation types as well as wool or blown-in insulation. If the new product will be a viable opponent for the materials currently used on the market, the company can consider expanding their field of insulation products production.

The PUR is tested as a material for the properties and then it is also simulated in an example case building for the visualisation of the effect it has on the LCC and LCA of the case building, where the applicability can be compared with the tools such as SimaPro and LCAbyg.

The LCC is one of the most important parts of the analysis since the main drawback of the PUR is that it is more expensive than other materials with worse thermal quality. The analysis of the cost efficiency utilises the software LCCbyg to define the possible economical benefit of renovation with this insulation instead of other options.

The material is investigated for applicability using the renovation of an old multi-storey residential building as a case. The different results will result in a comparison of different renovation options within the LCA and LCC.

Research questions:

- Is there a difference in the thermal conductivity of PUR with different recycling percentages?
- Is there a difference in the compressive strength and structure of PUR with different recycling percentages?

- What is the comparison between the new material and the other insulation products in different places in terms of LCC, LCA and applicability?

All those questions will be answered throughout the report and supported with documentation.

Introduction to laboratory measurements C

The recycling of demolished building materials is an important task, to reduce the overall environmental footprint of a renovation. The demolished PUR is not used currently to reduce the environmental footprint of the newly produced PUR, which can change now. Recycled particles can influence material properties such as thermal conductivity, strength and structural integrity. In the following sections, the listed material properties are observed and evaluated.

Measured three of the main properties:

- Thermal conductivity **See section D**
- Structural properties **See section E**
- Structural strength **See section F**

In every measurement, a short conclusion as a result of observation gave the possibility to neglect certain prototypes. These factors can be as density is out of range, structural uniformity is poor or the measured thermal conductivity varies too far from the regular virgin PUR. The chosen samples are further investigated until the end of the laboratory measurements.

C.1 Recyclated PUR

There is a possibility to recycle PUR chemically [9] and mechanically. This thesis is focused on mechanical recyclation with two different methods.

The first method is Fine granulated (section C.2) the second is Coarse granulated (section C.3)

The recyclate taken into consideration is from demolished buildings and or production waste with a density variation of $55kg \pm 8kg$.

C.2 Fine granulated

The PUR, which has to be recycled, must be milled until the particle size is under a millimetre.

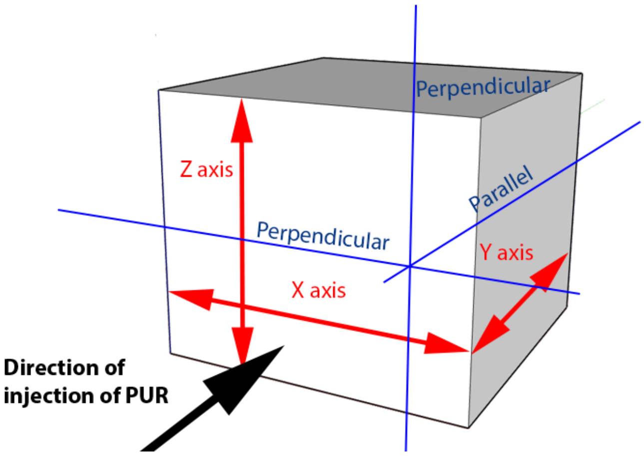

Figure C.1. Injection axis of fine granulated PUR

The direction of the injection is towards the horizontal X-axis surface (see figure C.1). Due to the force of the PUR with the mixed recycled particles flowing towards the sides of the form. In the meantime the free rising begins, which is restricted by the horizontal sidewalls and continuous upwards. According to internal material strength measurements, the measured strength values were different for the parallel and perpendicular angles with respect to the direction of the injection. When the PUR due to the expansion reached all the sidewalls, the material gets compressed. Due to the continuous force of the expansion, the pore structure gets deformed as a result of being more resistant to forces compared to the perpendicular sides after curing.

The difficulty of production is low. It is because the method can be automated and used in large-scale production facilities. The used recycled fine granulated particles and the polyol, isocyanate mixture can be measured precisely. It means that the reproduction of the same recycled percentage and density with $\pm 3\ kg$ is possible to compare to the PUR with coarse granulated pieces.

C.3 Coarse granulated method

The production of PUR with recycled coarse granulated pieces varies from the recycled fine granulated products. In this method, the recycled PUR uses particles which are larger than 1 cm.

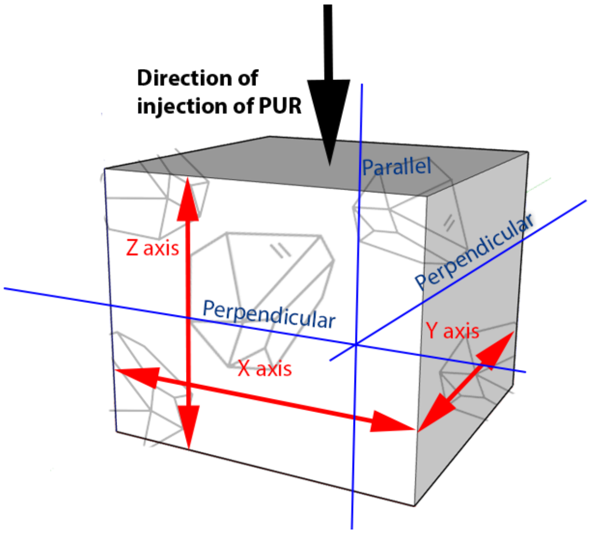

Figure C.2. Injection axis, of coarse, granulated PUR

Production technology of the coarse granulated samples requires more effort in terms of preparation before the PUR can be injected into the production form. The coarse granulated pieces have to be placed carefully and sorted according to their shape and density. They are influencing the structural properties and the density by approximately $\pm 5\ kg$. The production form can be over-packed and by the force of the expansion of the PUR, can move and squeeze the pieces together, leaving larger holes in the material.

C.4 Tested samples

There was a limitation of prototype production in terms of density and recycled percentage. The aim of the used percentage of recycled particles was to evaluate the material properties changes by producing prototypes for every 5 % of the increased amount of recycled particles. This issue was especially complicated for the coarse granulated recycling method because of the density of the recyclate parts. In table C.1, there is a set of measured samples from both fine and coarse granulated recycling methods.

Table C.1. Number of samples during the laboratory experiments

Method	**Recycled %**	**Amount of prototypes**
Virgin PUR		3
Fine granulated	15 %	3
	20 %	3
	25 %	1
	27 %	1
	35 %	2
	44 %	1
Subtotal:		**11**
Coarse granulated	15 %	2
	16 %	3
	25 %	3
	35 %	2
	37 %	1
	42 %	1
	43 %	2
	45 %	3
Subtotal:		**17**
In total:		**31**

Laboratory experiment - Thermal conductivity D

Thermal conductivity defines the heat transferred through the cross-section of the material by conduction when a temperature gradient exits perpendicular to the area.

The transmission coefficient for a building component is the relation between the heat flow and the area and the difference between the temperatures on each side of the building component. The definition of the thermal coefficient can be found in International Organisation for Standardisation (ISO) 7345 and DS/EN 7345 item 2.12.

D.1 Methodology

A building element consists of several different building components. These materials have various thermal conductivity values. To evaluate the building elements' final thermal transmittance, calculations are needed.

The equation D.1 explains the calculation method of the uncorrected thermal transmission for a building element. After the calculation, other correction aspects (described in DS418 [10]) must be considered to calculate the thermal coefficient.

$$\frac{1}{U'} = R_{si} + R_{se} + \sum_{i=1}^{n} R_i \tag{D.1}$$

U' - Uncorrected thermal transmission coefficient $[W/m^2K]$
R_{si} - Surface resistance at the inner surface $[m^2K/W]$
R_{se} - Surface resistance at the outer surface $[m^2K/W]$
R_i - Thermal resistance for each material layer $[m^2K/W]$
n - Number of layers

The R_{si} and R_{se} can be found in the DS418 while the R is calculated with equation D.2.

$$R = \frac{d}{\lambda} \tag{D.2}$$

R - Thermal resistance $[m^2K/W]$
d - Thickness of the material layer$[m]$
λ - Thermal conductivity of material $[W/mK]$

Therefore this thesis focuses on measuring the thermal conductivity of the samples prototypes to determine thermal properties.

D.1.1 Measurement of thermal conductivity

The additionally added recycled particles are capable to influence the thermal conductivity. To evaluate these changes measurements are needed. For the measurement, the Guarded Hot Plate Apparatus EP500 from Lambda-Messtechnik Gmbh was used.

General information about the Hot Plate Apparatus

The description of the Guarded Hot Plate Method for Thermal Conductivity Measurement guides the execution of the thermal conductivity measurement. The used Guarded Hot Plate Apparatus EP500 from Lambda-Messtechnik GmbH is capable of accurately measuring the steady-state thermal conductivity of insulation materials. The range of measured thermal conductivities is from 0,005 w/mK to 2 W/mK. The available temperature difference between the upper and lower plate ranges from 10°C to 40°C. with the difference being between 5 K to 15 K. The vertical pressure ranges from 500 Pa to 2500 Pa on the tested specimen. The final controlled pressure depends on its hardness [11].

The PUR prototypes are not available in the required dimension with a base size of 500 x 500 mm. There is a solution available, which is a smaller sample base size of 150 x 150 mm with a thermal protection shield around the prototype.

The target is to maintain a one-dimensional temperature gradient and heat flux between the plates. As the temperature on the cold guarded plate could get lower than the dew point and it could compromise the measurement. The testing zone is protected by a double coil protection ring. This ring prevents any external humidity penetration towards the testing zone.

The measurement is completed once the stability criteria are met when the difference between the maximum and minimum thermal conductivity number is not more than 1 % over 500 minutes of time [11].

D.1.2 Set up of test conditions

First, the temperature condition of testing was defined with the guidance of ISO 8302 [12], which includes the stability criteria corresponding to upper and lower measured limits. The measurement should be comprised in over a specified amount of time

The different average temperatures can result in different thermal conductivity due to the various performances of the materials, therefore the tested PUR has selected a temperature close to usage for building insulation. Guidance in ISO 8302 [12] only explains the set of average temperatures has to be considered according to the final place of usage of the tested specimen. The lowest available average temperature between the upper and lower plate was chosen, which is 10°C.

Condensation can occur due to the used temperature set because the hot side of the plate is chosen to be 17,5°C and 2,5 °C on the cold side during the measurement. The temperature goes under the dew point creating unwanted condensation. Rigid Polyurethane foam has very little absorption of water and rather acts as a repellent, this is because of its closed-cell structure and hydrophobic nature. Water resistance of rigid polyurethane study [13] shows that small-scale tests in the laboratory described a water absorption below 2%.

Sample dimension

To execute a measurement, an accurate dimension of samples is required. The measured samples are cut with the precise machine to the base size of 150 x 150 mm. The pieces were surrounded by a heat shield as figure D.1 represents.

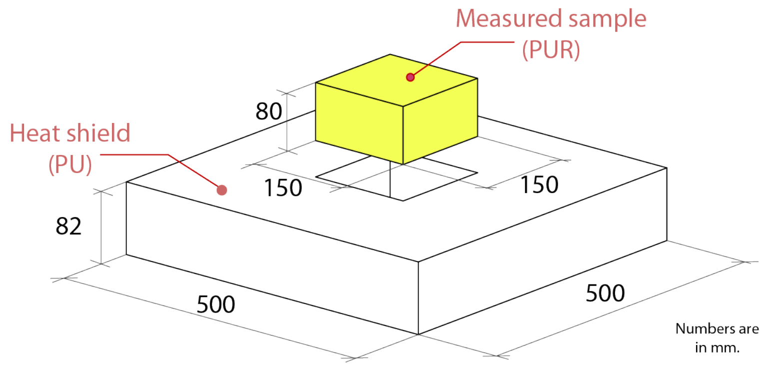

Figure D.1. Dimension of PUR sample and heat shield

Preparation before the testing

The following steps are executed on the apparatus EP500 software.

After weighing the prototype, it is placed into the PU heat shield, which can be only a few millimetres higher than the sample thickness. The following step is to place the heat shield with the sample in the middle of the test area and the hot side of the plate can be lowered. When the set pressure is applied for the sample, the displayed thickness must be below the thickness of the sample, since if it would be above, a slight air gap can occur, which can highly compromise the measurement. For rigid products, 1000 Pa pressure is set in order not to damage the surface.

Set up of EP500 Hot Plate Apparatus software

After the condition of the testing sample in the proper heat shield was located in between the plates, the EP500 software was set up.

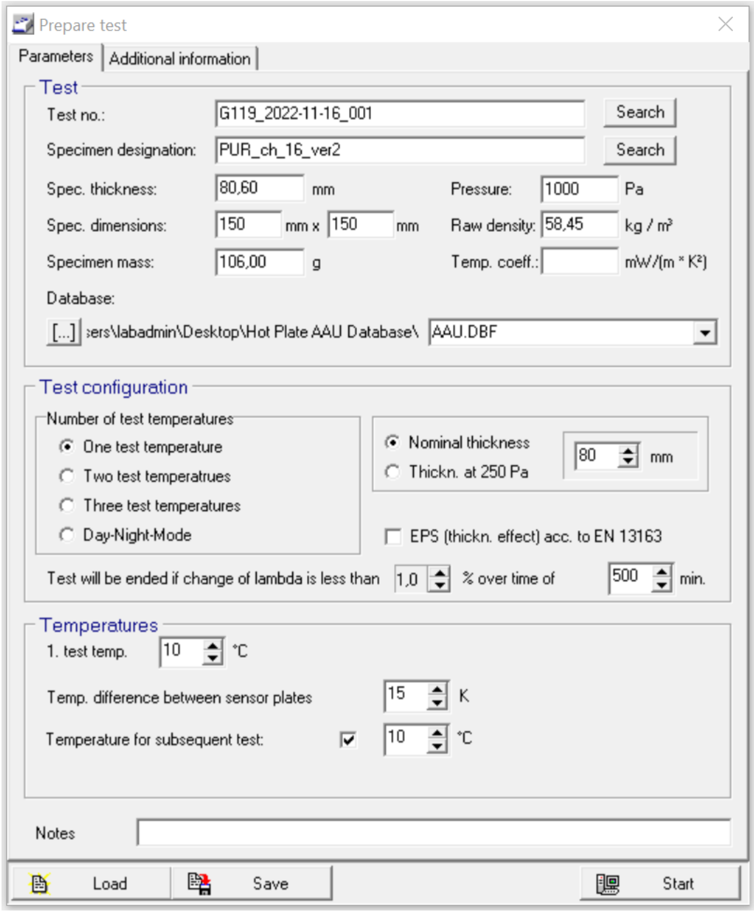

Figure D.2. EP500 Test preparation setup surface

Figure D.2 describes the setup conditions for the test, which is further explained below:

- Specimen designation describes the name of the test
- "Spec. thickness" filled up automatically from the Hot plate apparatus, after the currently set "pressure" 1000 Pa was loaded onto the sample.
- "Spec. dimension" is the dimension of the sample, which describes the measured area during the test.
- "Specimen mass" before the sample was inserted into the heat shield it was measured. The program automatically calculates the density of the specimen according to the dimension.
- As currently, the test result is important for one allocation condition the "One test temperature" was chosen.
- As the final usage category of the specimen is wall insulation, it will get in contact with winter conditions, regarding that 10°C was chosen.
- As ISO 8302 defines, at least 10 K to 20 K temperature differences are recommended to minimise the temperature-difference measurement error, chosen is 15 K
- Measurement uncertainty must be always below 1 % and mostly below 0.5 %. In the current case, 1 % was used, due to the fact that the resulting number is accurate enough to create an accurate conclusion of the materials' insulation performance.

D.2 Results

During the measurement procedures, a great amount of information could be collected. Most of the findings helped to improve the material properties to develop a material with better thermal conductivity. Table D.1 below collects all the measurement results.

Table D.1. Results of thermal conductivity measurements

Method	**Recycled %**	**Density** $[kg/m^3]$	**Thermal conductivity** $[W/(mK)]$
Virgin PUR		54,44	0,021
Fine granulated	15 %	54,29	0,026
	15 %	49,11	0,022
	15 %	46,38	0,021
	20 %	56,91	0,027
	25 %	58,42	0,021
	27 %	57,98	0,027
	35 %	60,50	0,033
	44 %	88,98	0,038
Coarse granulated	15 %	53,16	0,021
	15 %	54,79	0,021
	16 %	58,37	0,022
	25 %	64,19	0,026
	25 %	58,26	0,023
	25 %	58,06	0,022
	35 %	54,84	0,023
	35 %	55,41	0,023
	37 %	60,00	0,026
	42 %	68,11	0,027
	43 %	63,43	0,024
	43,3 %	63,93	0,023
	45 %	49,94	0,023
	45 %	58,11	0,023

Figure D.3 visualises the correlation between the density and the value of thermal conductivity. In the figure, the 44% fine granulated sample was neglected due to structural integrity issues.

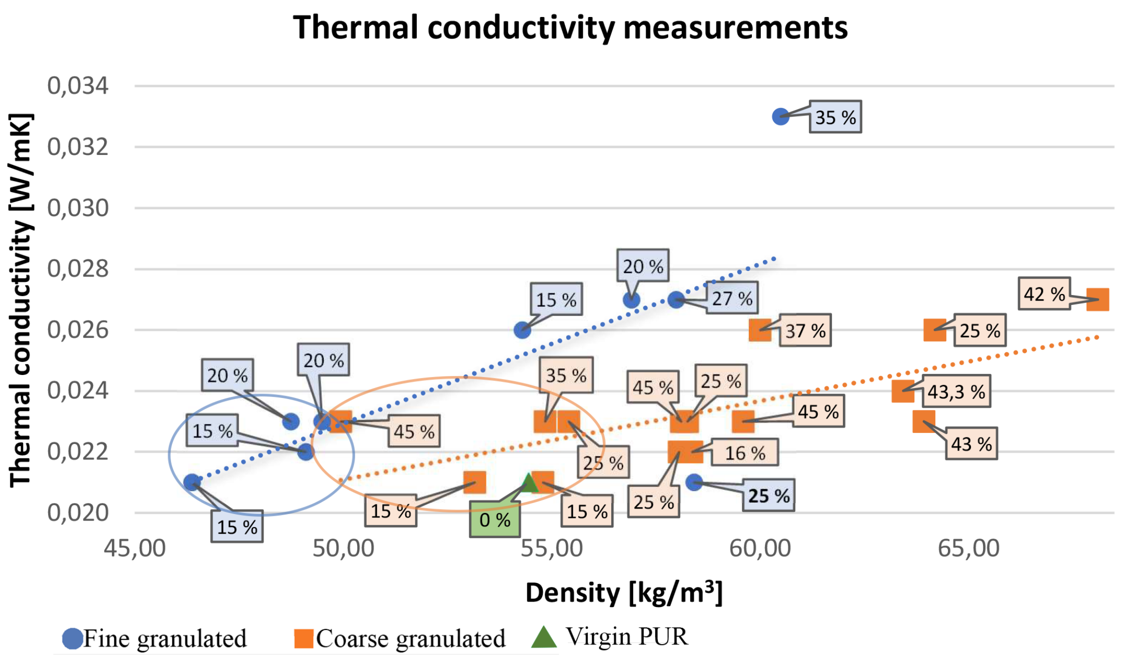

Figure D.3. Thermal conductivity results of fine and coarse granulated recycled samples

Observation of the received results from figure D.3 describes a clear pattern. The samples have the lower thermal conductivity the lower their density. Samples inside the blue circle visualise the fine granulated samples. It shows that the lowest thermal conductivity between 0,021 and 0,023 W/mK, can be reached within the range of 48 kg/m^3$\pm 3kg$ of density.

The coarse granulated samples showed a different tendency for lower thermal conductivity values. Samples included in the orange circled zone displays the lowest measured thermal conductivity between 0,021 and 0,023 W/mK, within the density range of 55 kg/m^3 ± 3 kg.

D.3 Conclusion

For the fine granulated samples, 15% and 20% were included in the blue circle with the lowest thermal conductivity. This means the repeatability of similar parameters within a similar density range is possible.

For the last measurement, a new 25% sample was created with a different mixing machine, which measured the thermal conductivity number closest to the virgin PUR. The injected PUR was mixed more evenly, therefore increased density was possible without the loss of the expansion energy through the particles. With more prototypes with this machine, there are possible changes in the case of lower density that can be done for further product development.

The coarse granulated samples have mostly lower thermal conductivity than the fine granulated particles. But the limitation of the coarse granulated method is that there is already a variable density of the recycled coarse granulated pieces. The density of the recyclate highly influences the final density as well as the thermal conductivity. The 45% coarse granulated sample spikes on the edge from the orange-circled zone due to density changes. This mixed density of coarse granulated pieces resulted in a rather low thermal conductivity.

In conclusion, the recycled amount of particles of the prototypes did not correlate with the measured thermal conductivity. The thermal conductivity was more dependent on the density of the samples, but the recyclate amount influences the possibility of the creation of specific density prototypes since the recyclate takes out the energy needed for the expansion of the PUR.

For the proper expansion and curing of the mixed PUR, sufficient heat is necessary. Due to the thermal conductivity of the recyclate particles, this heat is reduced during curing. Samples that use recyclate fine granulated particles are highly affected especially samples with higher recycled content such as 35% and 44% (read more in section E).

As a result, samples in table D.2 and other prototypes were sent for further analysis of structural and strength properties.

Table D.2. Chosen samples after thermal conductivity measurement

Method	**Recycled %**	**Density** $[kg/m^3]$	**Thermal conductivity** $[W/(mK)]$
Fine granulated	15 %	46,38	0,021
	20 %	48,78	0,023
	25 %	58,42	0,021
	35 %	60,50	0,033
	44 %	88,98	0,038
Coarse granulated	15 %	54,79	0,021
	25 %	58,06	0,022
	35 %	55,41	0,023
	45 %	58,11	0,023

D.3.1 Additional Findings

Condensation on the cold plate

Since the cold side of the apparatus runs under the dew point, condensation happens. This unwanted action can highly compromise the measurement result. However, as figure D.4 represents, the heating coil outside of the measuring 150 x 150 mm area creates a barrier, which does not allow external humidity to penetrate towards the centre of the measurement field.

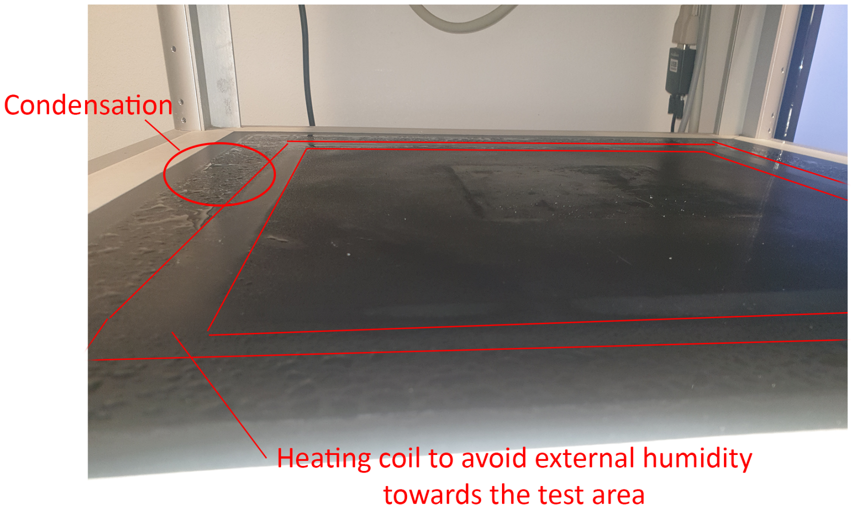

Figure D.4. Condensation on the cold plate

As to see the possible influence of condensation on the measurement result, one randomly selected sample was measured three times to evaluate the possible changes with an increased risk of condensation. The following results were measured for the coarse granulated 16% sample: 0,022 W/mK, 0,022 W/mK, and 0,022 W/mK. Resulting in an average of 0,022 W/mK. The result of the test allowed for the conclusion that the visible condensation did not influence the measurement and the heating coil on the cold side of the plate successfully avoids the penetration of outside humidity towards the measurement zone.

Thermal conductivity influenced by density

After several completed measurements, it could be concluded that the density of the test samples highly influences the reached thermal conductivity. Three samples of the fine granulated 15 % method were used, where the density was different to show the differences.

Table D.3. Property and measurement results of fine granulated 15% PUR

Sample	Density	Thermal conductivity
15 % (1)	53,21 kg/m^3	0,026 W/mK
15 % (2)	48,81 kg/m^3	0,022 W/mK
15 % (3)	46,09 kg/m^3	0,021 W/mK

Table D.3 describes changes due to the density differences.

Laboratory experiment - Structural properties

E

These tests are made to understand the pore system of the test samples and to understand what influenced the thermal conductivity. Test samples were taken under microscopic analysis to evaluate the pore system.

E.1 Methodology

A Carl Zeiss discovery v8 stereo microscope was utilised to evaluate the structural changes in the PUR. Thanks to its stereo lens system, the microscope can examine the sample in a 3D view.

Both fine and coarse granulated samples were inspected. The lens zoom was used on 1x to 2,5x magnification since the maximum magnification of 8x could not give more value to this evaluation. Lighting from below could highlight the structural pore system of the samples.

The examined samples were sliced up into 3 mm thick on their X or Y axis, as figure E.1 explains. Microscopic evaluation was made mainly on the Y-axis surface. Due to this reason, structural differences were the most visible from the axis. In case of visible structural deformation, X-axis was tested too.

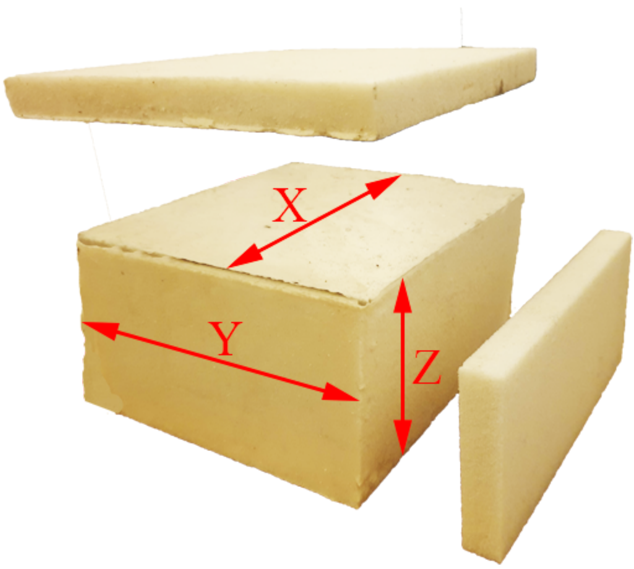

Figure E.1. Examined samples XYZ axis orientation

E.1.1 Visual evaluation of pore system

All the below-listed samples went through a visual observation, where assumptions could be made according to the level of structural uniformity or non-uniformity and the quality of their pore system.

E.1.2 Fine granulated samples

The evaluation for fine granulated samples includes the:

- 15%
- 20%
- 25%*
- 35%**
- 44%**

* Exception, as for further development of the product more information needs to be collected due to different mixing methods.

** Examined only for material development purposes.

Pore structure of 15% sample

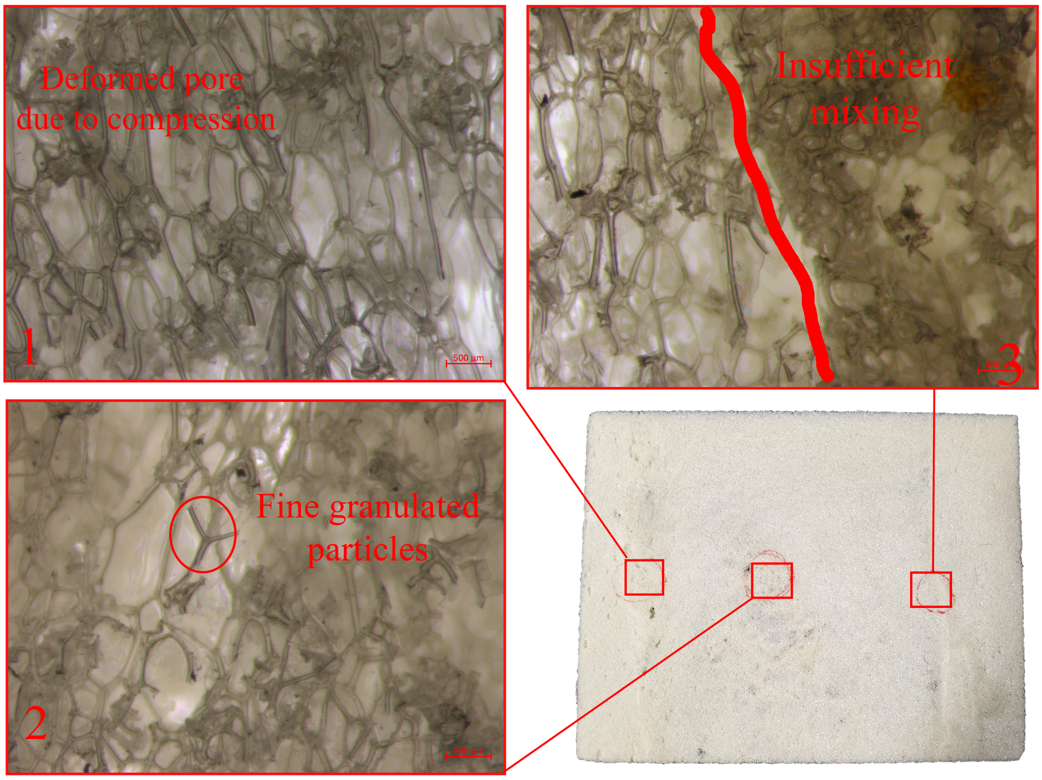

Figure E.2. Fine granulated 15% sample

Figure E.2 describes the examination of the 15% recycled fine granulated sample for pore structure. The observed number one area describes a pore system with long and narrow pores. This means that the material structure gets compressed, and the material loses structural uniformity. The number two area shows the brighter area indicates a larger portion of air bubbles, which can increase the thermal conductivity. The last highlighted spot the number three marks out an area where a more dense dark area can be observed. In this area, over-compression occurred, due to a lack of mixing of the recyclate particles during the production phase.

Pore structure of 20% fine granulated sample

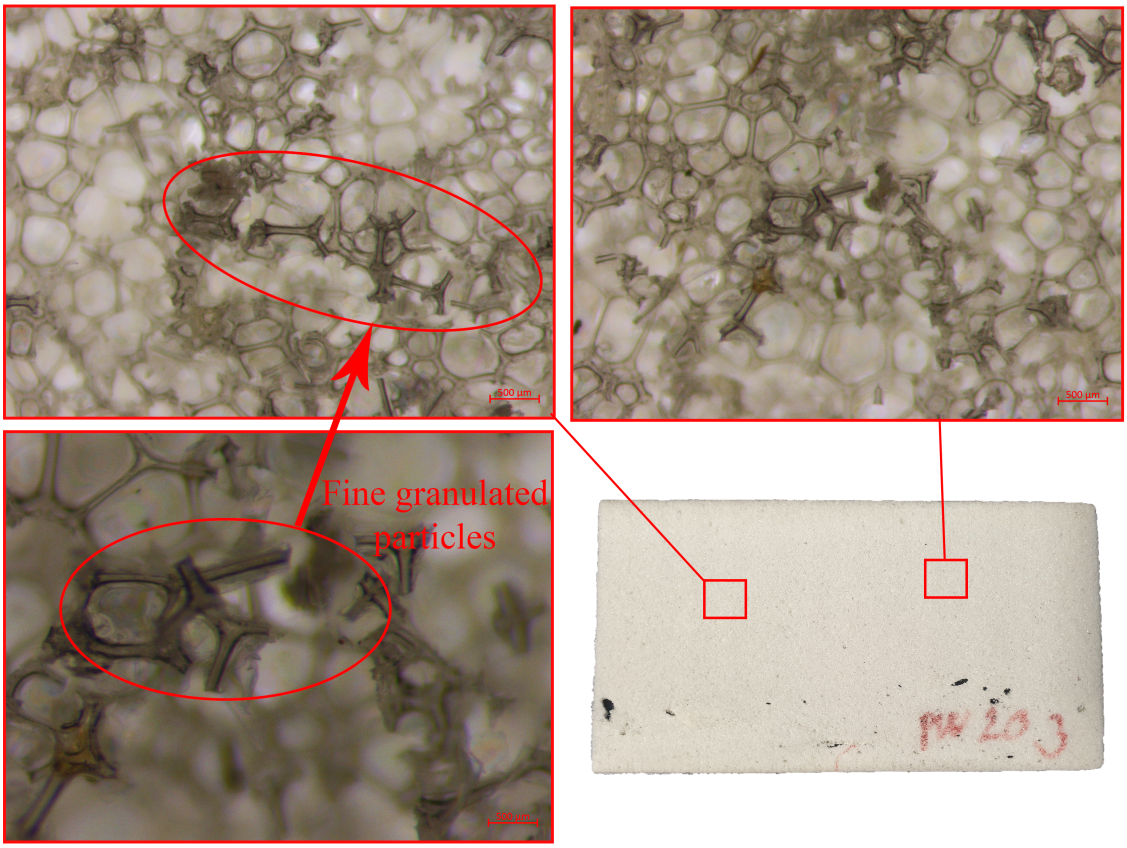

Figure E.3. Fine granulated 20% sample

The examined sample of the fine granulated 20% (see figure E.3) had a clear material structure and pore structure. The figure perfectly describes how the fine granulated recycled particles are located in the product.

Pore structure of 25% fine granulated sample

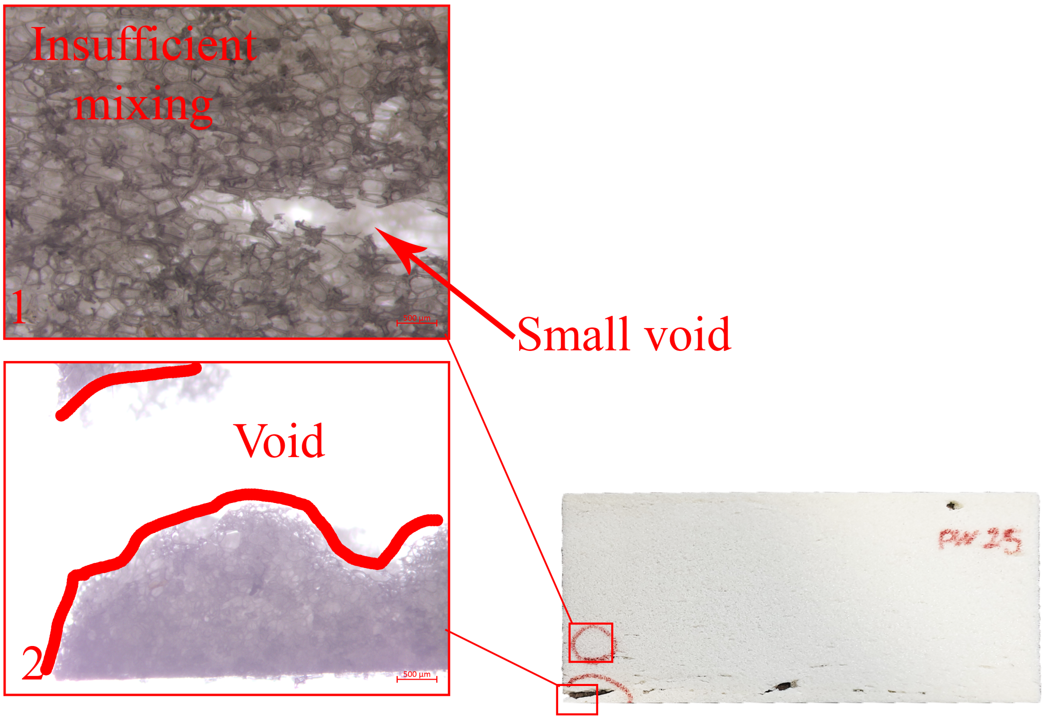

Figure E.4. Fine granulated 25% sample

The recycled sample with 25% of fine granulated particles has a clear uniform structure as figure E.4 represents. The improvement happened due to the new production technology. However, it is still possible to discover structural non-uniformity. The increased amount of mixed particles are visible in the number one area which is the dark black spots. The other defect of the sample can be found on the left bottom corner of the sample which is marked out on the number two area.

E.1.3 Coarse granulated samples

The evaluation for coarse granulated samples includes the:

- 15%
- 25%
- 35%
- 45%
- 46%

Pore structure of 15% coarse granulated sample

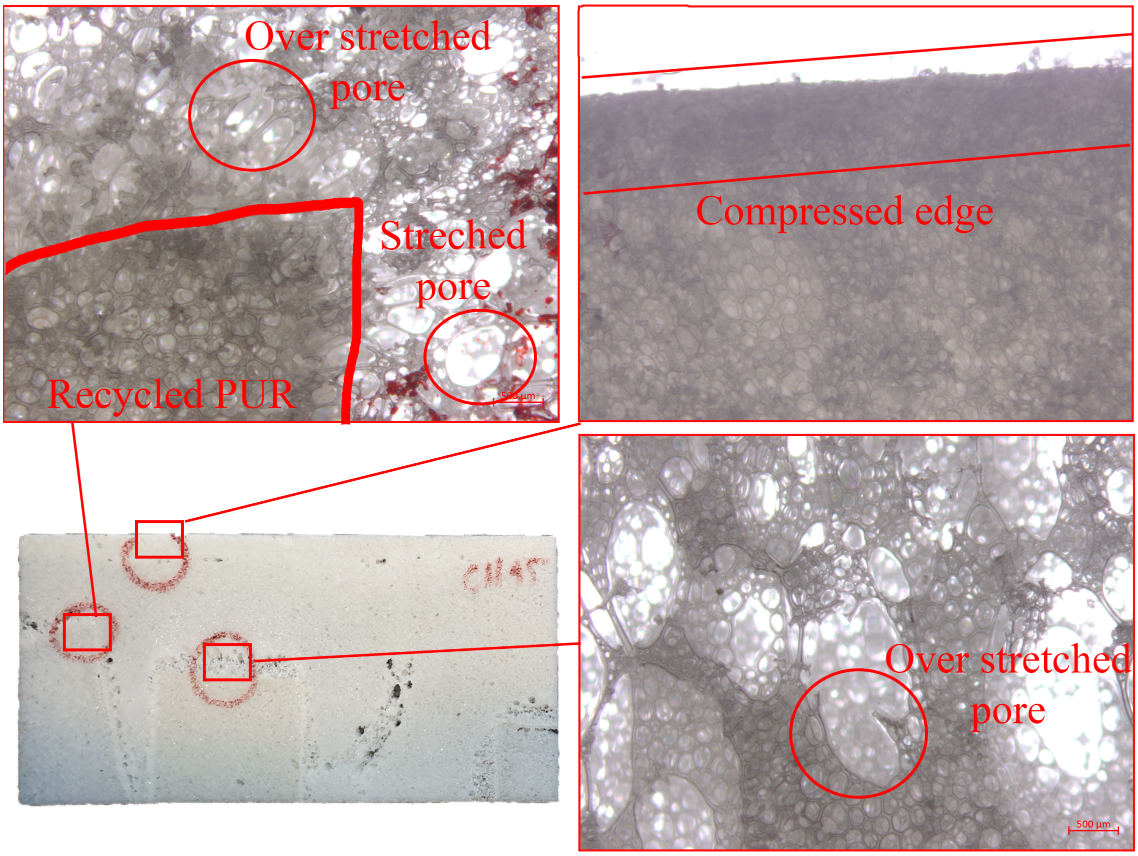

Figure E.5. Coarse granulated 15% coarse granulated sample

PUR with recycled 15% coarse granulated pieces highlights an issue when the added coarse granulated pieces integration is not clean. As figure E.5 represents the above-written case. The larger bubbled area clearly highlights where the recycled pieces are. The highlighted zone number three shows that due to the expansion and curing of the PUR during the production phase, it creates a more dense layer, which reduces the overall thermal conductivity.

Pore structure of 25% coarse granulated sample

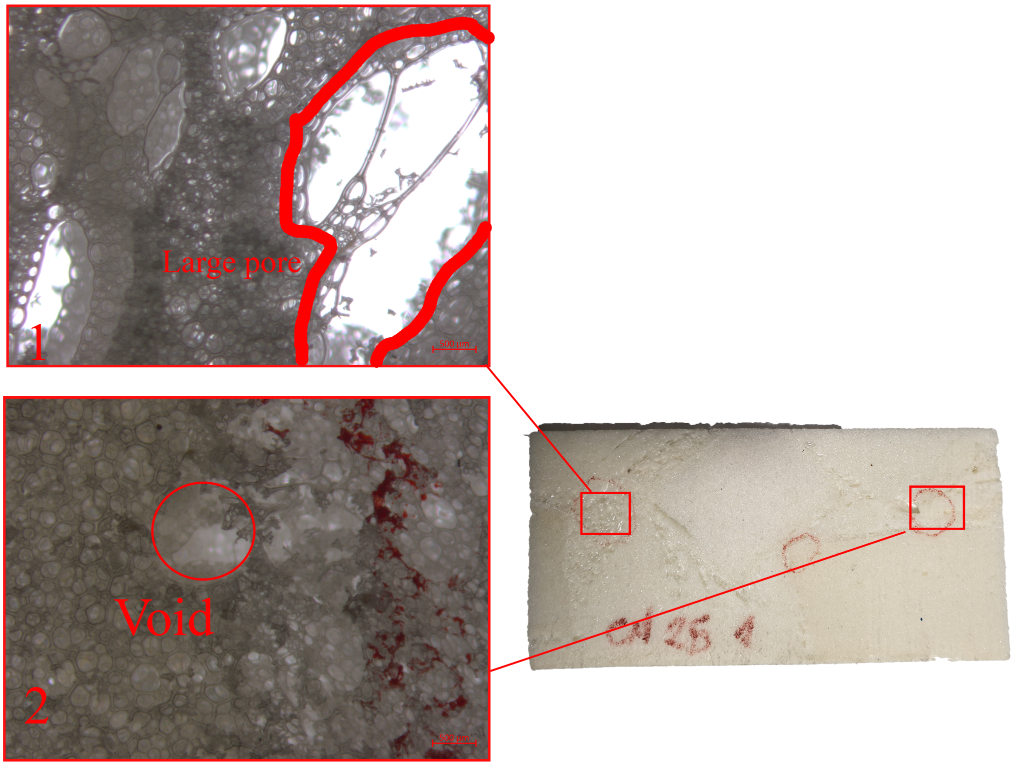

Figure E.6. Coarse granulated 25% sample

Figure E.6 represents the pore structure of the coarse granulated 25% sample. It can be observed that the structural deformity is similar to the above-mentioned coarse granulated 15% sample. The explanation can be that when the polyol + isocyanide mixture expands, it can suddenly move the coarse granulated pieces. The moving of the previously created pores deforms them, resulting in a much larger pore structure around the coarse granulated pieces. The third circled area is an example of how the previously mentioned coarse particle migration can increase the pore dimension. However, in this case, the pore is overstretched, creates cracks and leaves a larger scale of pore after.

Pore structure of 35% coarse granulated sample

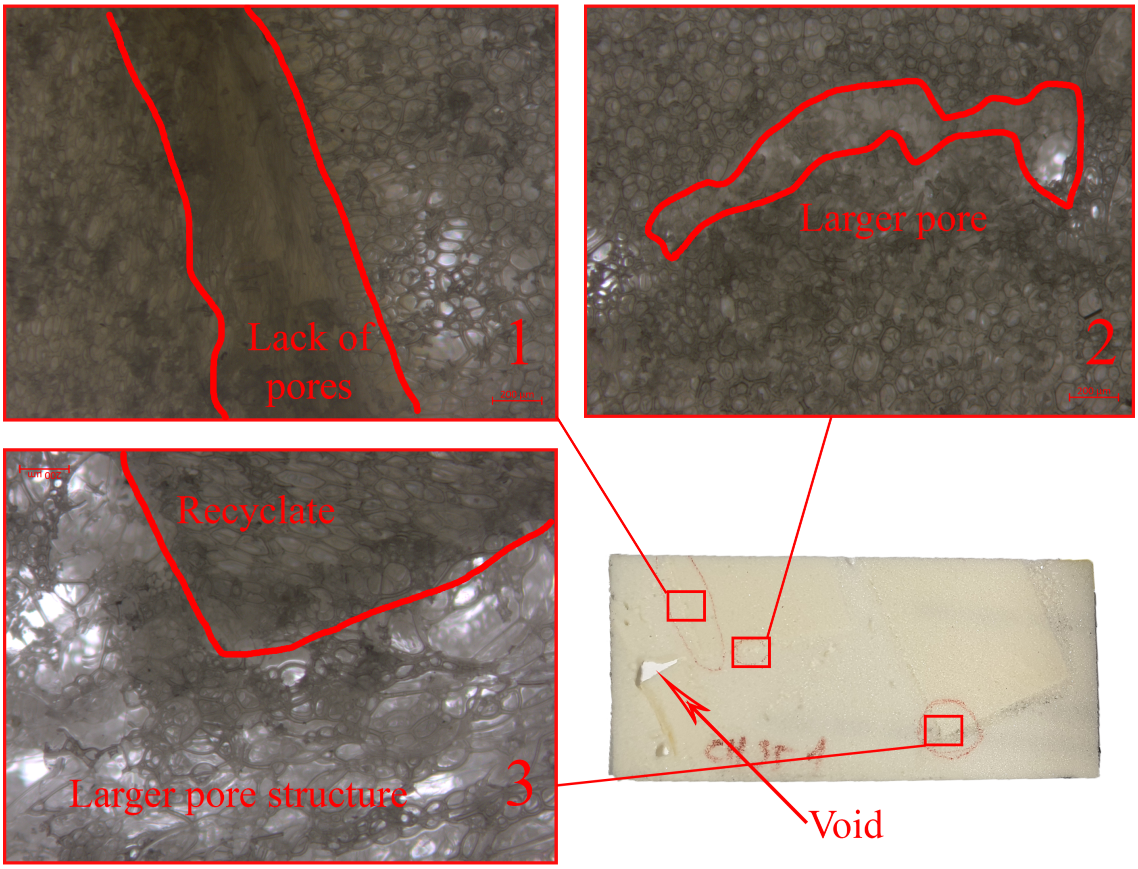

Figure E.7. Coarse granulated 35% sample

Coarse granulated 35% describes the previously mentioned observation in the coarse granulated 25%. As figure E.7 shows, on the right, where any other pieces do not surround the recycled block, had space to move. However, on the left, where the material is more packed, had no space to allocate. On the left side of the sample, a larger hole can be seen, which is the result of over packing on one side. Due to this effect, the injected and after expanded PUR could not reach and fill out that certain area. A certain issue was highlighted in section D where a coarse granulated 46% sample had a similar theme.

Pore structure of 45% coarse granulated sample

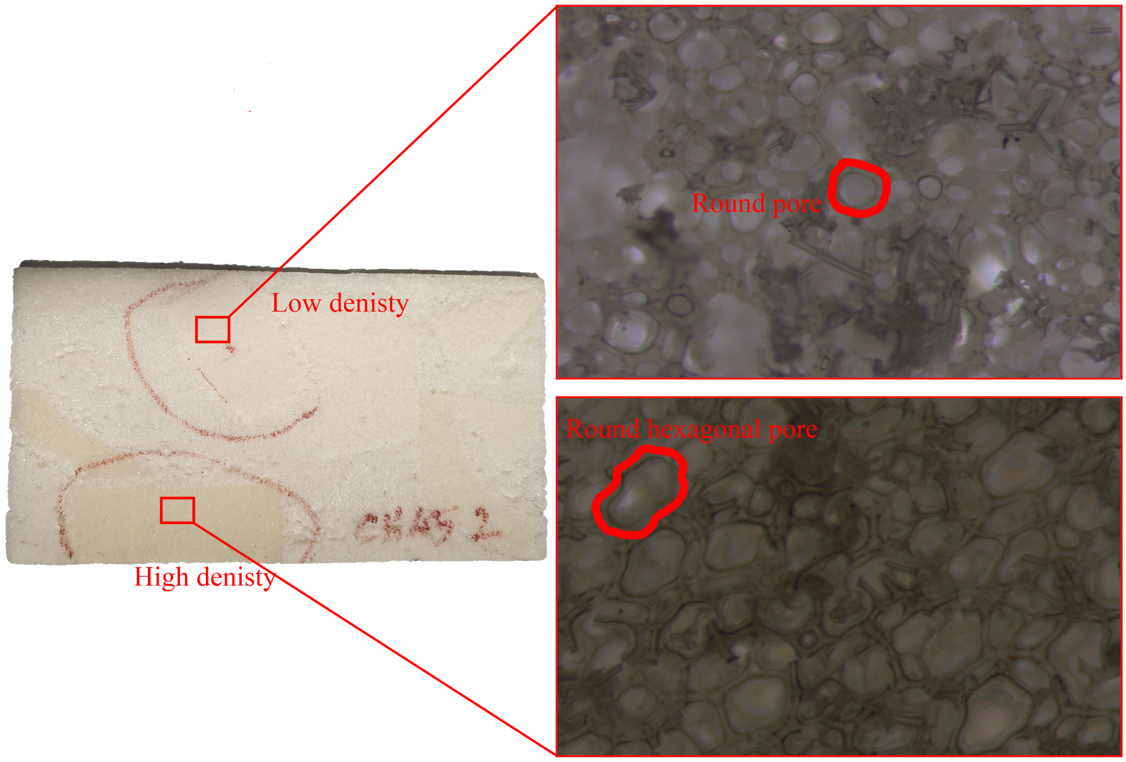

Figure E.8. Coarse granulated 45% sample

The last chosen sample from the coarse granulated recycling method was 45 % recycled. During the production of this sample, a general production task was simulated. As higher and lower density PUR was also utilised for this sample. Figure E.8 describes their location and colour of differences. The piece in circle number one highlights the lower-density PUR.

E.1.4 Findings

Two of the previously disqualified prototypes (Fine granulated 35 % and 44 %) were analysed for the pore structure. The evaluation could highlight and provide answers for the poor thermal conductivity and for the poor material structural integrity.

Fine granulated sample production difficulty

The PUR with fine granulated recycled particles shows several difficulties. However, the main challenge was to have enough thermal energy in the PUR after injection to the production form to cure properly. As the recycled particles are insulation materials they decrease the heat through conduction. To decrease this effect, the fine granulated particles and the production form are pre-heated. Due to this preparation task, the current issue can be minimized.

Fine granulated 35%

The highest applicable sample from the fine-granulated samples with 55 kg/mm^3 ± 3 kg was the 25% sample. Above that percentage of recycled particles, the overall structural porosity decreased drastically compared to the previously described samples.

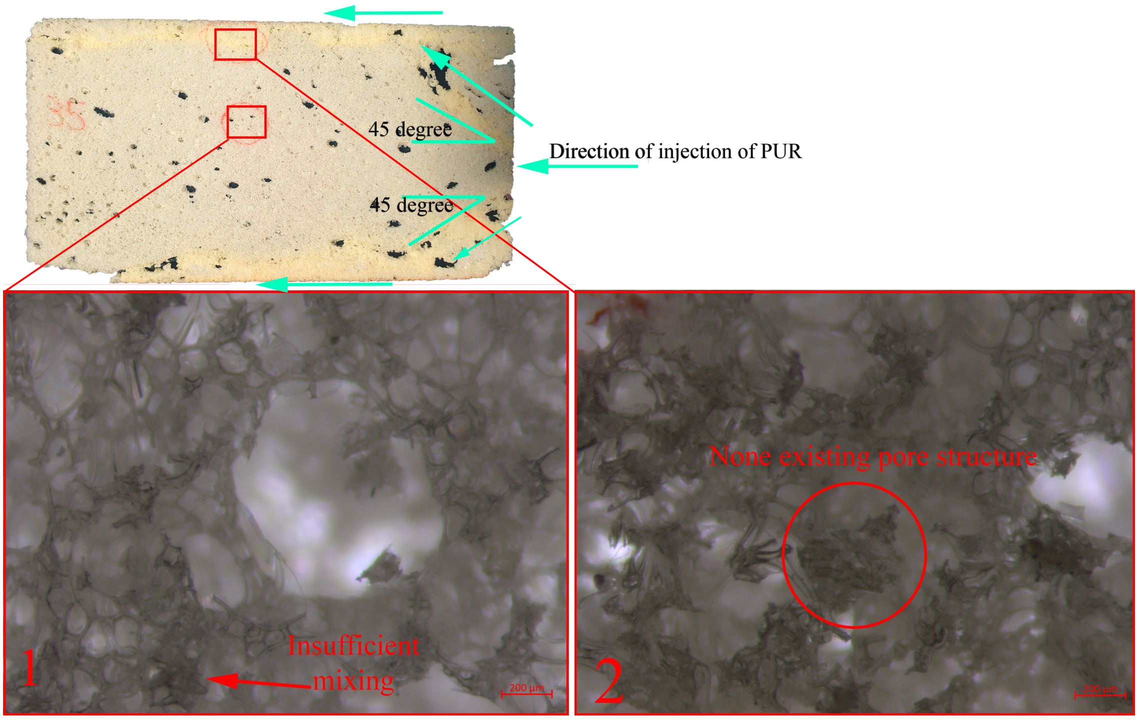

Figure E.9. Fine granulated 35% sample

Figure E.9 shows a structure with many large holes and a non-uniform structure. The inefficient mixing of the recycled particles is highly visible around the edges. The injection of the material from the right side is indicated by the arrows. In that area, it can be observed approximate 45° angle. This highlights the issue of the poorly mixed components in the mixing chamber. At the time when the material was injected by high force, the fine granulated particles from the side of the chamber simply entered the production form and created the visible path due to the high pressure of injection. This effect can conclude the relatively high thermal conductivity in section D.

In the highlighted zone one and two the material is not completely cured, as the pore system could not be created due to the lack of the mixing of the components.

Fine granulated 44%

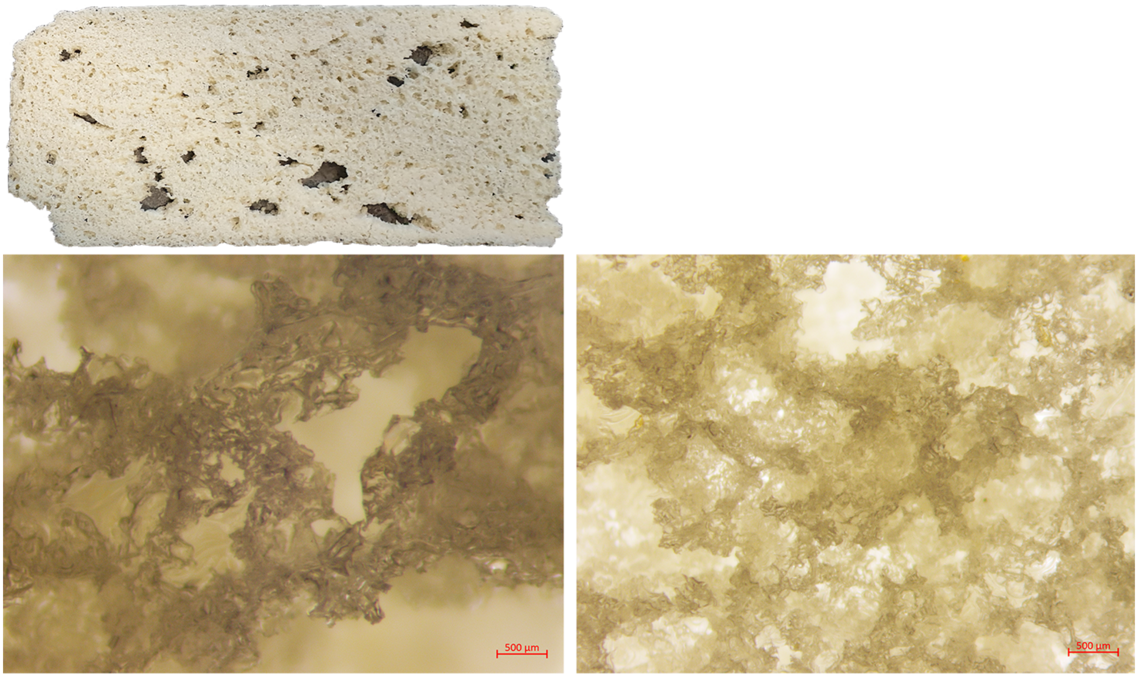

Figure E.10. Fine granulated 44% sample

The highest percentage of the recycled level was reached at 44% of recycled fine granulated particles. However, as result, the 45 % thermal conductivity and the 35 % higher density made these recycled percentages neglected to continue for further investigation. Similarly, other properties such as porosity and structural uniformity decreased as well compared to the 35% fine granulated sample. Figure E.10 represents the structural look of the material.

The source of the issue could be found during the procurement of the sample. Mixing the fine granulated particles and the mix of PUR the material already looks too dense in the mixing chamber, compared to other materials production.

Structural integrity

To explore the maximum reachable recycled percentage of particles in a PUR board, a further increment of recycled particles was initiated. The sample with fine granulated particles under 20 % had no visible structural integrity change. However, above that limit, visible changes were explored as figure E.11 represents. On the 44% sample, several open pores are visible, which results in a non-uniform surface. In relation to the structural integrity decrease the compressive strength decreased as well. Measurement was difficult as the material was the lack in thoroughness as it crumbles under the compression of the test. The result of structural strength measurement can be seen in section F. The thermal conductivity increase is significant (0,038 W/mK) compared to the coarse granulated 45% (0,023 W/mK).

More information can be found in section E.

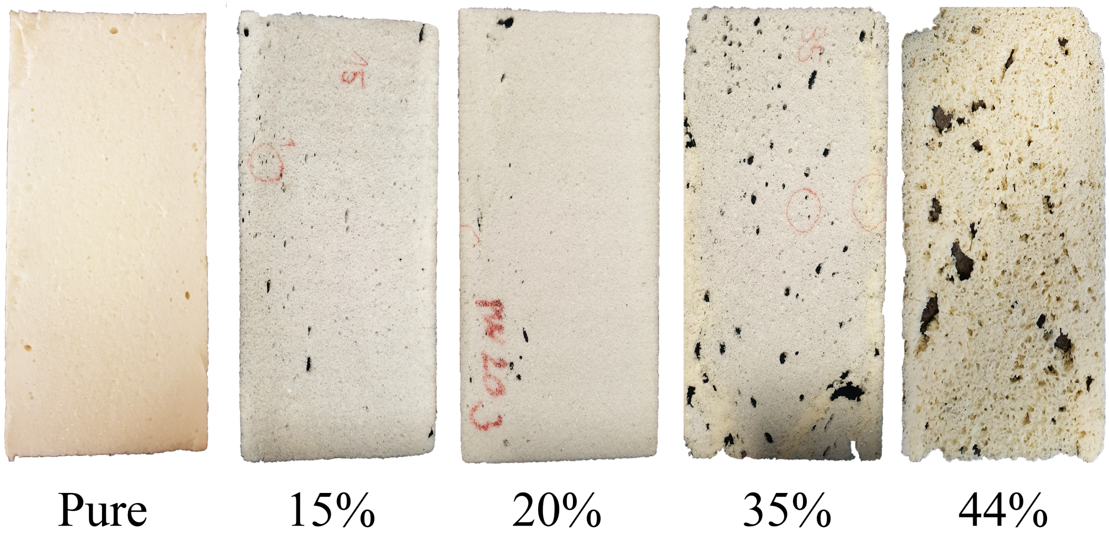

Figure E.11. Structural uniformity changes from the pure until the highest 44%

Non-uniform structure for the coarse granulated 46% sample

Different issues were found in the coarse granulated method compared to the fine granulated sample. As above 46% the structural uniformity drastically decreases. Figure E.12 represents the produced sample.

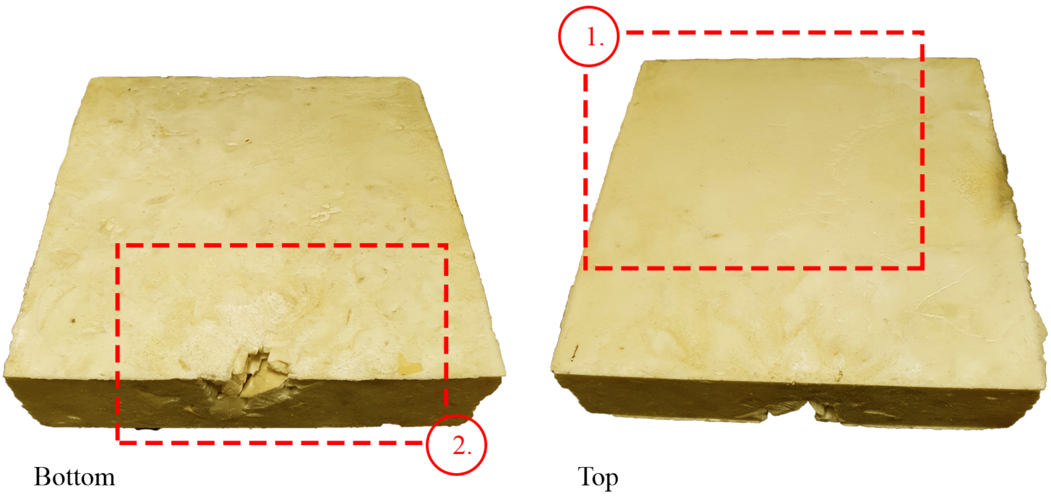

Figure E.12. Non-uniform structure of the 46% coarse granulated samples

On the top section in the number 1 zone, it is visible that the surface is unusually uniform, which did not occur in the less than 45% products. If the bottom area, in zone number 2. is visually inspected there is a large dent. This is a consequence of too many coarse pieces in the form as figure E.13 visualises the increased amount of coarse pieces in the product in different percentage stages.

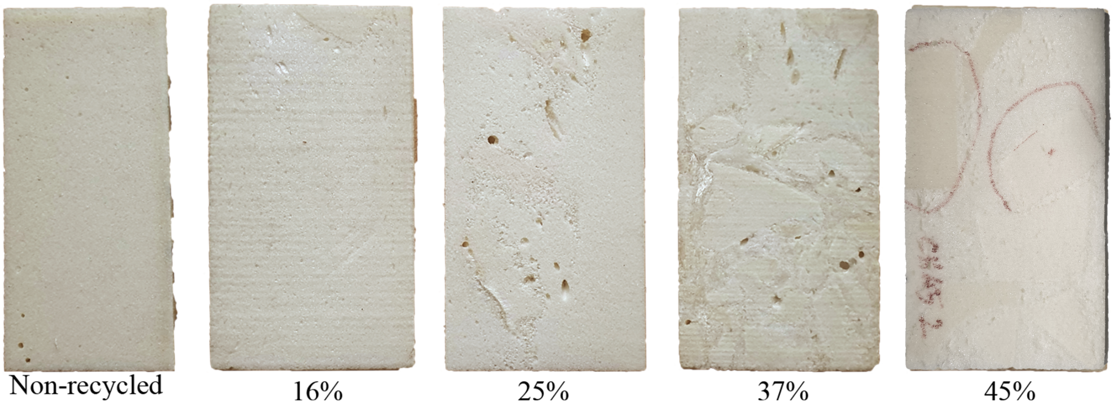

Figure E.13. Structural uniformity changes in different coarse recycling percentages

This sample created a limit where the amount of recycling cannot be increased, as no similar issue had occurred in the lower percentage. After cutting the 46% sample to half, the previously mentioned issue is clearly visible in figure E.14. On the left side where all the pieces are allocated due to the force of the expansion of PUR, it is visible that the sample is divided into two sections. The first half is the over-packed, over-expanded PUR with voids, and the second half is like a virgin PUR board.

Figure E.14. Coarse granulated 46% section

E.2 Conclusion

The above-explained microscopic evaluation of the pore system of the material highlighted several issues in both recycling methods. The fine granulated method has a recycling percentage amount limitation. As currently, the sample with a clear structural system is 27%. The two other samples 35% and 44% highlighted issues which verify the fact of the choice of sample for further investigation for development purposes.

The coarse granulated method resulted significantly better in this evaluation, especially in the range where a higher level of recycled particles was used. Due to the fact, that no proper mixing of two different components is needed. In this method, it is only necessary to selectively organise used pieces in the production form.

Table E.1 collects the samples where the material properties were sufficient enough to further evaluate for sustainability properties.

Table E.1. Chosen samples after laboratory measurements

Method	**Recycled %**	**Density** $[kg/m^3]$	**Thermal conductivity** $[W/(mK)]$	**Strength** $[kPa]$
Fine granulated	15 %	46,38	0,021	239
	20 %	48,78	0,023	225
	25 %	58,42	0,021	174
Coarse granulated	15 %	54,79	0,021	240 ±17
	25 %	58,06	0,022	240 ±17
	35 %	55,41	0,023	240 ±17
	45 %	58,11	0,023	240 ±17

Laboratory experiment - Compressing strength properties

F

Structural strength defines the capability to transit various loads safely through the material. This capability is important as in case the material's structural strength is inadequate for the use of place (floor partitions), cracks and deformation can occur on the surfaces.

The testing methodology and guidelines can be found in ISO 844 [14], which is specially made for rigid cellular plastics - Determination of compression properties.

The test was made on all three directional axis of the specimens due to the different expansions of the PUR. Figure F.1 guides the orientation of measuring for the fine granulated products. The injection of mixed material is in the direction of the X-axis. The measurement was made parallel and two perpendiculars to the direction (X-axis) of injection to the mixed material.

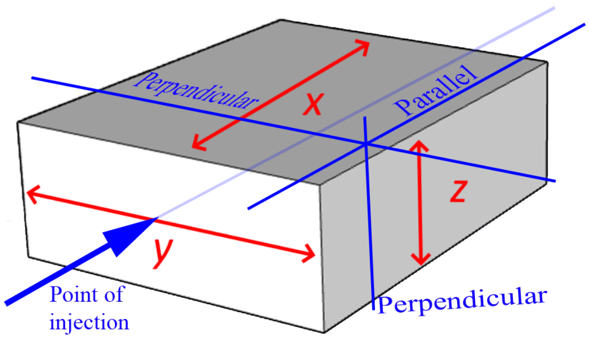

Figure F.1. Orientation of measured sides

F.1 Methodology

ISO 844 [14] states that the thickness of the specimen must be usually 50±1 mm. But for the purposes of these prototypes, the minimum requirement for the thickness is to be thicker than 10 mm, and the maximum thickness is not greater than the width and length.

All the surfaces of the sample must be parallel to the opposite side by the maximum 1 % of tolerance.

The temperature and the relative humidity of the specimen must be in the range of 23±2 °C and 50±10 % respectively.

The samples were sliced up for the test into three 30 x 30 x 30 mm blocks, coded to A-B-C and tested separately to validate the results of the test.

F.1.1 Test procedure

The first step is to measure the specimens on their X, Y and Z axis according to ISO 1923 [15] and place the object in between the two parallel plates of the compression-test machine. Increase the pressure of the plates on the specimen at a rate of 10 % of the specimen height. Continue this until the thickness is reduced to 85 % of the initial thickness. Then note the maximum force during the reduction of the thickness. Repeat this on all three samples, as differences can occur due to the production technology of the product.

F.1.2 Calculation of results

The compressive strength σ_m is given in kPa by the following equation:

$$\sigma_m = 10^3 \times \frac{F_m}{A_0} \tag{F.1}$$

σ_m - Compressive streght $[kPa]$
F_m - Maximum force reached $[N]$
A_0 - Initial cross-section area of the specimen $[m^2]$

All three sides of the specimen must be measured. However, due to the fact that the two different scenarios are produced differently, this also affects the compressive strength. That is why a specimen can be used only once per measurement, due to that three different specimens had to be used, because the used force can damage the material strength and describe a false result in case of further measurements.

F.2 Results

Figure F.2 shows the relation between the strength and density for fine granulated samples.

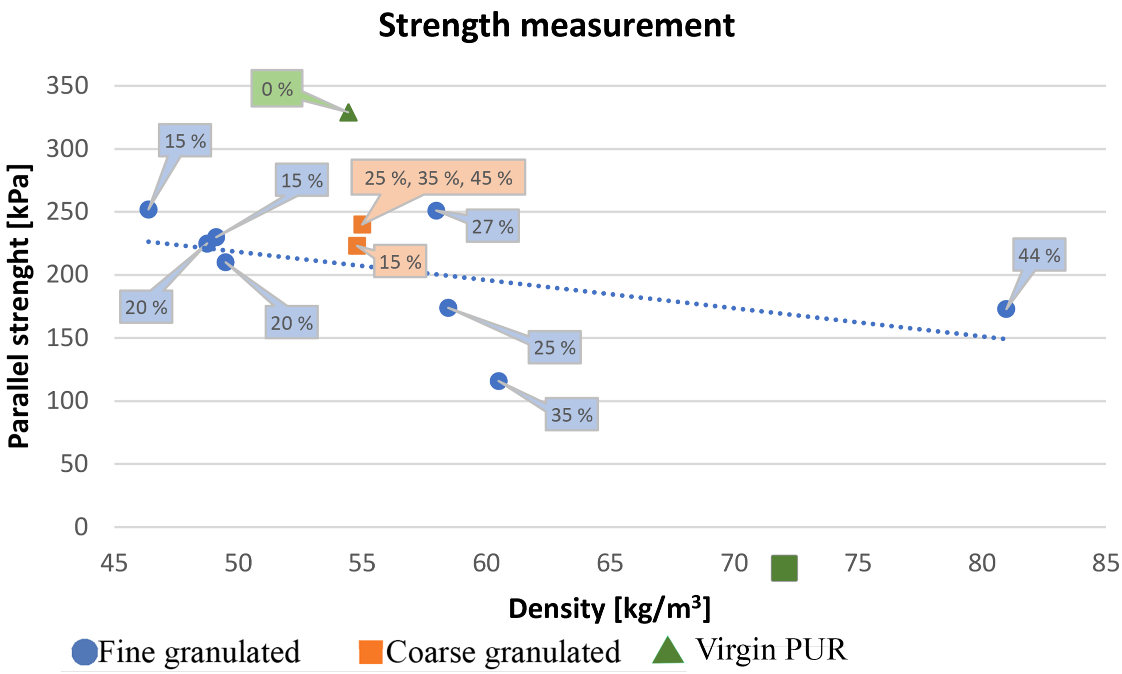

Figure F.2. Results of strength measurements for fine granulated samples

F.2.1 Fine granulated samples - results

Table F.1 contains all the parallel and perpendicular strength tests, however, the common industry practice only takes into account the parallel results.

Table F.1. Results of fine granulated strength test

Sample	**Density** $[kg/m^3]$	**Direction of test**	**Displacement** $[mm]$	**Force** $[N]$	**Strength** $[kPa]$
Test (Virgin PUR)	58,11	Parallel	4,53	298	329
15% - A	54,29	Parallel	4,50	207	230
15% - B	54,29	Perpendicular	4,50	170	190
15% - C	54,29	Perpendicular	4,49	149	166
20% - A	49,49	N/A	4.50	190	210
20% - B	49,49	N/A	4.50	164	180
20% - C	49,49	N/A	4.48	147	160
20% - A	48,78	N/A	4.50	190	210
20% - B	48,78	N/A	4.51	201	225
20% - C	48,78	N/A	4.49	164	180
25% - A	58,42	N/A	4.45	148	165
25% - B	58,42	N/A	4.47	133	150
25% - C	58,42	N/A	4.47	155	174
27% - A	57,98	Parallel	4,50	227	251
27% - B	57,98	Perpendicular	4,54	173	194
27% - C	57,98	Perpendicular	4,50	164	182
35% - A	60,50	Parallel	4,48	105	116
35% - B	60,50	Perpendicular	4,51	77	86
35% - C	60,50	Perpendicular	4,51	80	89
44% - A	88,98	Parallel	5,29	146	116
44% - B	88,98	Perpendicular	5,30	217	173
44% - C	88,98	Perpendicular	5,31	162	129

F.2.2 Coarse granulated samples - results

Table F.2 collects the result of PUR with recycled coarse granulated pieces. The compressive strength of coarse granulated samples is similar to the virgin PUR. Due to the fact that the foam contains only virgin PUR and coarse granulated recyclate, which are not influencing the overall compressive strength. This means that the coarse granulated samples' strengths according to internal measuring showed that the measured values are similar in the interval of 216 N ± 15 N for the Force and 240 kPa ± 17 kPa for the strength.

Table F.2. Results of coarse granulated strength test

Sample	Density $[kg/m^3]$	Direction of test	Displacement $[mm]$	Force $[N]$	Strength $[kPa]$
Test (Virgin PUR)	58,11	Parallel	4,53	298	329
15% - A	54,79	N/A	4.49	168	189
15% - B	54,79	N/A	4,49	190	214
15% - C	54,79	N/A	4,50	198	223

F.3 Conclusion

Evaluation of the measured strengths properties for the recycled products with fine granulated particles allows the observation of above 58 kg/m^3 of density the strength begins to decrease by approximately 80 kPa. However, as can see in table F.1 that the strength of the fine granulated 25% and fine granulated 44% is similar. This observation also allows the conclusion that the amount of the added recyclate to the PUR mix does not influence the strength linearly through the percentage.

Products with recycled coarse granulated pieces allow the conclusion of the strength was diminished, but for all the percentages of recycling by the same amount.

The requirement for further analyses in this category is the maximum measured strength with the lowest density of the samples. This supports the previous observation from the thermal conductivity measurements. However, the 25% fine granulated prototype is an exception, as even with a relatively high density and lower strength than the other fine granulated 15% and fine granulated 20% prototypes the thermal conductivity of it is the closest to the virgin PUR.

According to internal strength measurement, it was observed, that in the case of lower density than 40 kg/m^3, the strength of the materials exponentially decreased. As a consequence of the smaller content of injected mixed PUR have more space to expand, as a result, creates larger air bubbles, weakening the overall structure. The strength is decreased to 116 kPa, but in comparison to other materials on the market for example Jackson EPS S150 has a 150 kPa and Rockwool Hardrock Energy roof and ceiling insulation 30 kPa [16] of compressive strength. Meaning the compressive strength of the PUR makes it capable of multiple areas of use, for example unlike the Rockwool as it cannot have any load-bearing capacity. In most cases, the building insulation material does not require to have a minimum compressive strength as it is not a load-bearing element.

Table F.3 collects the chosen samples, from the fine granulated samples and the coarse granulated samples. As it was mentioned above the results of the test showed similar capabilities of strength for the coarse granulated samples.

Table F.3. Chosen samples for further investigation

Method	**Recycled %**	**Density** $[kg/m^3]$	**Thermal conductivity** $[W/(mK)]$	**Strength** $[kPa]$
Fine granulated	15 %	46,38	0,021	239
	20 %	48,78	0,023	225
	25 %	58,42	0,021	174
Coarse granulated	15 %	54,79	0,021	240 ±17
	25 %	58,06	0,022	240 ±17
	35 %	55,41	0,023	240 ±17
	45 %	58,11	0,023	240 ±17

Life cycle assessment - LCA G

The life cycle assessment (LCA) is the best-known quantitative analysis of the environmental aspects of a product over its entire life cycle. The LCA is a systematic tool for analysing the environmental burdens of the product over its life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to the use and end-of-life treatment and disposal.

The reason for the calculation of the life cycle assessment is to reduce impact due to raising awareness about the building industry contributing highly to the production of greenhouse gasses. The carbon dioxide from the building represents nearly 40% of annual global emissions, where approximately 28% comes from operations of the building and 12% comes from building materials and construction. Therefore, to reduce the impact, it should be traced. Danish Government had embraced a Climate Act [17], which goal is to reduce the emission of CO_2 by 70% by 2030 [17]. New regulation planned in 2025, requires all new buildings to perform LCA analysis with a limit value to carbon dioxide emission from the building.

The ISO 14040 [18] standard method describes the LCA and also how to identify individual processes. There are four phases in LCA, goal and scope definition, inventory analysis, impact assessment and interpretation. These are described in the following sections. The main focus will be an evaluation of the environmental impact of recycled PUR, which can be compared with mineral wool, extruded polystyrene and blow-in cellulose as an option for the renovation of the external wall. The assessment also follows EN 15804 [19] Sustainability of construction works - environmental product declarations (EPD).

G.1 Goal and scope

The goal of the LCA of the PUR is to create an environmental impact table which can be compared with EPD results for LCA documentation of the mineral wool, extruded polystyrene and cellulose. The selected standard parameters according to The ISO 14040 [18] can be found in the table G.1. The functional unit for the results is one kg of the PUR.

Table G.1. Parameters according to the ISO 14040 [18]

Parameter	**Environmental indicator**	**Abbreviation**
Global warming potential	$kg\ CO_2 - eq$	GWP
Depletion potential of the stratospheric ozone layer	$kg\ CFC11 - eq$	ODP
Acidification potential of land and water	$kg\ SO_2 - eq$	AP
Eutrophication potential	$kg\ (PO_4)^3 - eq$	EP
Formation potential of tropospheric ozone photochemical oxidants	$kg\ ethene - eq$	POCP
Abiotic depletion potential for non-fossil resources	$kg\ Sb - eq$	ADPE
Abiotic depletion potential for fossil resources	MJ	ADPF

The parameters will be calculated for each version of the material recycling as can be seen in the table G.2.

Table G.2. Samples for SimaPro modelling

Recyclation method	**Recyclate [%]**
Fine granulated	15
Fine granulated	20
Fine granulated	25
Coarse granulated	15
Coarse granulated	25
Coarse granulated	35
Coarse granulated	45

The following table in figure G.1 summarises the system boundary as described in EN 15804 [19]. The X means it is included in the LCA and the MND stands for Module not declared.

Product stage			Construction process stage		Use stage							End of life stage				Benefits and loads beyond the system boudnaries
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational use	Operational water use	De construction demolition	Transport	Waste processing	Disposal	Reuse recovery recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	X	MND	X	X

Figure G.1. Description of the system boundary

The included modules are:

- Product stage (A1) Raw material supply
- Product stage (A2) Transportation to the manufacturer

- Product stage (A3) Manufacturing
- End of life stage (C2) Transport to waste processing
- End of life stage (C4) Waste disposal
- Benefits and loads beyond the system boundary (D) Reuse, recovery and/or recycling potential

The used allocation method for recycling is the Cut-off method. This method works with the basic assumption that all inputs and outputs of the product system throughout the entire life cycle are the responsibility of the product system. This means that recycling is not included and instead the recycled amount is included in the production stage. The amount of raw material is then proportionally subtracted based on the amount of recyclate included. Then the total load of the disposal material is proportional to the amount of waste after recycling the specific amount.

G.2 Life cycle inventory analysis - LCI

This section includes the collection of data regarding all the materials and energy used during the stages of the product. The values of weight represent how much materials are needed for the creation of 1 kg of the sample.

There are two major components, Polyol and Diisocyanate, that need to be produced and transported to the factory. The two main components are mixed together and the other two components (a release agent and a cleaning agent) are used for the treatment of the machinery. The visualisation of the processes in each module for the 20 % recycled sample of PUR is shown in figure G.2. The blue marked labels changes for each version of the sample with different recycling and the two methods of sample creation.

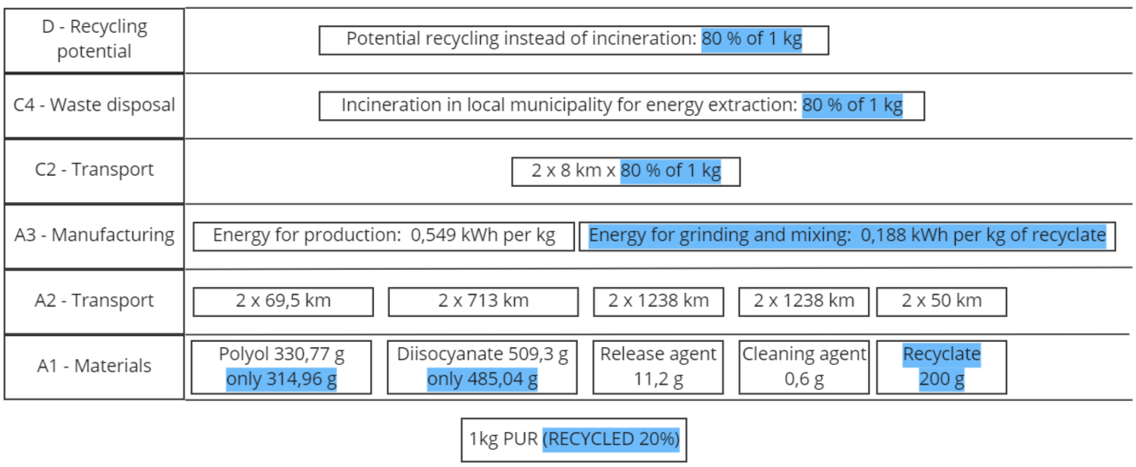

Figure G.2. Process map of the recycled PUR production

The main components are:

- Diisocyanate (Demsodur 44 v29L) [20]
- Polyol (Polyol RF2100PT8) [21]
- Release agent (PU-6222L) [22]
- Cleaning agent (Gamma-butyrolactone) [23]
- PUR recyclate

These components consist of several chemical parts described in the table G.3. Each of the chemicals is also listed with their Chemical Abstracts Service (CAS) which helps to specify the chemical with the unique registration number that can be found. CAS contains most substances from 1957 to the present, with the addition of some substances from the early 1900s. The weights listed in the table G.3 are proportionally assigned according to the product sheet composition (not all components are listed).

Table G.3. Products composition

Component	**Parts**	**CAS**	**Weight [g]**	**Share [%]**
Demsodur 44 v29L	Diphenylmethane diisocyanate	101-68-8	343,57	33,96
Demsodur 44 v29L	2,4'-MDI	5873-54-1	192,00	18,98
Demsodur 44 v29L	2,2'-MDI	2536-05-2	70,74	6,99
Polyol RF2100PT8	Cyclopentane	287-92-3	147,64	14,59
Polyol RF2100PT8	Propylene carbonate	108-32-7	127,95	12,65
Polyol RF2100PT8	Cyclohexyldimethylamine	98-94-2	118,11	11,67
Cleaning agent	Gamma-butyrolactone Dihydrofuran-2(3H)-one	96-48-0	0,6	0,06
Release agent	Distillates (petroleum) Hydrotreated heavy naphthenic	64742-52-5	6,05	0,60
Release agent	Distillates (petroleum) Hydrogenated heavy paraffinic	64742-54-7	4,37	0,43
Release agent	Octadecylamin	124-30-1	0,78	0,08

The estimation of the energy needed for the production of 1 kg of the PUR is 0,549 kWh/kg for the complete process.

Additional energy is needed for recycled material to be ground and mixed into the substance. For fine granulated recyclate, it is 0,253 kWh per kg of recyclate and for coarse granulate, it is 0,188 kWh per kg of recyclate.

G.2.1 Calculation model

The SimaPro software offers a broad selection of options for the selection of processes involved, but it does not contain all the chemicals and their specific parts therefore the components were simplified into the data that is shown in the table G.4. The methylene diphenyl diisocyanate and polyol are modelled already in the SimaPro as a full substance on the other hand the Release agent had to simplify from the hydro-treated heavy paraffinic and hydro-treated heavy naphnetic into the petroleum and paraffine from which they are derived. The RER stands for the European modelled process, NO for the Norwegian and the DK stands for the Danish modelled process. The distances for transport were given by the Dan-iso A/S from the distributor to the factory.

Table G.4. Processes simulated in SimaPro

Material	**Weight** [g]	**Transport** [km]
Methylene diphenyl diisocyanate RER	606,3	713
Polyol RER	393,7	69,5
Petroleum NO	6,44	1238
Paraffin RER	4,76	1238
Butane - 1,4 diol RER	0,6	1238

Since polyol and methylene diphenyl diisocyanate are two main components, their weight needed for production is lowered with the increased percentage of recycling. The other chemicals are used for the treatment of the equipment for each process without any regard for the materials used. The final amount of the chemicals used can be seen in table G.5.

Table G.5. Recyclation and products weights in the various cases

Recyclate [g]	**Methylene diphenyl diisocyanate** [g]	**Polyol** [g]
0 (0%)	606,30	393,70
150 (15%)	515,36	334,65
200 (20%)	485,04	314,96
250 (25%)	454,73	295,28
350 (35%)	394,10	255,91
450 (45%)	333,47	216,54

For modules C2 transport and C4 waste disposal, there is only one process for each. The C4 waste disposal has the process of municipal incineration. The amount of the waste simulated for incineration is equal to 1 kg with subtracted the recycled amount. The C2 transport is from the factory to the municipal incineration facility located 8,4 km away.

Module D is the potential of the material for 100 % recyclation, therefore it is 0 with the value of C2 and C4 subtracted. therefore a negative value.

After the data were obtained, they were simulated in SimaPro software and the following section offers results.

G.3 Life cycle impact assessment - LCIA

The significance of potential environmental impacts of a product system based on life cycle inventory results is evaluated by using LCIA. The LCIA consist of elements classified with impact on the environment in selected categories mentioned in the section G.1.

The results for comparison in tables G.6 and G.7 are shown only for modules A1 - A3 for materials, transport and manufacturing.

The category of Acidification had resulted in the software in $molH+$ eq to covert the result to $SO_2 - eq$ was used a transformation formula from [24], where 1 $kg SO_2$ equals to 1000/32 mol H+.

Table G.6. Results for modules A1 to A3 for the fine granulated PUR

Cat.	Environmental indicator	A1 - A3 production for Fine granulated PUR			
		0 %	15 %	20 %	25 %
GWP	$kg\ CO_2 - eq$	5,25E+0	4,51E+0	4,26E+0	4,02E+0
ODP	$kg\ CFC11 - eq$	8,37E-7	7,14E-7	6,72E-7	6,31E-7
AP	$kg\ SO_2 - eq$	1,00E-3	8,60E-4	8,12E+4	7,65E-4
EP	$kg\ (PO_4)^3 - eq$	1,69E-3	1,47E-3	1,40E-3	1,33E-3
POCP	$kg\ ethene - eq$	2,04E-2	1,75E-2	1,65E-2	1,55E-2
ADPE	$kg\ Sb - eq$	6,71E-5	5,90E-5	5,64E-5	5,37E-5
ADPF	MJ	1,09E+2	9,36E+1	8,84E+1	8,32E+1

Table G.7. Results for modules A1 to A3 for the coarse granulated PUR

Cat.	Environmental indicator	A1 - A3 production for Coarse granulated PUR				
		0 %	15 %	25 %	35 %	45 %
GWP	$kg\ CO_2 - eq$	5,25E+0	4,51E+0	4,02E+0	3,51E+0	3,02E+0
ODP	$kg\ CFC11 - eq$	8,37E-7	7,14E-7	6,31E-7	5,49E-7	4,66E-7
AP	$kg\ SO_2 - eq$	1,00E-3	8,60E-4	7,65E-4	6,69E-4	5,74E-4
EP	$kg\ (PO_4)^3 - eq$	1,69E-3	1,47E-3	1,33E-3	1,17E-3	1,03E-3
POCP	$kg\ ethene - eq$	2,04E-2	1,75E-2	1,55E-2	1,35E-2	1,16E-2
ADPE	$kg\ Sb - eq$	6,71E-5	5,90E-5	5,37E-5	4,83E-5	4,29E-5
ADPF	MJ	1,09E+2	9,36E+1	8,32E+1	7,26E+1	6,21E+1

The graph G.3 visualises the tables G.6 and G.7 for a clear understanding of the differences. The reference material that stands for the 0 % in the graph stands for the virgin PUR.

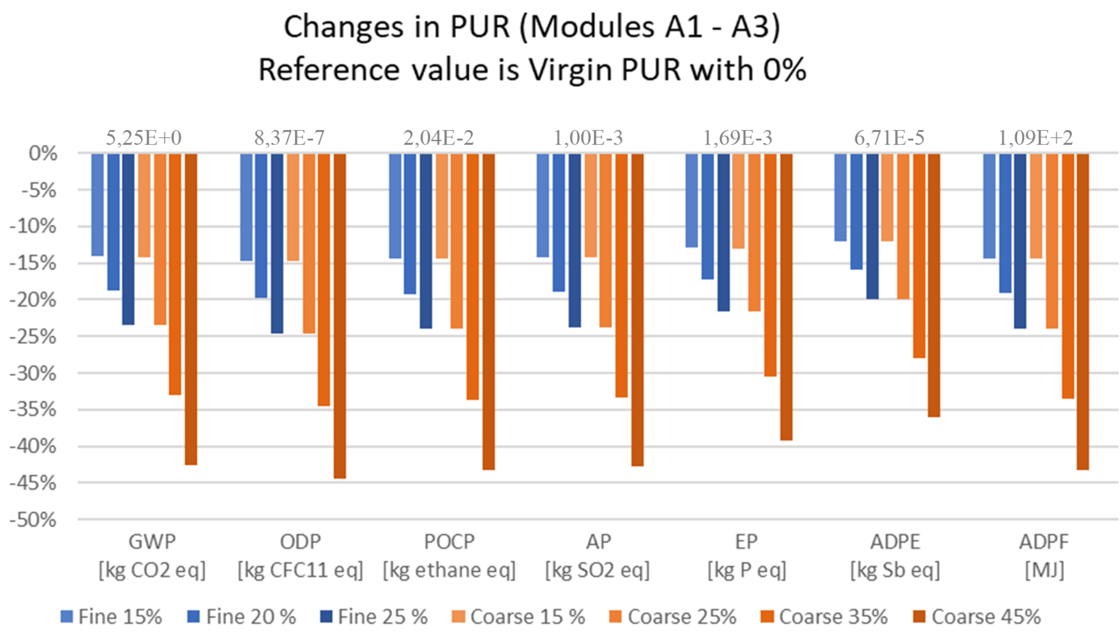

Figure G.3. Changes in PUR (Modules A1 - A3)

The waste transport C2 and waste disposal C4 are tight with the amount of recyclation since it is the remaining part of the material as shown in the tables G.8 and G.9. The most important change is that recycling can in theory reduce waste disposal even to non-existent incineration for energy recovery.

Table G.8. Results for modules C2 for all the samples

Cat.	**Environmental indicator**	**C2 - transport for all samples**					
		0 %	15 %	20 %	25 %	35 %	45 %
GWP	$kg\ CO_2-eq$	8,58E-3	7,29E-3	6,86E-3	6,43E-3	5,58E-3	4,72E-3
ODP	$kg\ CFC11-eq$	1,87E-9	1,59E-9	1,49E-9	1,40E-9	1,21E-9	1,03E-9
AP	$kg\ SO_2-eq$	1,07E-6	9,07E-7	8,54E-7	8,01E-7	6,94E-7	5,87E-7
EP	$\$kg\ (PO_4)^3-eq$	7,96E-7	6,76E-7	6,37E-7	5,97E-7	5,17E-7	4,38E-7
POCP	$kg\ ethene-eq$	3,12E-5	2,65E-5	2,49E-5	2,34E-5	2,03E-5	1,71E-5
ADPE	$kg\ Sb-eq$	5,32E-8	4,52E-8	4,26E-8	3,99E-8	3,46E-8	2,93E-8
ADPF	MJ	1,27E-1	1,08E-1	1,02E-1	9,55E-2	8,28E-2	7,00E-2

Table G.9. Results for modules C4 for all the samples

Cat.	**Environmental indicator**	**C4 - Disposal for various recyclation**					
		0 %	15 %	20 %	25 %	35 %	45 %
GWP	$kg\ CO_2-eq$	2,73E+0	2,32E+0	2,19E+0	2,05E+0	1,78E+0	1,50E+0
ODP	$kg\ CFC11-eq$	1,79E-8	1,52E-8	1,43E-8	1,34E-8	1,16E-8	9,85E-9
AP	$kg\ SO_2-eq$	7,41E-5	6,30E-5	5,93E-5	5,56E-5	4,82E-5	4,08E-5
EP	$kg\ (PO_4)^3-eq$	8,90E-6	7,56E-6	7,12E-6	6,67E-6	5,78E-6	4,89E-6
POCP	$kg\ ethene-eq$	2,93E-3	2,49E-3	2,35E-3	2,20E-3	1,91E-3	1,61E-3
ADPE	$kg\ Sb-eq$	2,86E-7	2,43E-7	2,29E-7	2,14E-7	1,86E-7	1,57E-7
ADPF	MJ	1,78E+0	1,51E+0	1,42E+0	1,33E+0	1,16E+0	9,78E-1

G.4 Life cycle interpretation

Results of LCI and LCIA analysed concerns completeness, sensitivity and consistency. The key elements are the identification of crucial issues, evaluation and conclusions.
Figure G.4 shows the contribution of used materials to the impact of the product. In the comparison is the virgin PUR with the coarse granulated sample. The sample impact as can be seen in figure G.3 is approximately 35 to 45 % of the virgin PUR, while the contribution of the materials in the product to the impact is relatively similar.

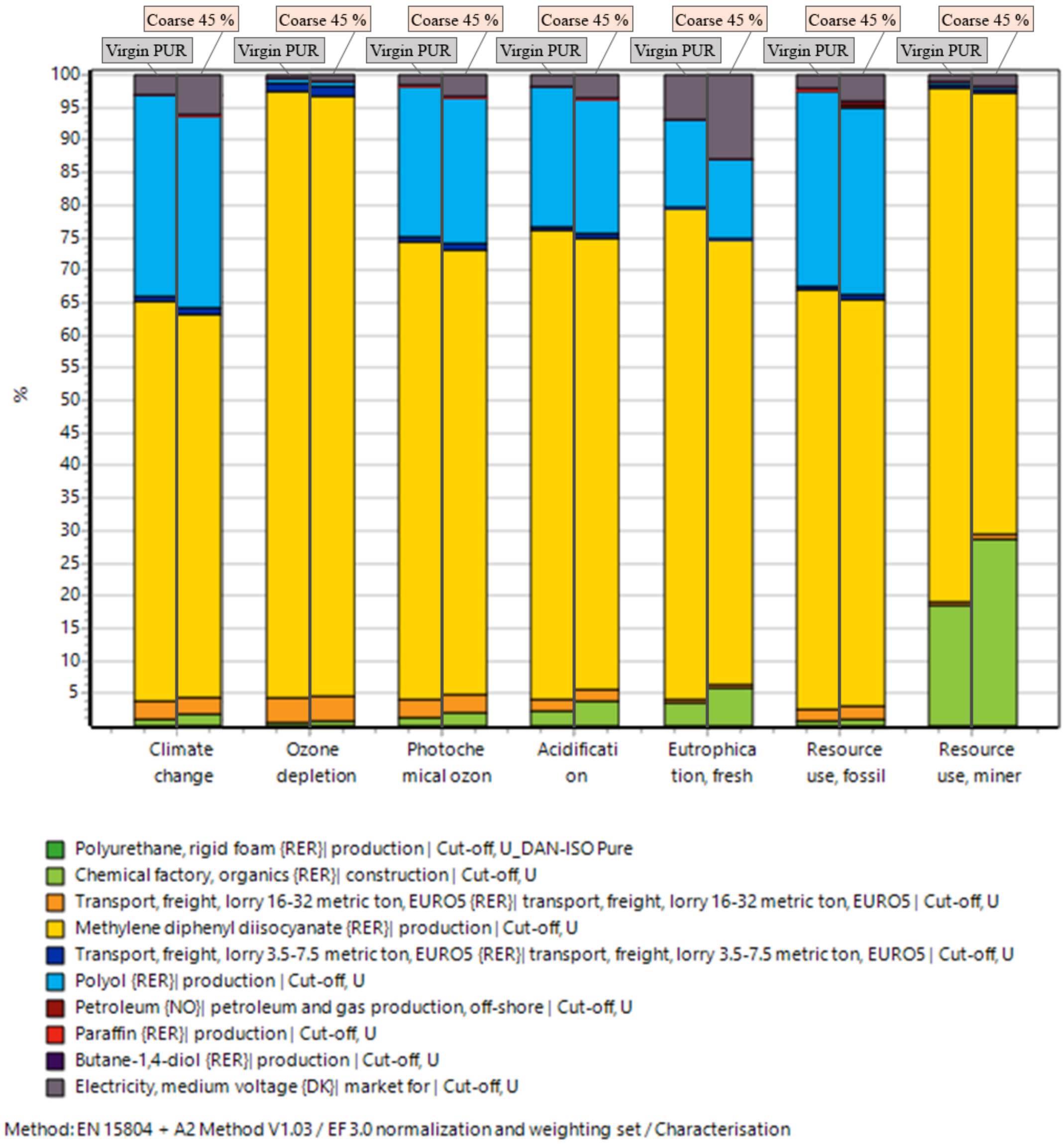

Figure G.4. Contribution (Modules A1 - A3)

From this can be concluded that the main driving force of the differing impact is the reduction in the number of main production elements such as diisocyanate and polyol.
The difference between the recycling methods (coarse granulated and fine granulated) is almost not relevant as can be seen in the table G.10 it is close to 0 %.

Table G.10. Difference between Fine granulated 15 % and coarse granulated 15 %

Cat.	Environmental indicator	Fine granulated 15 %	Coarse granulated 15 %	Change
GWP	$kg\ CO_2 - eq$	4,50977	4,50692	0,001 %
ODP	$kg\ CFC11 - eq$	0,00000	0,00000	0,000 %
AP	$kg\ SO_2 - eq$	0,00086	0,00086	0,000 %
EP	$kg\ (PO_4)^3 - eq$	0,00147	0,00146	0,001 %
POCP	$kg\ ethene - eq$	0,01748	0,01748	0,000 %
ADPE	$kg\ Sb - eq$	0,00006	0,00006	0,000 %
ADPF	MJ	93,64652	96,60760	0,001 %

This small difference is caused by the fact that the only difference between the methods is the energy use during production and it has a significantly lower impact than other sources of the impact

The possibility for lowering the total environmental impact of the material is in further progression with the reduction of the amount of the main components polyol and diisocyanate.

Overall the recycling of the product significantly improves the environmental impact of the PUR in all categories.

Renovation of case building H

In the thesis, the PUR with different percentages of recyclate is tested for its properties such as thermal conductivity and strength. There was also a life cycle analysis of the material, but how do the samples compare to other insulation materials?

For the purpose of visualisation and taking the results into context, there is a need for an example such as a renovation of a case building. The goal of the renovation is to compare the insulation material in the cavity brick wall. The cavity has limited space between the bricks therefore the thickness for all the samples is 90 mm. The materials chosen for the comparison can be found in table H.1. The result is calculated as the change of the heating demand in kWh/m^2year. It is not a realistic expectation for a renovation, because it expects to exchange only the external wall insulation and normal renovation would take care of all the problematic parts of the building. This serves only as a direct comparison of one option.

Table H.1. Materials for the renovation options

Material	**Recycled percentage**	**Density** $[kg/m^3]$	**Thermal conductivity** $[W/mK]$
Fine granulated	15 %	46,38	0,021
	20 %	56,91	0,027
	25 %	58,42	0,021
Coarse granulated	15 %	54,79	0,021
	25 %	58,06	0,022
	35 %	54,84	0,023
	45 %	58,11	0,023
Rockwool Murbatts 34 [25]		60	0,034
JACKON EPS S150 [26]		40	0,035
ISODAN Warmfiber Papirisolering [27]		46	0,037

Figure H.1 visualises the thermal conductivity changes from the table H.1.

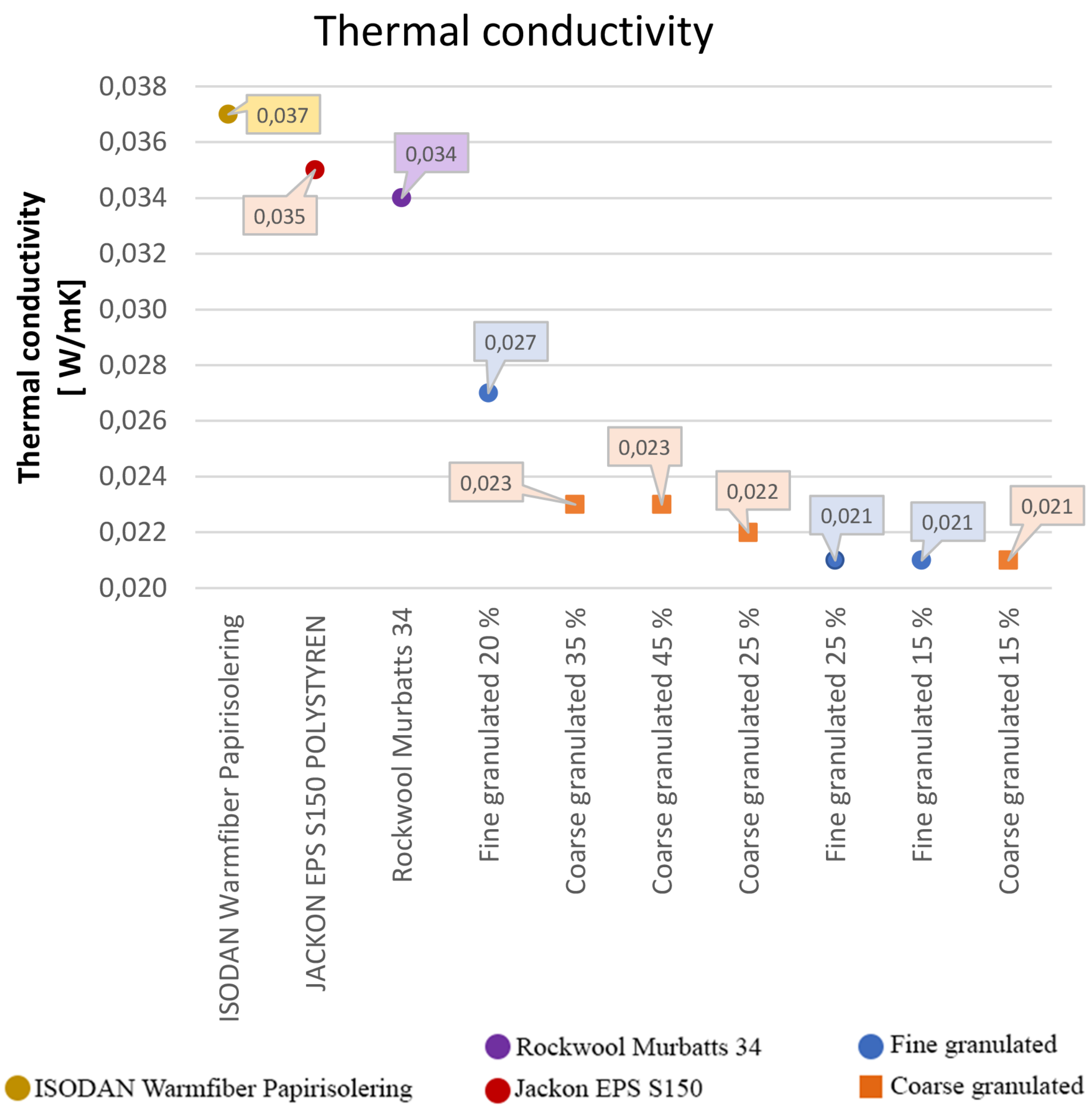

Figure H.1. Thermal conductivity of materials in the case building

There are no specific requirements for the strength of the insulation materials if they are not used as a load-bearing element.

The comparison focuses on life cycle analysis (LCA) and life cycle cost (LCC). The LCC includes the cost of renovation as well as the operation cost changes for the building which includes the heating demand (influenced by the thermal conductivity of insulation).

H.1 Insulation materials

The materials have many differences which are not described simply by their properties in table H.1. This section collects specific information about the materials.

H.1.1 Rockwool Murbatt 34

Murbatt 34 is a product of Rockwool A/S which is located in Rockwoolvej 2, 9500 Hobro Denmark.

Advantages

Mineral wool insulation offers exceptional longevity, where the thermal conductivity will not decrease over time. The material itself is highly fireproof as it can resist up to 1600°C, also having high soundproofing capabilities [28]. The material structure is tightly packed, however inside there are natural air pockets which allow for the material to breathe, preventing moisture built-ups. This capability prevents the growth of mould, mildew, and fungus due to the lack of organic compounds.

Disadvantages

Because of the tiny slivers and fibres of mineral wool insulation is necessary to wear different protections during application. It can be easily inhaled causing respiratory irritation. The fibres touching naked skin can cause rashes, itchiness, and general skin irritation [28]. Working with mineral wool is hard due to the high material density, which is in the range of 25 to 200 kg/m^3.

H.1.2 Jackopor EPS 150

EPS 150 is a product of Jackon Danmark A/S, which is located in Lundagervej 20, 8722 Hedensted Denmark.

Advantages

EPS is 98% air, helping make it one of the lightest of all packaging materials. due to the closed polymer matrix cells, it is having a relatively low thermal conductivity. Moisture Resistant and Rot-proof material. [29].

Disadvantages

Highly flammable that is not suitable for several areas as animals can create nests in it. [30].

H.1.3 ISODAN Warmfiber Papirisolering blown in insulation

Warmfiber papirisolering blown-in insulation is a product of Isodan ApS located in Østervej 2, 4960 Holeby Denmark

Advantages

Cellulose is a highly eco-friendly material, due to the fact that it is min 50% made from recycled newspapers and denim. Cellulose insulation is odourless, rot-resistant, non-hygroscopic and does not promote mould formation or fungal or bacterial growth [31].

Disadvantages

For the application of the material special tooling is required. It cannot be applied without a vapour barrier as cellulose itself absorbs around $1kg/m^2$ of moisture content.

H.2 Case building

The first step for choosing a relevant case building was to analyse the amount of built multi-storey buildings in Denmark in different year periods. The amounts were from Dansk Statistik [32] in figure H.2. The periods were defined according to the Tabula webtool [33], buildings typology references the years, which represents the different danish standards used in the building industry.

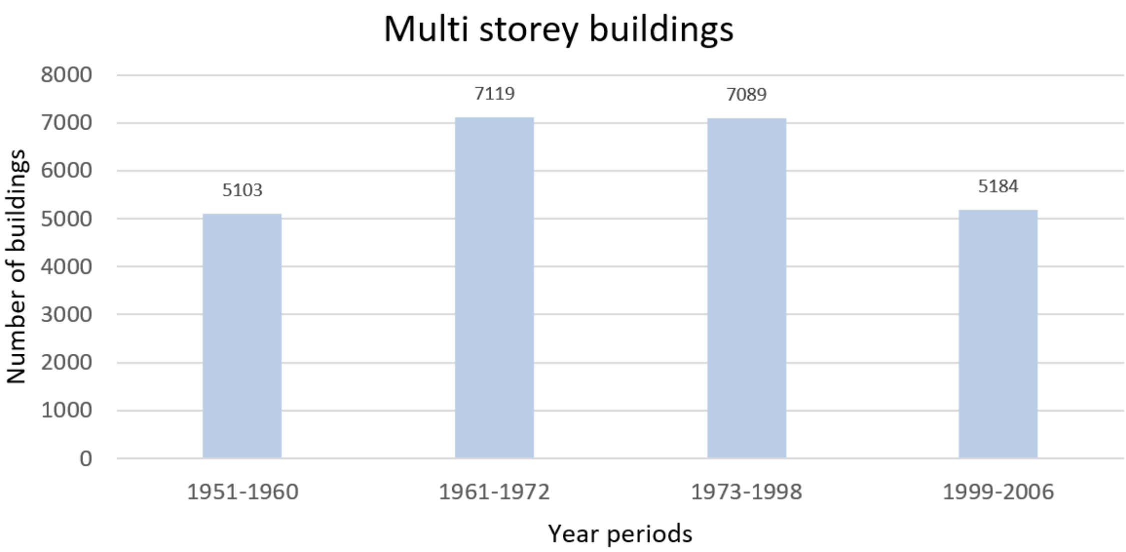

Figure H.2. Amount of multi-storey buildings built in different year periods

Most buildings were built between 1961 and 1972 as can be seen in figure H.2, therefore the case building from the year 1964 was selected to represent the building type from the largest era. The standards and the reality does not match, therefore the thermal transmittance were recalculated according to the case building instead of taking the required value from the standards.

H.2.1 Building information

The construction was finished in 1964 and the location is in Aalborg in the Hasseris district H.3.

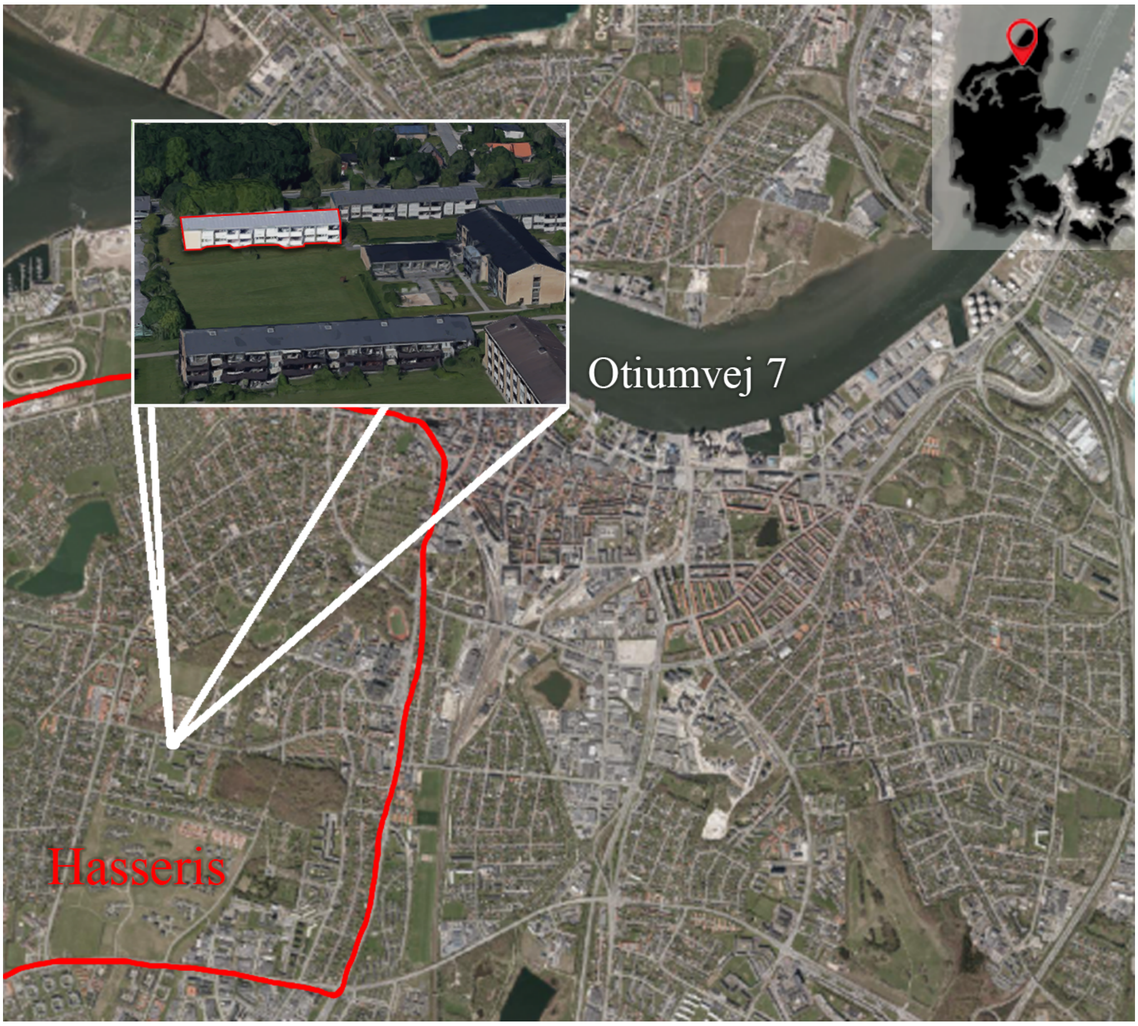

Figure H.3. Location of Otiumvej 7

The building is a 2-storey building complex serving the purpose of an elderly home. Figure H.4 shows the northern facade, which describes a typical yellow brick building from this age.

Figure H.4 shows the northern facade.

Figure H.4. South facade

In most cases, buildings are partially renovated every 20 years and deeply refurbished after every 40 years to complete the modern requirements. There is although in this case it was not followed and the refurbishment is delayed due to financial or other reasons. The floor area is two times 720.5 m^2 and figure H.5 shows the floor plan.

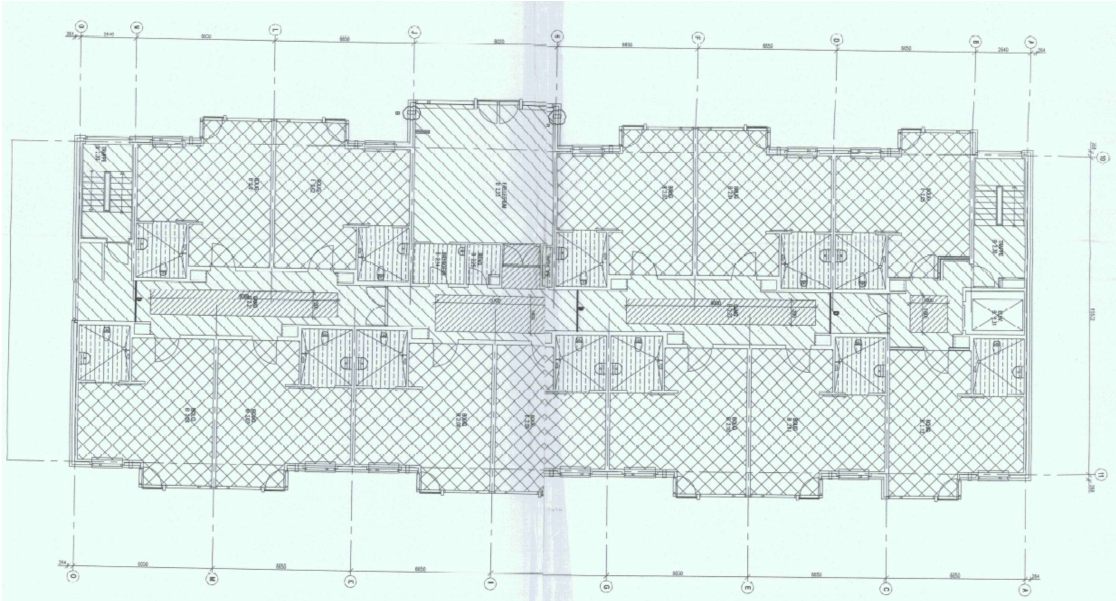

Figure H.5. 1st floor plan

The information about the construction elements was taken from the tabula webtool [33] and the thermal transmittance coefficient was calculated according to the DS 418 [10] with the thermal conductivity numbers for the bricks taken from SBI 5 - Varmeisolering [34] to ensure the calculation is with the older version of materials. The results can be found in the table H.2.

Table H.2. The case building envelope elements and their parameters

Element	**Area** $[m^2]$	**Thermal transmittance coefficient** $[W/m^2K]$
External wall	462,1	1,64
Ground floor slab	720,7	1,11
Roof	720,7	0.34
Windows	294,7	2.7
Doors	14,3	3

H.2.2 External wall renovation

The construction of the building is following the classical danish building structures as the load and non-load-bearing walls are from bricks (dimension: 228 x 108 x 54 mm) and in between the inner and outer leaf, there is an empty wall cavity of 90 mm. The existing building and the proposed renovation can be seen in figure H.6.

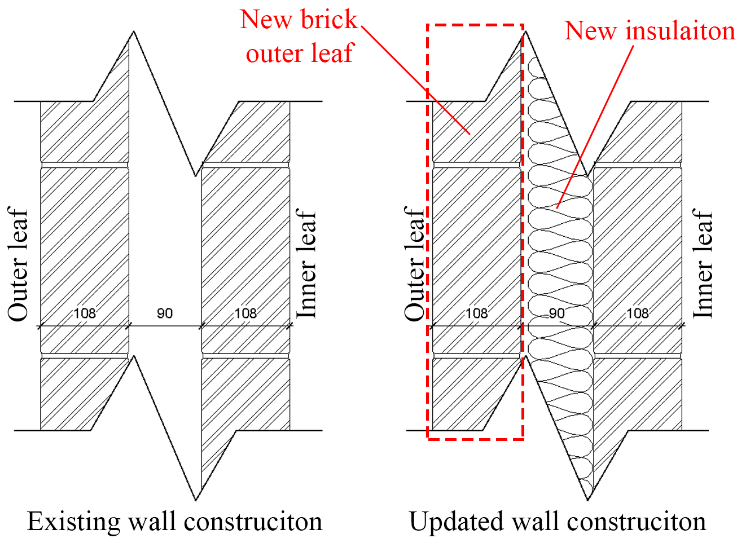

Figure H.6. Wall structure before and after the renovation

In table H.3 can be found the calculated thermal transmittance coefficients for the external wall for different material options for the insulation between the bricks.

Table H.3. Calculated thermal transmittance coefficient for external wall

Material in the wall cavity	**Recycled percentage**	**Thermal transmittance coefficient** $[W/m^2K]$
Fine granulated	15 % 25 %	0,212 0,212
Coarse granulated	15 % 25 % 35 % 45 %	0,212 0,221 0,230 0,230
Fine granulated	20 %	0,266
Rockwool Murbatts 34		0,325
JACKON EPS 150 POLYSTYREN		0,334
ISODAN Warmfiber Papirisolering		0,350

Figure H.7 visualises the thermal transmittance of the external wall element options from the table H.3.

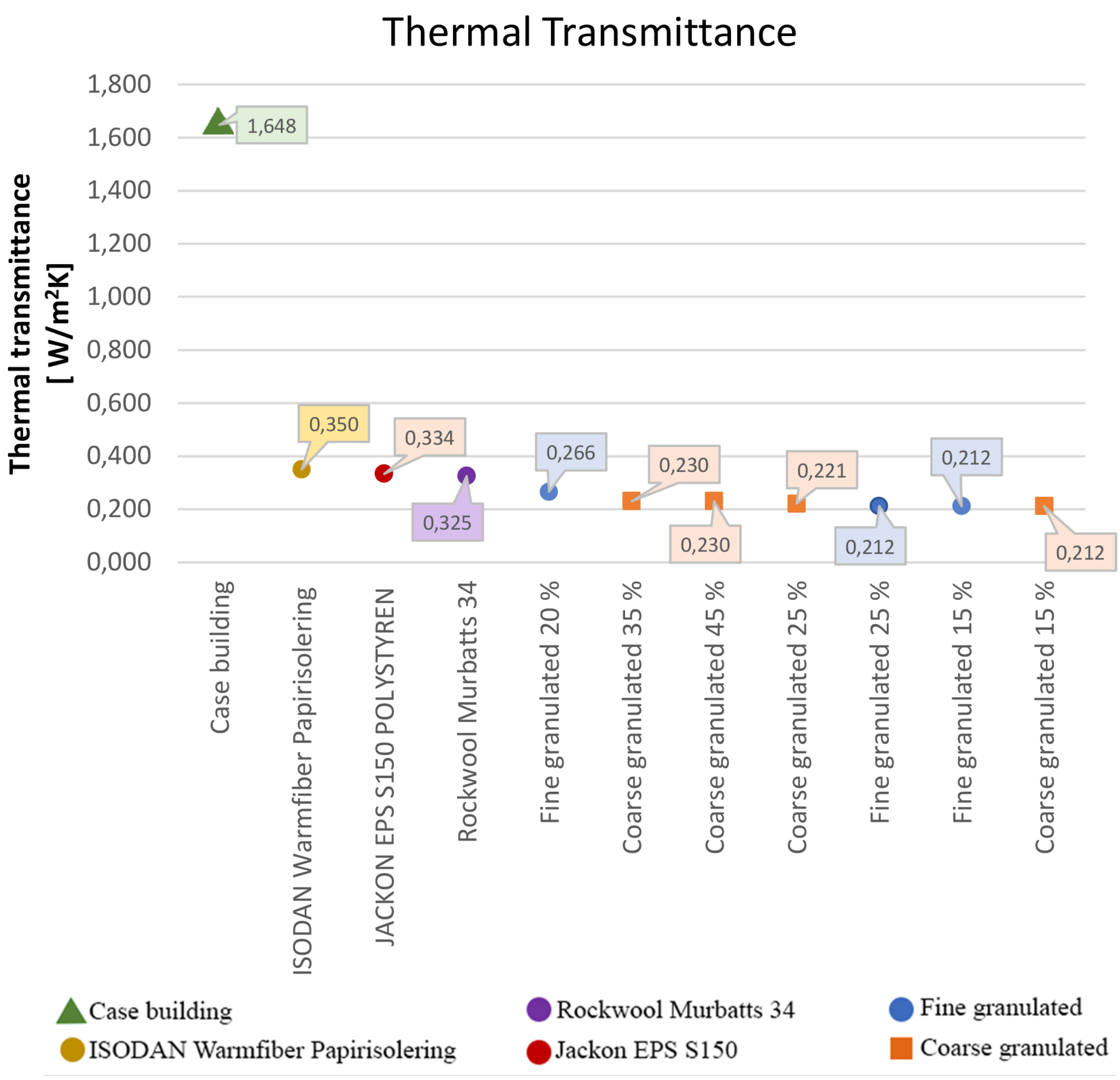

Figure H.7. Thermal transmittance of the wall element options in the case building

The differences between the thermal transmittance values for the materials used are not large as can be seen in the thermal conductivity graph. This is caused by the fact that the bricks which are two times 108 *mm* are the same for all the options and the insulation is only 90 *mm*.

H.2.3 Heating demand

The case building was modelled using the software BE18 which included all the building elements of the envelope. The other parameters such as heat from the building occupants or the natural ventilation remained the same for all the cases. All the construction sizes as well as the window placement with shadings are also defined the same to compare with the result only the differences in the energy demand between the external wall materials. All the linear losses are also identically calculated according to the DS 418 and all of them are the same for all the different materials.

The resulting values can be seen in the table H.4.

Table H.4. Energy requirements in different eras

Material in the wall cavity	**Recycled percentage**	**Heating demand** [kWh/m^2year]
Case building		171,9
Fine granulated	15 % 25 %	127,7 127,7
Coarse granulated	15 % 25 % 35 % 45 %	127,7 127,9 128,2 128,2
Fine granulated	20 %	129,3
Rockwool Murbatts 34		131,2
JACKON EPS 150 POLYSTYREN		131,5
ISODAN Warmfiber Papirisolering		132

Figure H.8 visualises the heating demand of the case building from table H.4.

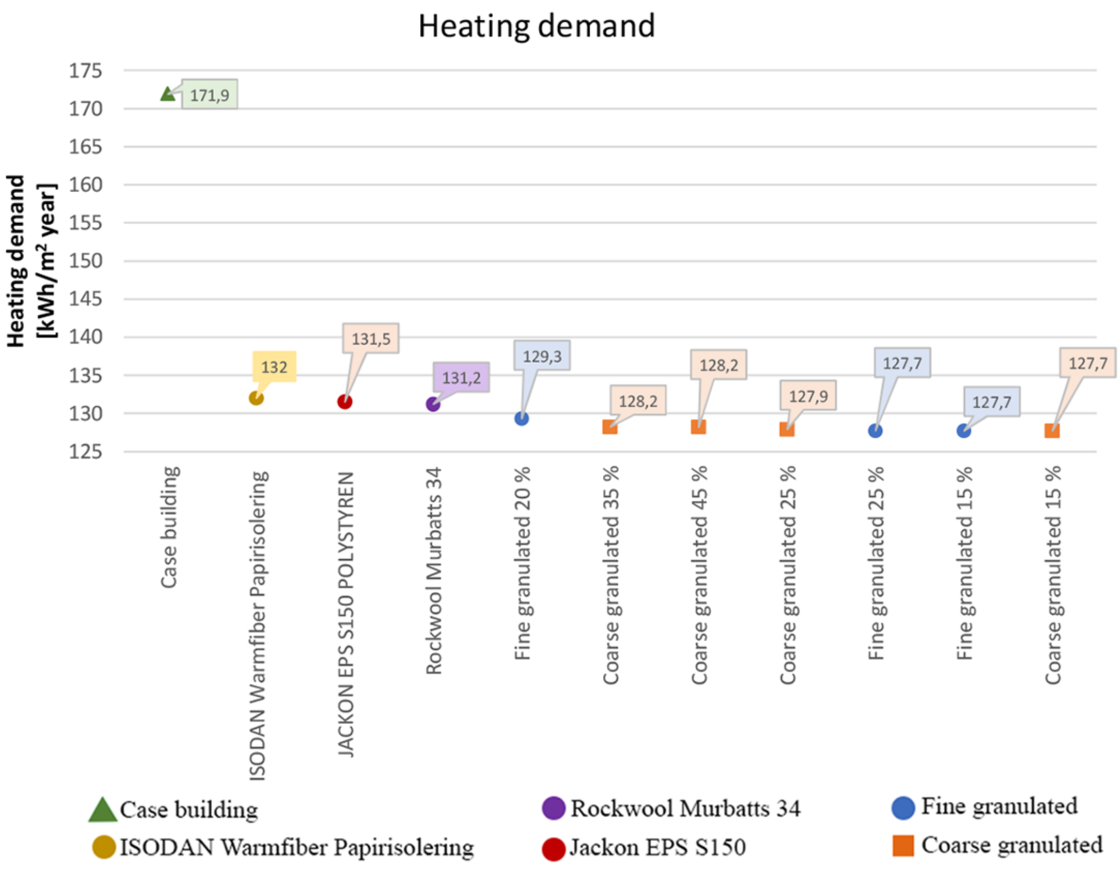

Figure H.8. Thermal transmittance of the wall element options in the case building

The span of the heating demand between the lowest and highest value for the renovation options is from 127,7 to 132 kWh/m^2year.

H.3 Life cycle analysis Case building

The comparison of the insulation materials' environmental impacts is focusing on comparing the calculated parameters (according to ISO 14040 [18]) and the LCA parameters declared for the Rockwool Murbatts 34 [35], Jackon EPS 150 polystyrene [36] and ISODAN Warmfiber papirisolering [37] in their respective EPD documents.

Only modules A1, A2, A3 and D (Production stage and Benefits and loads beyond the system boundaries) were included since the EPDs of the materials do not declare consistent other values.

The changes are represented as a percentage change from the reference material which is for the graphs H.9 and H.10 the virgin PUR.

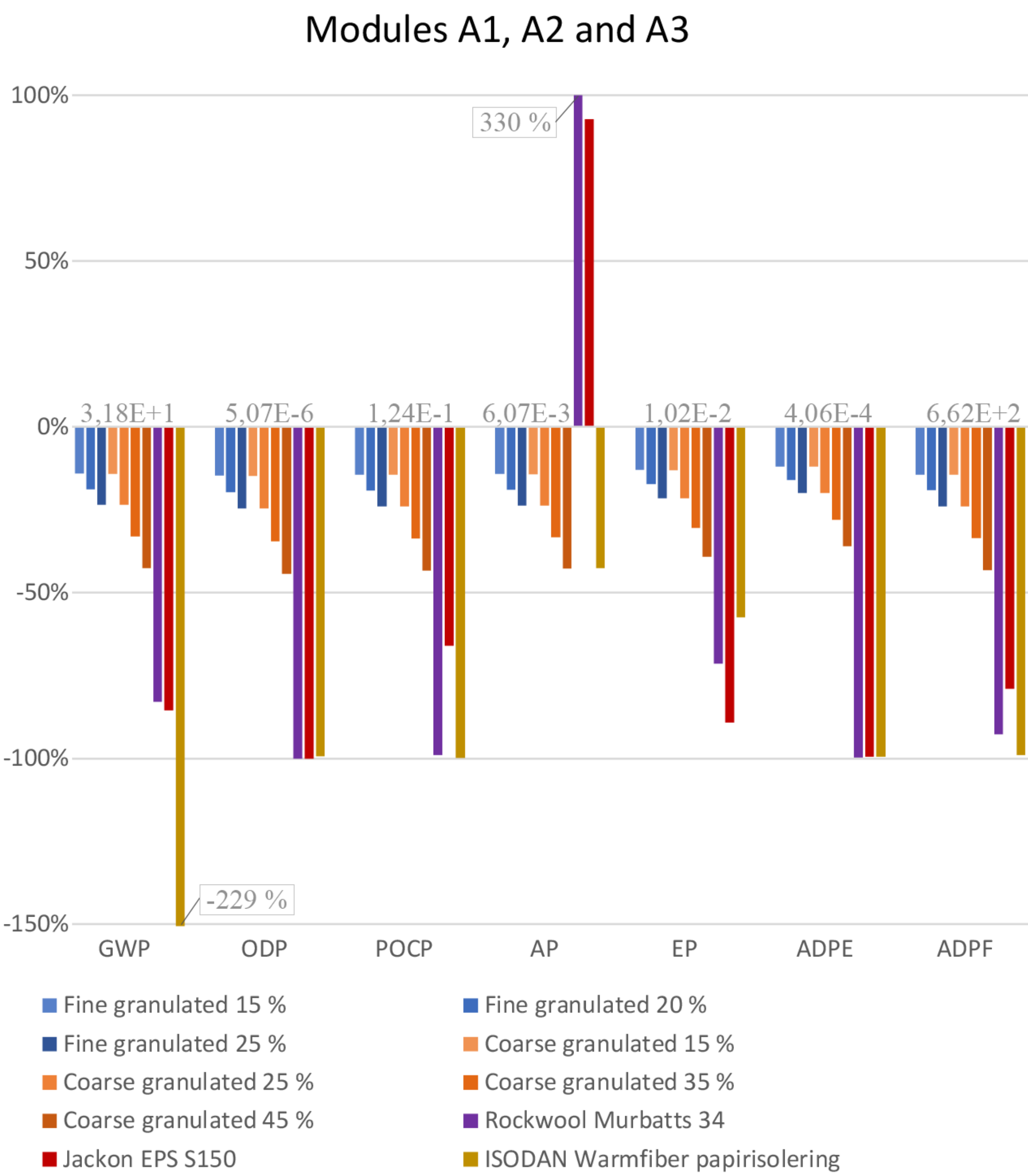

Figure H.9. Differences between the insulation materials LCA (Modules A1,A2 and A3)

From the graph H.9 is apparent that the PUR has a lower impact only in the parameter Acidification potential of land and water. These findings are highlighted even more in the graph H.10 where the Rockwool Murbatts 34 has 362 % greater environmental impact compared to the virgin PUR.

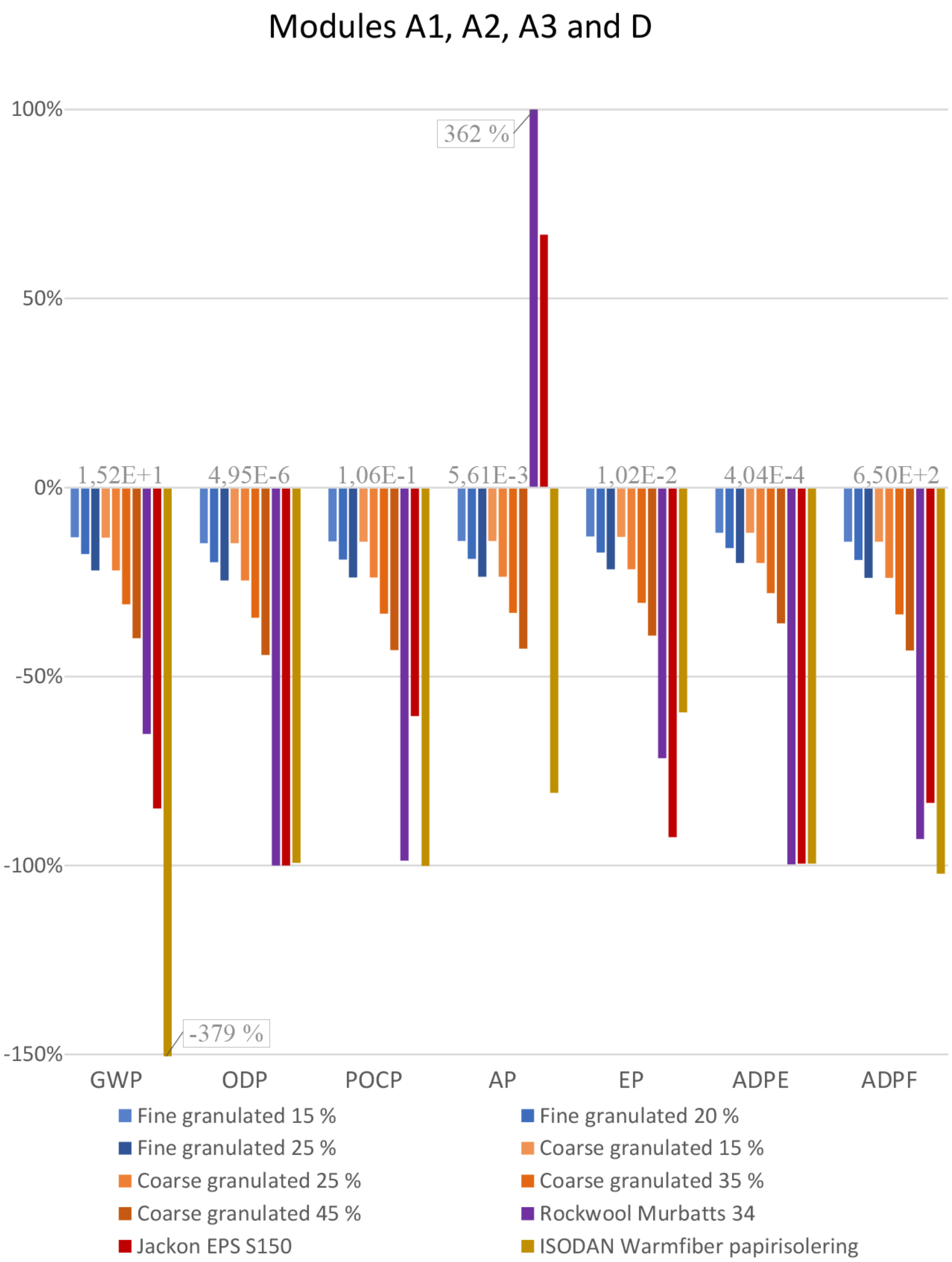

Figure H.10. Differences between the insulation materials LCA (Modules A1, A2, A3 and D

For the understanding of the environmental impact of the renovation of the external wall, not only insulation material is compared. Unlike other materials in this study, cellulose does not require the demolition and building of a new outer layer from bricks.

The life cycle assessment of the case building is calculated using LCAbyg which is a tool that helps analyse the environmental profile and consumption of resources. it has a broad database with elements commonly used in the building industry. It has usually only LCA modules A1, A2 and A3 included in the database, which is the production stage.

The results from the LCAbyg in the table H.5. It is per m^2 of the external wall from bricks. It is a sum of the impact of the bricks, lime plaster and finishing layer.

Table H.5. The results for the brick wall

Cat.	**Environmental indicator %**	**External wall**
GWP	kg $CO_2 - eq$	6,67E+1
ODP	kg $CFC11 - eq$	2,03E-2
AP	kg $SO_2 - eq$	5,75E-2
EP	kg $(PO_4)^3 - eq$	1,14E-2
POCP	kg $ethene - eq$	8,45E-3
ADPE	kg $Sb - eq$	3,22E-5
ADPF	MJ	8,91E+2

Since the cellulose was already best performing in many categories and since these environmental burdens are added only for the other insulation options it would be considered the best. The problem with cellulose is the limited amount of recycled paper from which the cellulose is created and the most problematic part is the fact that it can not be used in many places because it does not hold its form.

H.4 Life cycle cost calculation

Life cycle cost (LCC)investigates the costs related to the lifetime of a component and it is a decision-making process with a long-term approach. Life cycle cost broadens the perspective from focusing on acquisition costs to also including the costs that arise during the operation and use of the building. The study of LCC is crucial if the project involves multiple options because LCC allows seeing the full picture of the benefits and losses occurring during different stages of the building's lifetime. The life cycle cost assessment of the building was calculated using LCCByg, which is the Danish tool that helps to evaluate the life cycle costs for the entire building or single components. In this case, the building's external walls scenario is compared.

The calculation usually takes into consideration the price for construction, operation, maintenance, cost of supply and utility as well as the cleaning. But in this case, the cleaning and utility costs are neglected due to reason the building insulation options carry the same cost as the non-insulated building. In this project, the software was used to calculate the net present value of the existing building component cost over the period of 50 years and then it is compared with the renovation option scenarios as well as the option for no renovation at all.
Prices and additional costs were used from Molio Prisdata [38], which is the most comprehensive tool for price calculation in the construction industry.

The assumptions for the price development are taken from the DGNB certification suggestions where the discount rate is determined nominally and prices are stated in current prices over the entire calculation period.

H.4.1 Supply cost

As the current building is connected already to the Aalborg Fjernvarme A/S system the price of the meters is neglected. Additionally, even if a refurbishment happens or not the monthly subscription fee is added to the tenant's A-conto contribution meaning, this cost is also neglected.

Prices of the district heating is varying yearly, however, due to global conflicts prices are still increasing. The cost of 1 kWh energy from the district heating plant in Aalborg increased by 1,5 % from 2021 to 2022 and 17 % to 2023 [39]. This means the price now is standing currently at 0,684 DKK/kWh.

H.4.2 Insulation material prices

For the PUR, according to the Dan-iso A/S, the price of one m^2 of the product with a thickness of 90 mm is 283 DKK. The internal calculation on savings is that the cost of the raw materials is reduced by the amount of recycling. However, the recycling process of grinding and mixing also has its price and on the other hand, the company will not have to pay for the removal of the product waste during production. An estimate is the savings from recycling are 80 % of the raw material savings. The material cost for each percentage of recyclation can be seen in table H.6.

Table H.6. PUR prices changes

Sample	**Recycled percentage**	**Price [DKK/m^2]**
Virgin PUR		283
Fine granulated	15 %	249
	20 %	238
	25 %	226
Coarse granulated	15 %	249
	25 %	226
	35 %	204
	45 %	181

The table H.7 shows the prices for the other considered materials per m^2 with the same thickness as PUR of 90 mm.

Table H.7. Prices of other insulations

Materials	**Price [DKK/m^2]**
ISODAN Warmfiber Papirisolering [40]	67
JACKON EPS 150 POLYSTYREN [41]	114
Rockwool Murbatts 34 [42]	125

H.4.3 Application of insulation

Application of blown-in insulation takes fewer labour hours (according to Molio) and needs organisation for construction. All the included costs are listed in table H.8 are taken from element Hulmursisolering in Molio.

Table H.8. Used cost for blown-in insulation

Item	**Unit**	**Quantity**	**Unit cost**
Labour and machinery	hours/m^2	0,2793	455,10 DKK
Total cost	m^2	1	127,11 DKK

The application of rigid board insulation materials is including the demolition of the external leaf, removal of existing insulation, and application and cost of new wall and new insulation material. Prices for the renovation can be seen in table H.9, which is including work tasks from Molio.

Table H.9. Cost for application of the PUR, EPS and Mineral wool insulation as well as the new wall

Item	**Unit**	**Quantity**	**Unit cost**
Demolition of brick external leaf	m^2	1	66,55 DKK
Application of new insulation	hours/m^2	0,1278	455,1 DKK
Building the new external leaf	m^2	1	1032,23 DKK
Total cost	m^2	1	1156,94 DKK

H.4.4 Results of the LCC

The full result can be found in the L. The figure H.11 shows the initial cost of the investment.

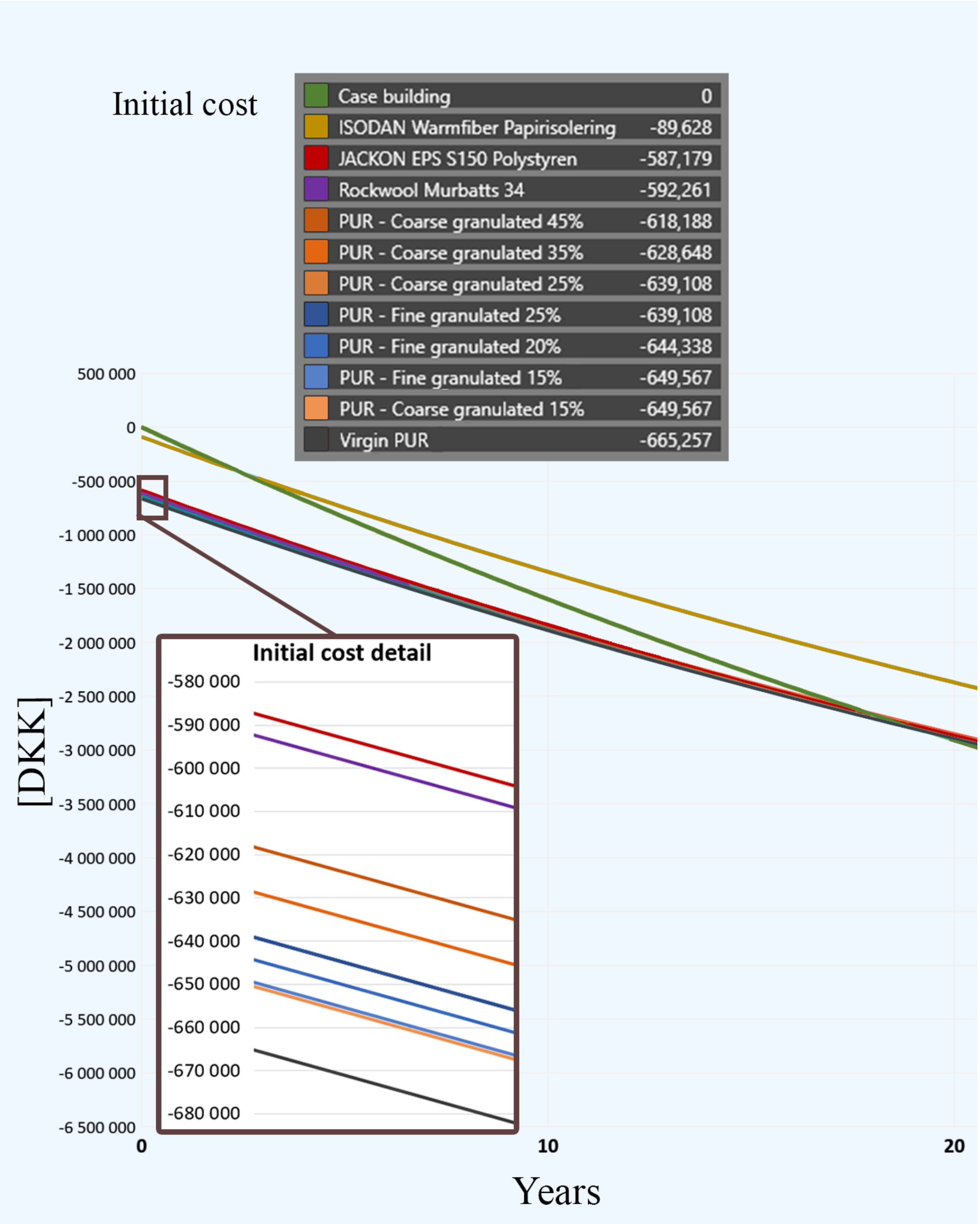

Figure H.11. Results of LCC over the period of 1 - 20 years

Figure H.12 shows the total cost caused by the building element from 30 to 50 years period.

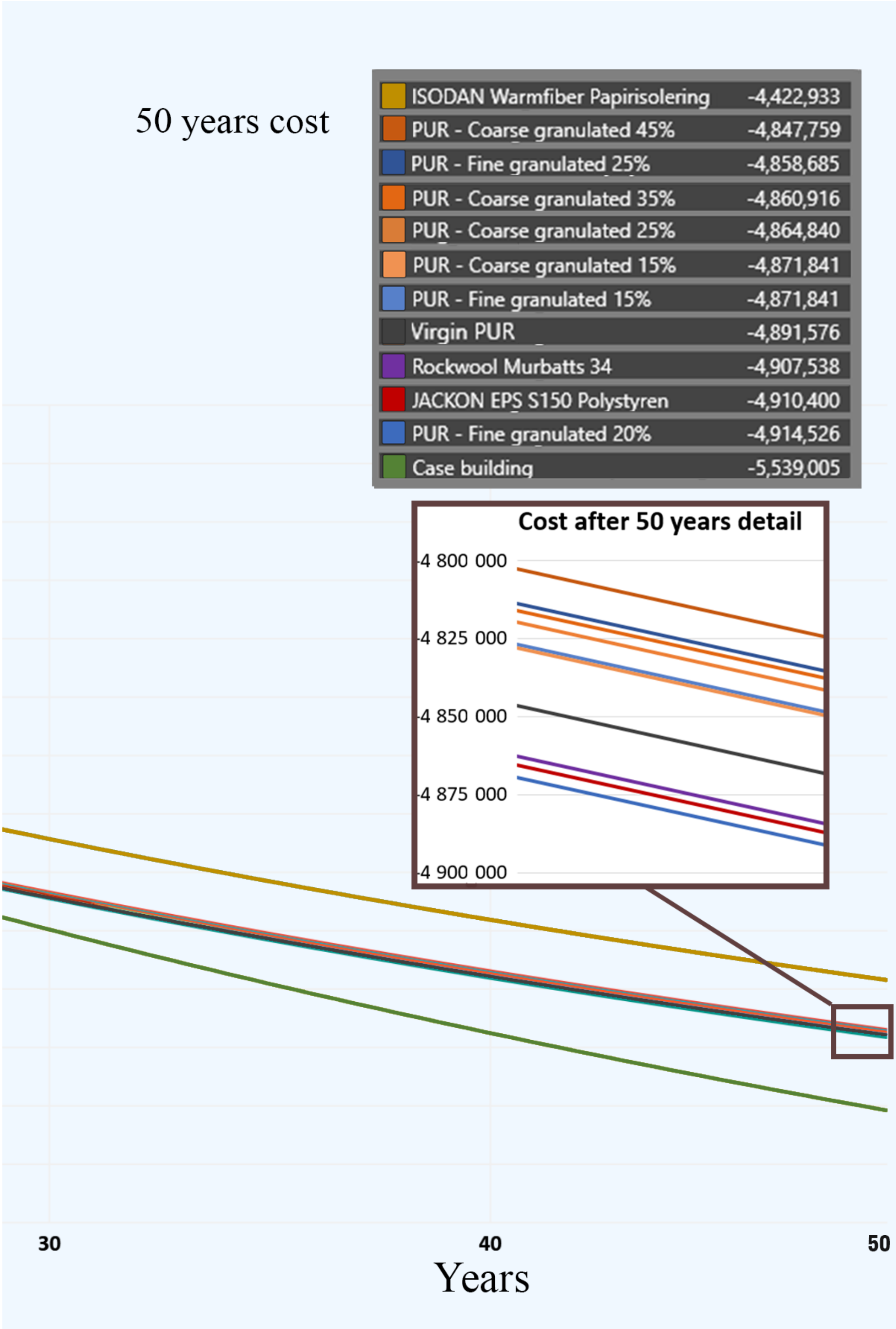

Figure H.12. Results of LCC over the period of 30 - 50 years

In conclusion, the cheapest for acquisition cost as well as the cost after 50 years is the ISODAN warmfiber papirisolering. But the cellulose has many problems with the containment of the particles and also cellulose is highly vulnerable to moisture. Another problem is that the cellulose can not be used in many other places such as the insulation of pipes and ducts in the building. Or can not be used as external insulation on the walls.

As for the other materials the initial cost of the EPS and Rockwool is lower, but after the span of 50 years, the Virgin PUR and also the tested samples show better performance in comparison.

H.5 Conclusion of the external wall renovation

Chosen recycled PUR was compared with other insulation materials from the market and applied to a building renovation. This practical evaluation could give a clear image of the properties on the building scale. The analysis of the environmental impact shows that the PUR is not as good as the other materials, but as can be seen from the end-of-life cost, the energy requirement for the building decreased. The LCA analysis does not cover the modules for the operational use environmental burdens, which would be in favour of the PUR since the energy needed for heating is lower than that of its competitors.

The return of the investment for the wall renovation as can be seen in figure L.1 located in the appendix L, is apparent that the cellulose has investment returns already after around 3 years while all the other materials have the return of the investment in around 18 years.

Conclusion

I

The tested 31 fine and coarse granulated samples delivered the following result. The content of recyclate in the recycled PUR influences the density of the sample and the thermal conductivity is highly dependent on the density. Furthermore, the material structural integrity was influenced by the percentage of recyclate in the fine granulated samples. Fine granulated samples limit, as neither the samples with 35 % nor 44 % of recyclate had their structure feasible with the intended use. The fine granulated recyclate takes a high amount of heat away from the PUR chemicals during the expansion process and restricts the curing. This can be clearly seen in the microscopic pictures of 35% and 44% fine granulated samples, where a lack of pore structure could be identified. Coarse granulated samples on the other hand reached the highest amount of recyclate content reached with 45 %, whereas the sample with 46% suffered from structural integrity deformation.

The compressive strength of the coarse granulated samples was similar to that of a virgin PUR in an interval of $\pm 17\ kPa$. On the other hand, fine granulated samples' strengths vary, which was influenced by the use of fine granulated particles. As the particles cannot bind with the virgin PUR on a high level to create a durable material structure. There is no specific requirement for the strength of the insulation material but all of the PUR samples have a strength much higher than commonly used mineral wool. In comparison with the other materials, cellulose was a clear winner in terms of the LCA and the return on investment from the LCC. But cellulose runs often into many problems. The cellulose has a limited amount of recycled paper from which the cellulose is created and the most problematic part is the fact that it can not be used in many components because it does not hold its form. For example external insulation on the wall or insulation around pipes or also insulation for some types of roofs and ceilings.

New simulations showed that the usage of fewer raw materials for PUR production can improve the environmental properties. The environmental impact could be reduced by around 40 % for the 45% coarse granulated samples. This improvement could move the product closer to Rockwool and Jackon EPS products. However, this does not describe a clear overall picture of the environmental impact as several categories were not included in the competitors' EPD documentation to compare the full LCA.

The initial cost of recycled PUR decreased and with the 38 % lower thermal conductivity compared to other insulation materials the return on the investment time of the recycled samples is lower by several years in comparison with the virgin PUR, after the calculation of LCC. For the summary, it is very feasible solution for the PUR to be recycled, since it reduces the environmental impact and also the cost of the final product, while keeping similar properties.

I.1 Key findings

The key findings of material properties can be found in the laboratory experiments, where both recycling methods samples were texted and compared. Fine granulated samples faced several drawbacks during the measurements, as no usable sample of 27 % could be produced due to problems with the structure of the pores. On the other hand, coarse granulated samples could be produced with 45 % of recyclate and have similar thermal conductivity results as a virgin PUR. The LCA calculation of the final chosen samples showed a significant improvement in comparison with virgin PUR, but the recycling methods (coarse granulated and fine granulated) are almost the same with a difference very close to 0.000 %. The only difference between the methods was the used energy during their production, but the most significant impact on the environment has the raw materials used during the production. The environmental impact of PUR can be further decreased by the increase of the recyclate percentage, which would decrease the amount of raw materials used for production.

Production of recycled PUR is more affordable, as the energy and extra labour require less financial found than the cost of raw polyol and diisocyanate. This is beneficial for the PUR as even with its higher cost but better thermal conductivity it is a more competitive (in terms of thermal conductivity) insulation material on the market compared to Rockwool and EPS.

I.2 Further research

In this study, all of the samples were recycled prototypes, where few modifications of material properties could result in large changes. This was especially valid for the fine granulated 25% sample. The change in the mixing machine (due to the malfunction of the old one), the material significantly improved its thermal conductivity to reach the level of virgin PUR. However, only one produced sample with this new method was tested therefore for the final evaluation it could not be validated. Since it showed a new path for improvement for the fine granulated recycling method the mixing should be further researched. According to Dan-iso A/S internal material development, the fine granulated method has a maximum between 20-27 % where the material structure is still uniform, but can this new mixing technology increase the stability of the sample reaches a higher amount of recyclate?

Further research can be made on another type of case building. Since there is a number of buildings which require high insulation (passive houses), where the high difference in thermal conductivity between the PUR, Rockwool and EPS could create varying results. The result of this study can decrease the initial cost of construction and decrease future property tax payments too. Because if the property tax is paid based on the external floor area (including the wall thickness) and therefore with PUR the building can reach the same thermal transmittance with a smaller thickness of the insulation than for example Rockwool.

The PUR can be precisely shaped and serve as insulation of pipes for the installations in the building. Further research is needed on the recycling ability of these smaller elements with different recycling methods.

Further research can be made with the full LCA comparison including all the modules, for example, module B6 Operational use can be in favour of the PUR since it has a better thermal conductivity in comparison to the other materials.

The repeatability of recycling is another part that can be investigated. How many times can the PUR be recycled before it loses its value in thermal conductivity strength and pore structure?

Appendix Results of LCA for each tested sample

J

The Section has a collection of all the results of the tested samples.

J.1 Virgin PUR

Table J.1. Results for modules A1-A3, C2, C4 and D for the pure sample

Cat.	Unit	Virgin PUR			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	5,25E+0	8,58E-3	2,73E+0	-2,74E+0
ODP	kg CFC11-eq	8,37E-7	1,87E-9	1,79E-8	-1,98E-8
AP	kg SO_2-eq	1,00E-3	1,07E-6	7,41E-5	-7,52E-5
EP	kg $(PO_4)^3$-eq	1,69E-3	7,96E-7	8,90E-6	-9,69E-6
POCP	kg ethene-eq	2,04E-2	3,12E-5	2,93E-3	-2,96E-3
ADPE	kg Sb-eq	6,71E-5	5,32E-8	2,86E-7	-3,39E-7
ADPF	MJ	1,09E+2	1,27E-1	1,78E+0	-1,91E+0

J.2 Fine granulated 15%

Table J.2. Results for modules A1-A3, C2, C4 and D for the 15 % fine granulated sample

Cat.	Unit	15% fine granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	4,51E+0	7,29E-3	2,32E+0	-2,33E+0
ODP	kg CFC11-eq	7,14E-7	1,59E-9	1,52E-8	-1,68E-8
AP	kg SO_2-eq	8,60E-4	9,07E-7	6,30E-5	-6,39E-5
EP	kg $(PO_4)^3$-eq	1,47E-3	6,76E-7	7,56E-6	-8,26E-6
POCP	kg ethene-eq	1,75E-2	2,65E-5	2,49E-3	-2,52E-3
ADPE	kg Sb-eq	5,90E-5	4,52E-8	2,43E-7	-2,88E-7
ADPF	MJ	9,36E+1	1,08E-1	1,51E+0	-1,62E+0

J.3 Fine granulated 20%

Table J.3. Results for modules A1-A3, C2, C4 and D for the 20 % fine granulated sample

Cat.	Unit	20% fine granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	4,26E+0	6,86E-3	2,19E+0	-2,19E+0
ODP	kg CFC11-eq	6,72E-7	1,49E-9	1,43E-8	-1,58E-8
AP	kg SO_2-eq	8,12E-4	8,54E-7	5,93E-5	-6,01E-5
EP	kg $(PO_4)^3$-eq	1,40E-3	6,37E-7	7,12E-6	-7,75E-6
POCP	kg ethene-eq	1,65E-2	2,49E-5	2,35E-3	-2,37E-3
ADPE	kg Sb-eq	5,64E-5	4,26E-8	2,29E-7	-2,71E-7
ADPF	MJ	8,84E+1	1,02E-1	1,42E+0	-1,52E+0

J.4 Fine granulated 25%

Table J.4. Results for modules A1-A3, C2, C4 and D for the 25 % fine granulated sample

Cat.	Unit	25% fine granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	4,02E+0	6,43E-3	2,05E+0	-2,06E+0
ODP	kg CFC11-eq	6,31E-7	1,40E-9	1,34E-8	-1,48E-8
AP	kg SO_2-eq	7,65E-4	8,01E-7	5,56E-5	-5,64E-5
EP	kg $(PO_4)^3$-eq	1,33E-3	5,97E-7	6,67E-6	-7,27E-6
POCP	kg ethene-eq	1,55E-2	2,34E-5	2,20E-3	-2,22E-3
ADPE	kg Sb-eq	5,37E-5	3,99E-8	2,14E-7	-2,54E-7
ADPF	MJ	8,32E+1	9,55E-2	1,33E+0	-1,43E+0

J.5 Coarse granulated 15%

Table J.5. Results for modules A1-A3, C2, C4 and D for the 15 % coarse granulated sample

Cat.	Unit	15% coarse granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	4,51E+0	7,29E-3	2,32E+0	-2,33E+0
ODP	kg CFC11-eq	7,14E-7	1,59E-9	1,52E-8	-1,68E-8
AP	kg SO_2-eq	8,60E-4	9,07E-7	6,30E-5	-6,39E-5
EP	kg $(PO_4)^3$-eq	1,47E-3	6,76E-7	7,56E-6	-8,24E-6
POCP	kg ethene-eq	1,75E-2	2,65E-5	2,49E-3	-2,52E-3
ADPE	kg Sb-eq	5,90E-5	4,52E-8	2,43E-7	-2,88E-7
ADPF	MJ	9,36E+1	1,08E-1	1,51E+0	-1,62E+0

J.6 Coarse granulated 25%

Table J.6. Results for modules A1-A3, C2, C4 and D for the 25 % coarse granulated sample

Cat.	Unit	25% coarse granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	4,02E+0	6,43E-3	2,05E+0	-2,06E+0
ODP	kg CFC11-eq	6,31E-7	1,40E-9	1,34E-8	-1,29E-8
AP	kg SO_2-eq	7,65E-4	8,01E-7	5,56E-5	-5,64E-5
EP	kg $(PO_4)^3$-eq	1,33E-3	5,97E-7	6,67E-6	-7,27E-6
POCP	kg ethene-eq	1,55E-2	2,34E-5	2,20E-3	-2,22E-3
ADPE	kg Sb-eq	5,37E-5	3,99E-8	2,14E-7	-2,54E-7
ADPF	MJ	8,32E+1	9,55E-2	1,33E+0	-1,43E+0

J.7 Coarse granulated 35%

Table J.7. Results for modules A1-A3, C2, C4 and D for the 35 % coarse granulated sample

Cat.	Unit	35% coarse granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	3,51E+0	5,58E-3	1,78E+0	-1,78E+0
ODP	kg CFC11-eq	5,49E-7	1,21E-9	1,16E-8	-1,29E-8
AP	kg SO_2-eq	6,69E-4	6,94E-7	4,82E-5	-4,89E-5
EP	kg $(PO_4)^3$-eq	1,17E-3	5,17E-7	5,78E-6	-6,30E-6
POCP	kg ethene-eq	1,35E-2	2,03E-5	1,91E-3	-1,93E-3
ADPE	kg Sb-eq	4,83E-5	3,46E-8	1,86E-7	-2,20E-7
ADPF	MJ	7,26E+1	8,28E-2	1,16E+0	-1,24E+0

J.8 Coarse granulated 45%

Table J.8. Results for modules A1-A3, C2, C4 and D for the 45 % coarse granulated sample

Cat.	Unit	45% coarse granulated sample			
		A1-A3	C2	C4	D
GWP	kg CO_2-eq	3,02E+0	4,72E-3	1,50E+0	-1,51E+0
ODP	kg CFC11-eq	4,66E-7	1,03E-9	9,85E-9	-1,09E-8
AP	kg SO_2-eq	5,74E-4	5,87E-7	4,08E-5	-4,14E-5
EP	kg $(PO_4)^3$-eq	1,03E-3	4,38E-7	4,89E-6	-5,33E-6
POCP	kg ethene-eq	1,16E-2	1,71E-5	1,61E-3	-1,63E-3
ADPE	kg Sb-eq	4,29E-5	2,93E-8	1,57E-7	-1,86E-7
ADPF	MJ	6,21E+1	7,00E-2	9,78E-1	-1,05E+0

Appendix Thermal conductivity measurements K

This appendix collects all the thermal conductivity graphs made by the EP500 Guarded Hot Plate. The measured samples are separated due to their recycling method.

K.1 Virgin PUR

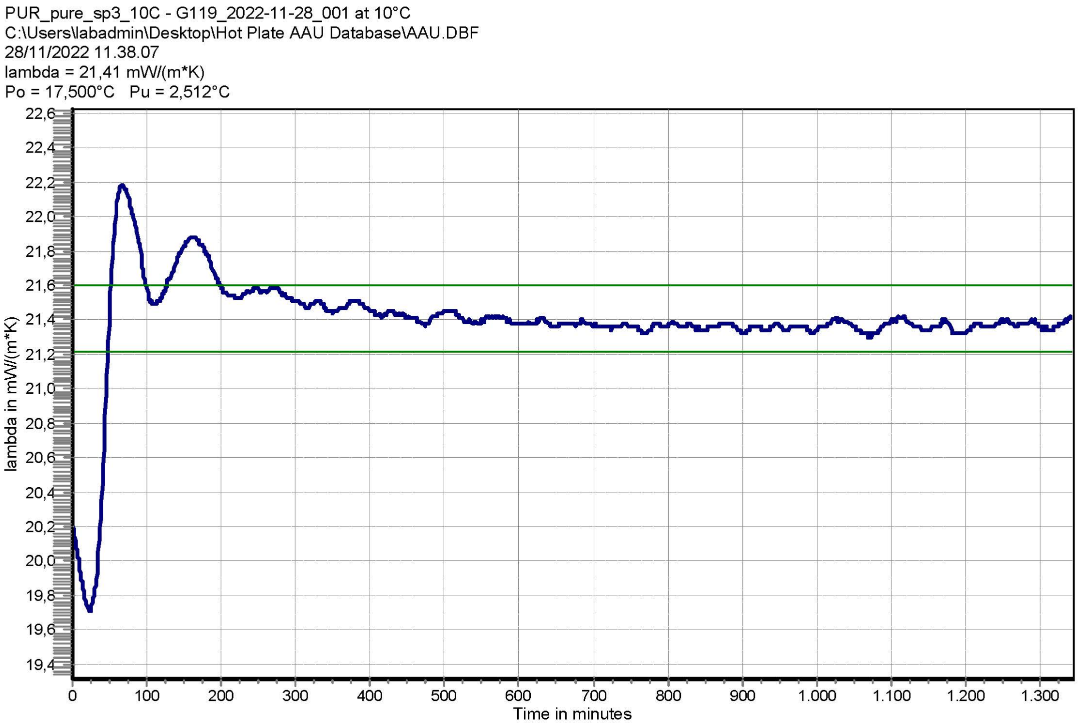

Figure K.1. Virgin PUR thermal conductivity measurement

K.2 Fine granulated PUR

K.2.1 15% recyclate

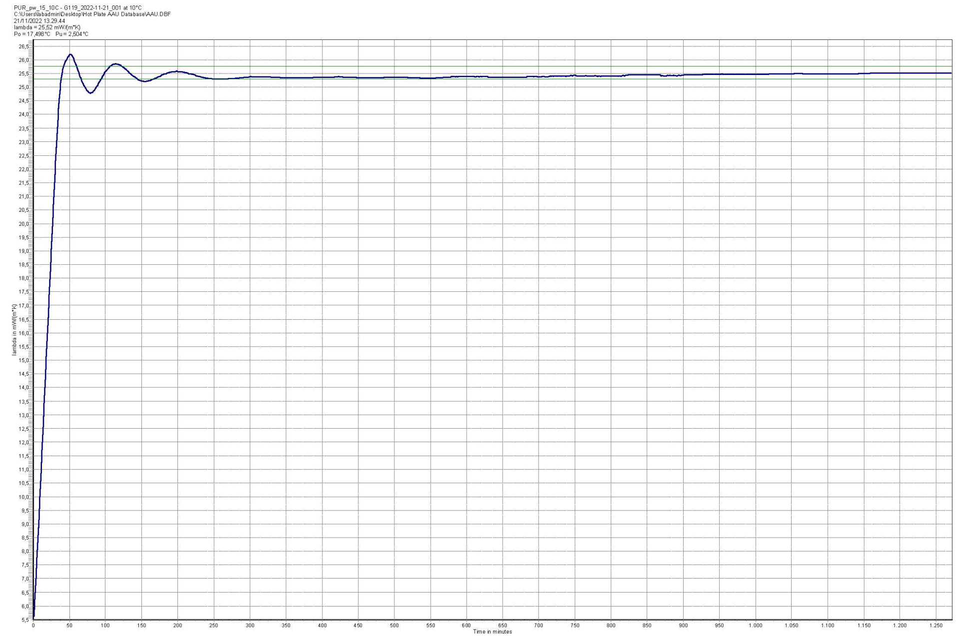

Figure K.2. Fine granulated 15% sample 1 PUR thermal conductivity measurement

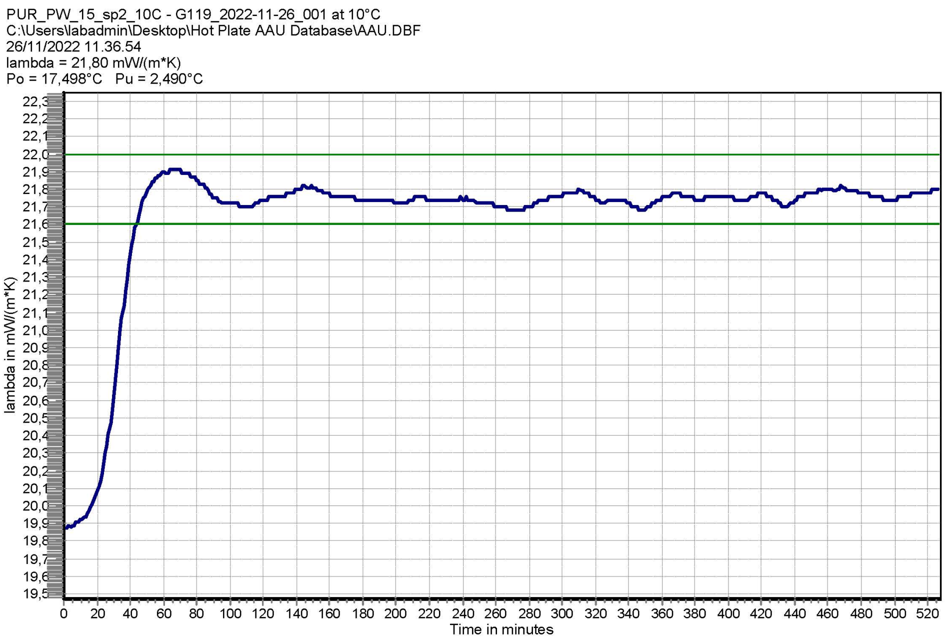

Figure K.3. Fine granulated 15% sample 2 PUR thermal conductivity measurement

K.2.2 20% recyclate

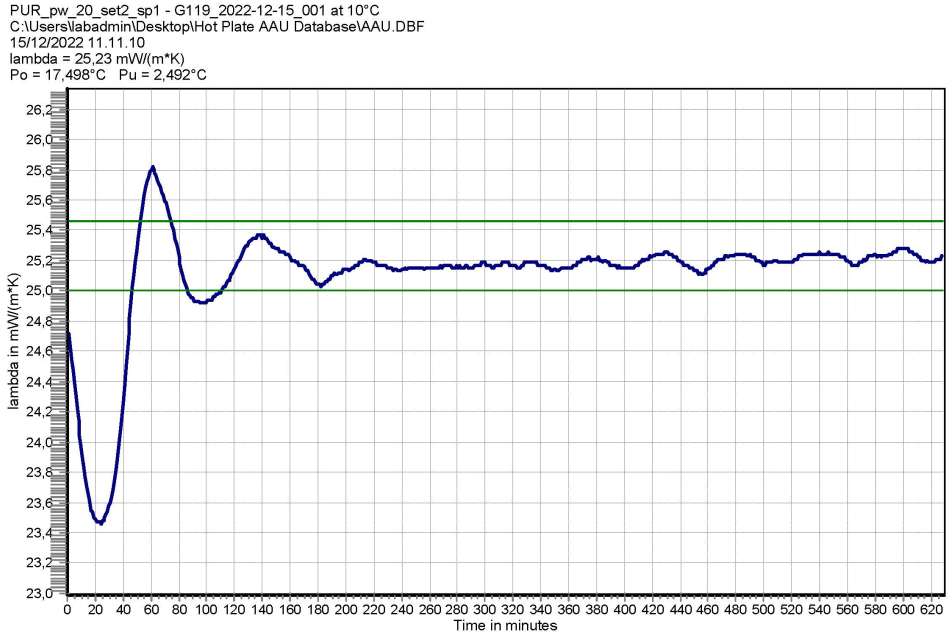

Figure K.4. Fine granulated 20% PUR thermal conductivity measurement

K.2.3 25% recyclate

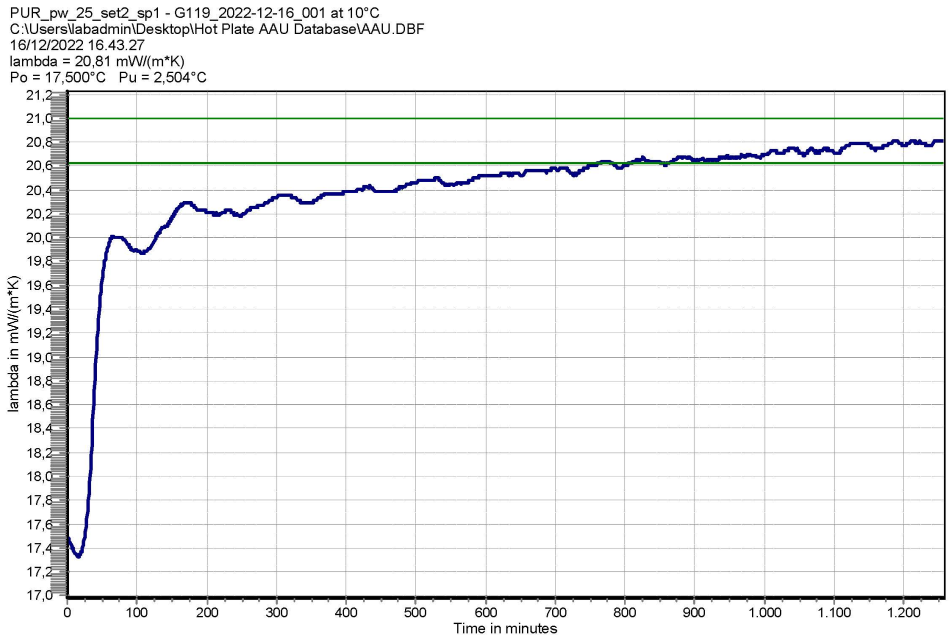

Figure K.5. Fine granulated 25% PUR thermal conductivity measurement

K.2.4 27% recyclate

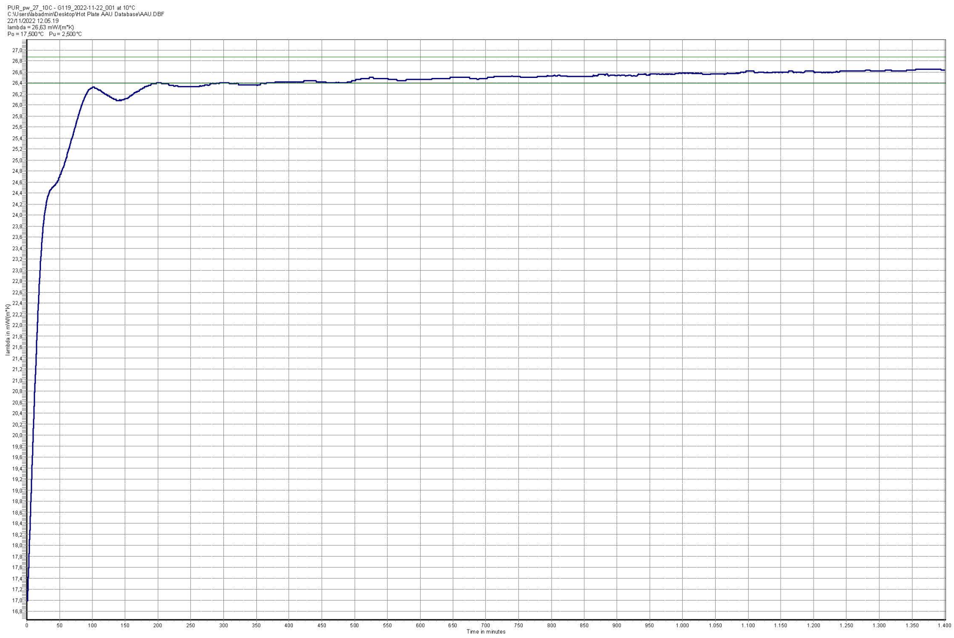

Figure K.6. Fine granulated 27% PUR thermal conductivity measurement

K.2.5 35% recyclate

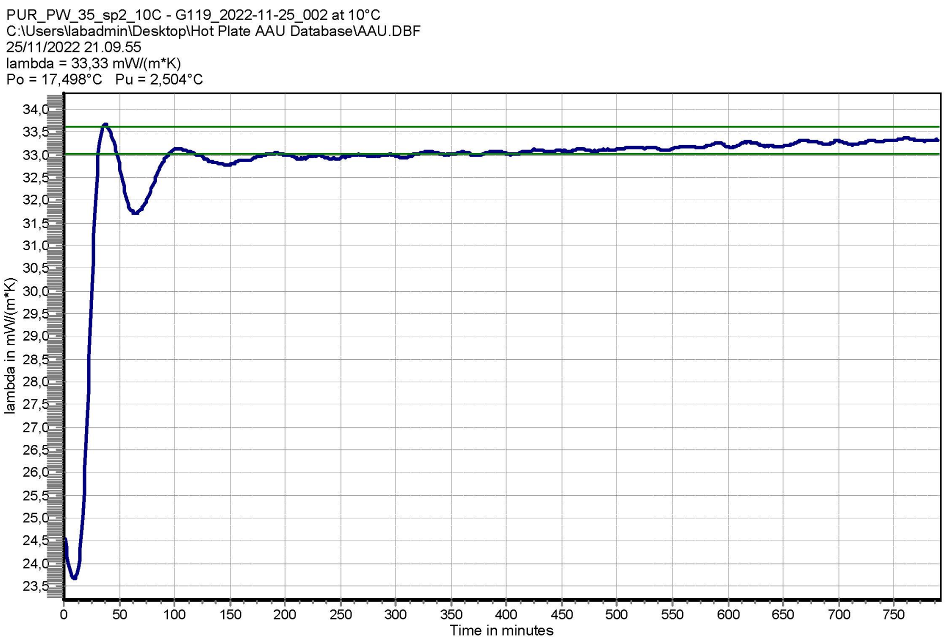

Figure K.7. Fine granulated 35% PUR thermal conductivity measurement

K.2.6 44% recyclate

Figure K.8. Fine granulated 44% PUR thermal conductivity measurement

K.3 Coarse granulated PUR

K.3.1 15% recyclate

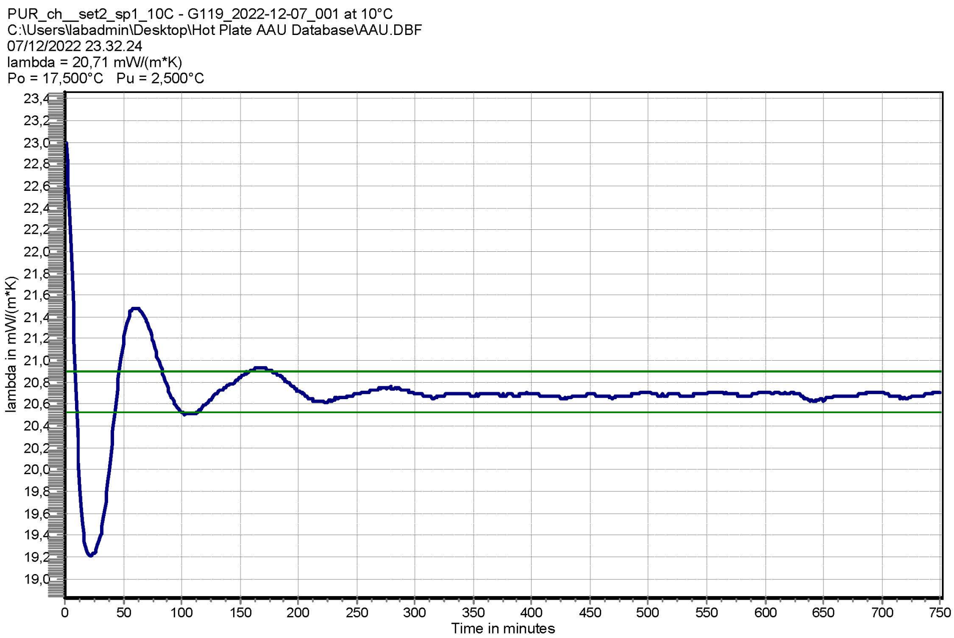

Figure K.9. Coarse granulated 15% PUR sample 1 thermal conductivity measurement

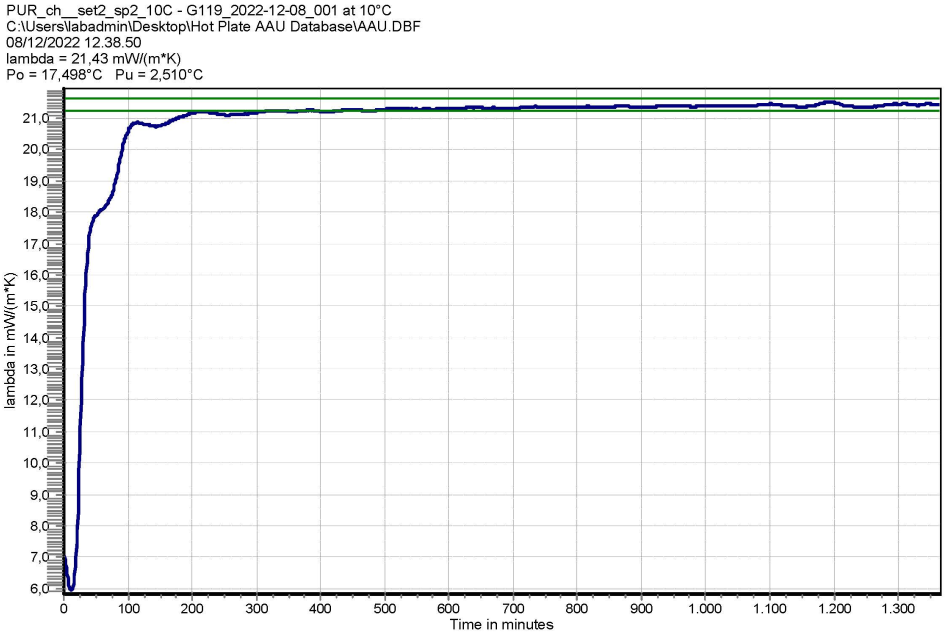

Figure K.10. Coarse granulated 15% PUR sample 1 thermal conductivity measurement

K.3.2 16% recyclate

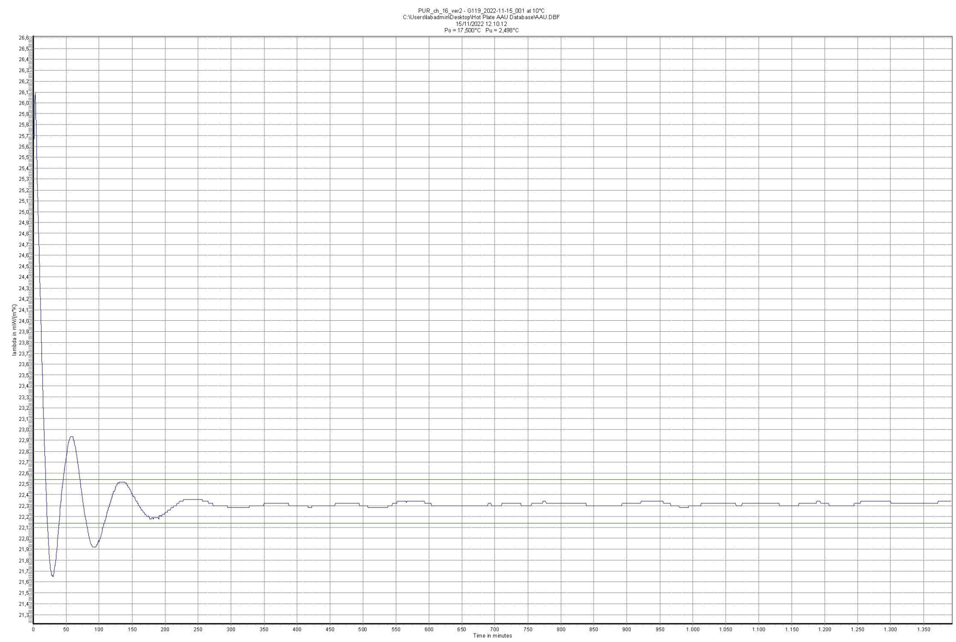

Figure K.11. Coarse granulated 16% PUR thermal conductivity measurement

K.3.3 25% recyclate

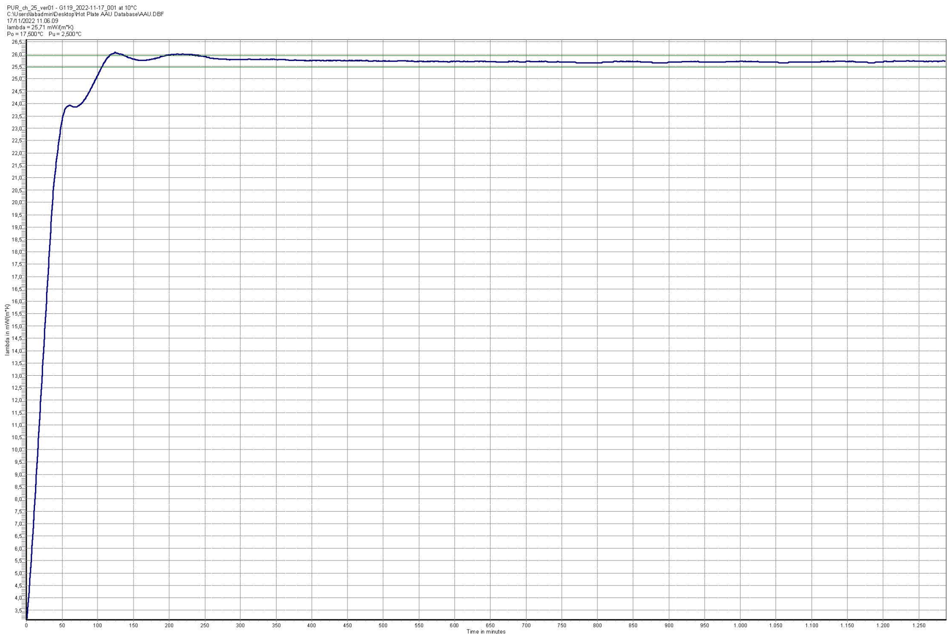

Figure K.12. Coarse granulated 25% PUR first set thermal conductivity measurement

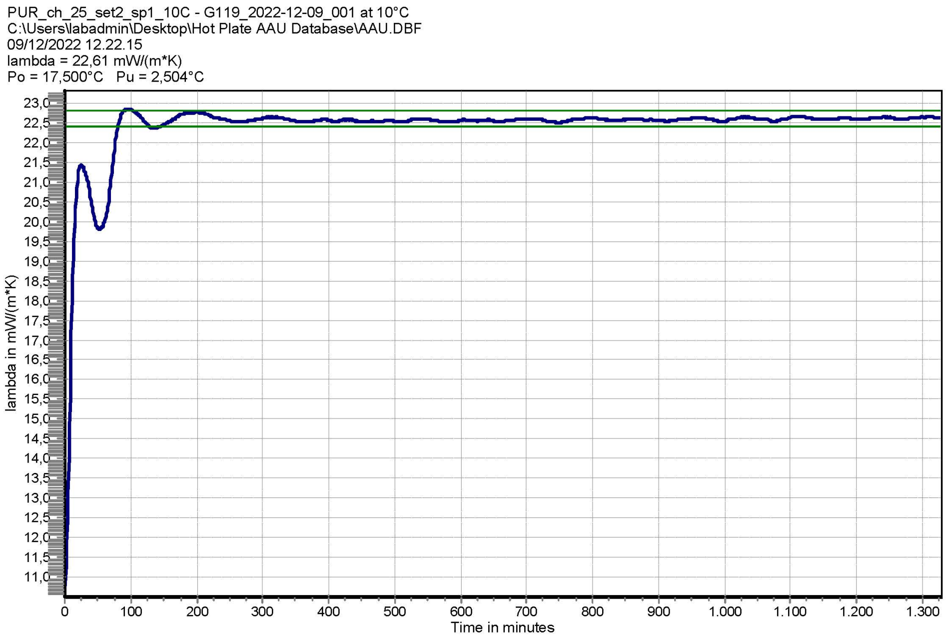

Figure K.13. Coarse granulated 25% PUR second set sample 1 thermal conductivity measurement

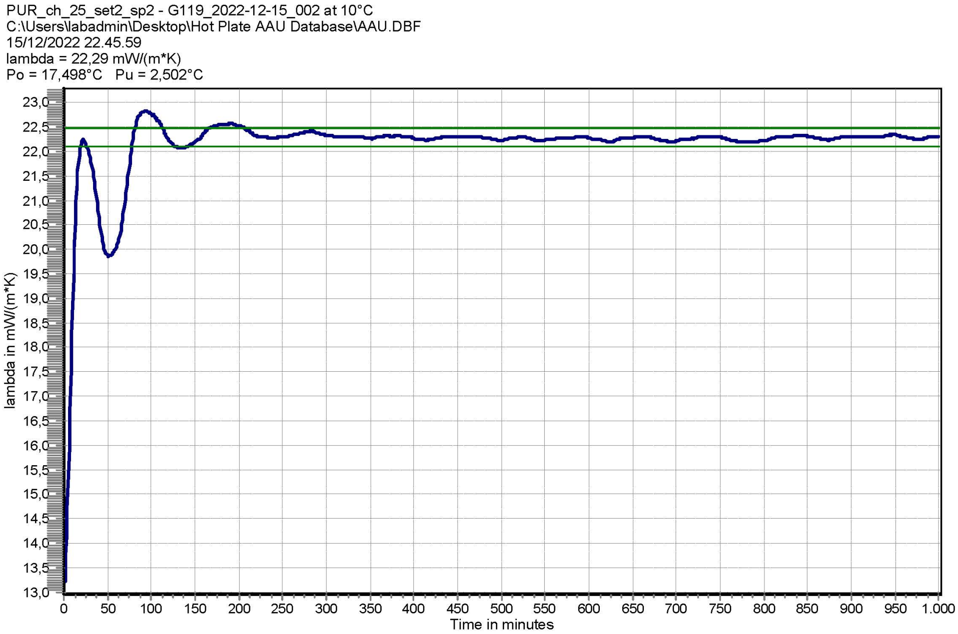

Figure K.14. Coarse granulated 25% PUR second set sample 2 thermal conductivity measurement

K.3.4 35% recyclate

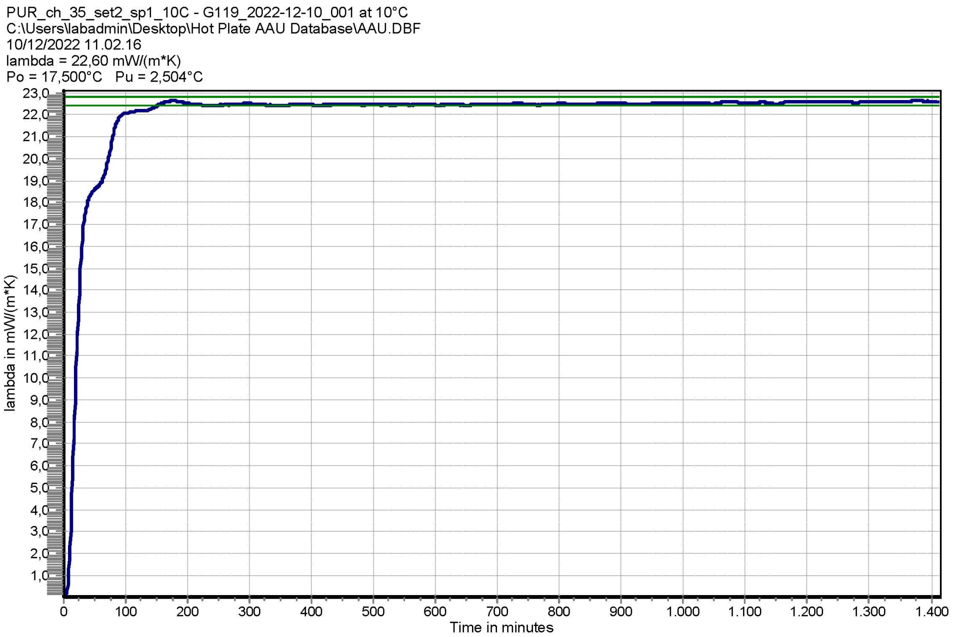

Figure K.15. Coarse granulated 35% PUR sample 1 thermal conductivity measurement

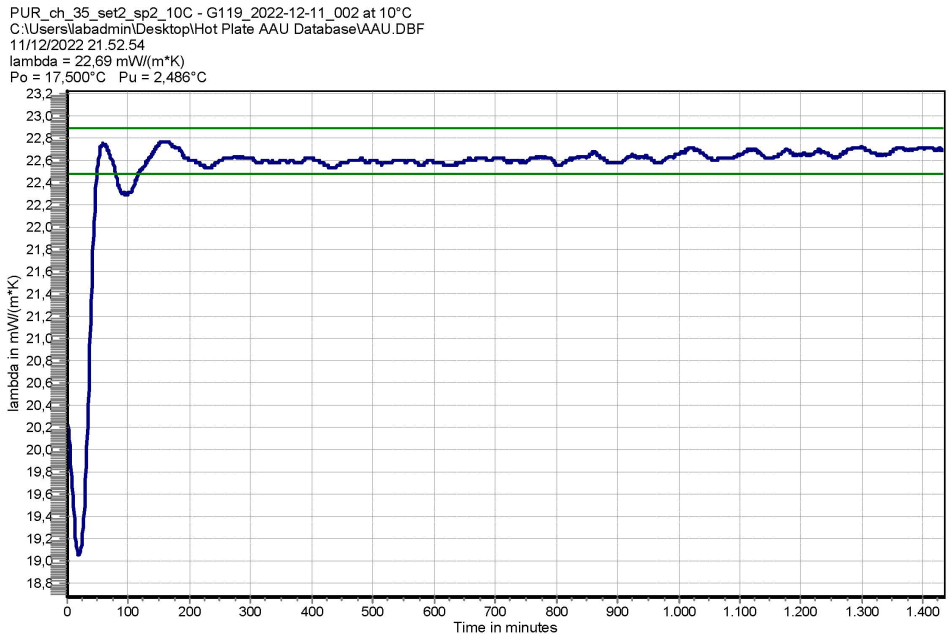

Figure K.16. Coarse granulated 35% PUR sample 2 thermal conductivity measurement

K.3.5 37% recyclate

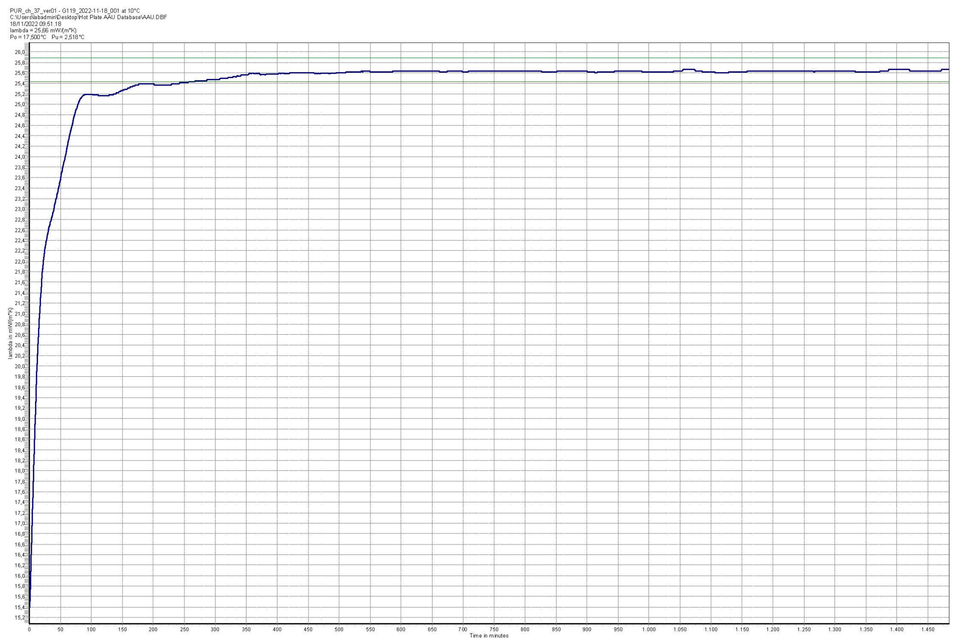

Figure K.17. Coarse granulated 37% PUR thermal conductivity measurement

K.3.6 43% recyclate

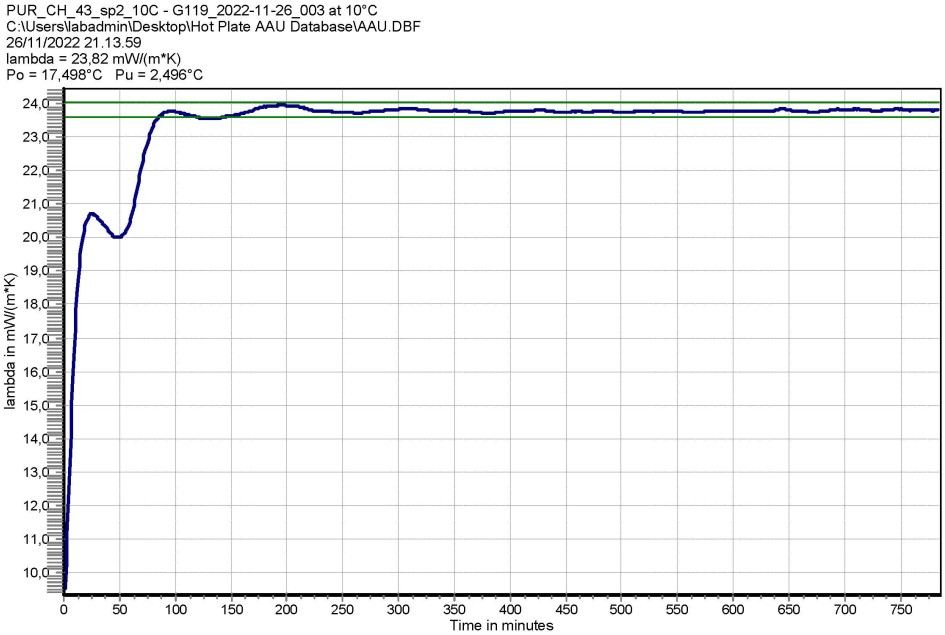

Figure K.18. Coarse granulated 43,3% PUR thermal conductivity measurement

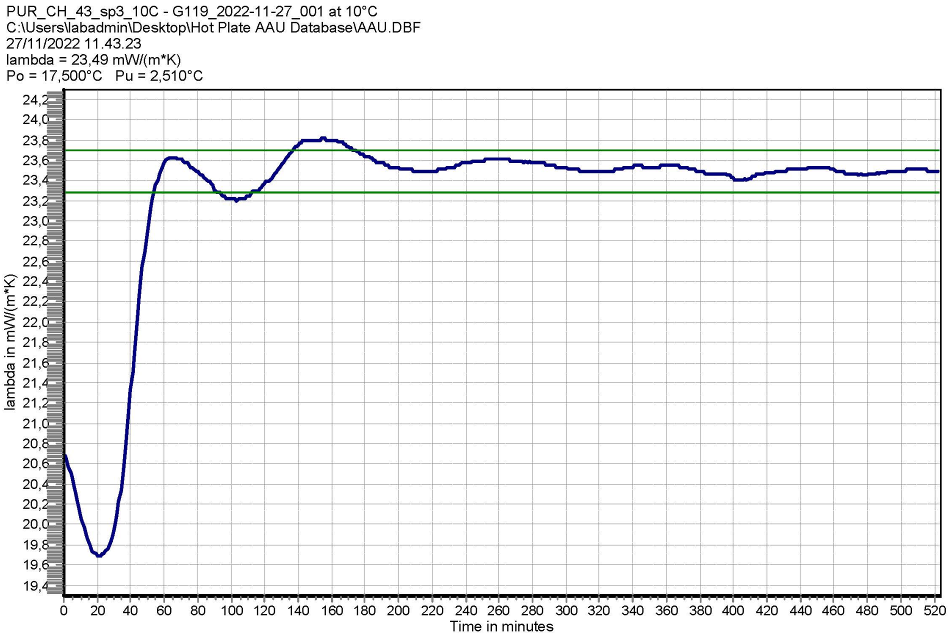

Figure K.19. Coarse granulated 43% PUR thermal conductivity measurement

K.3.7 45% recyclate

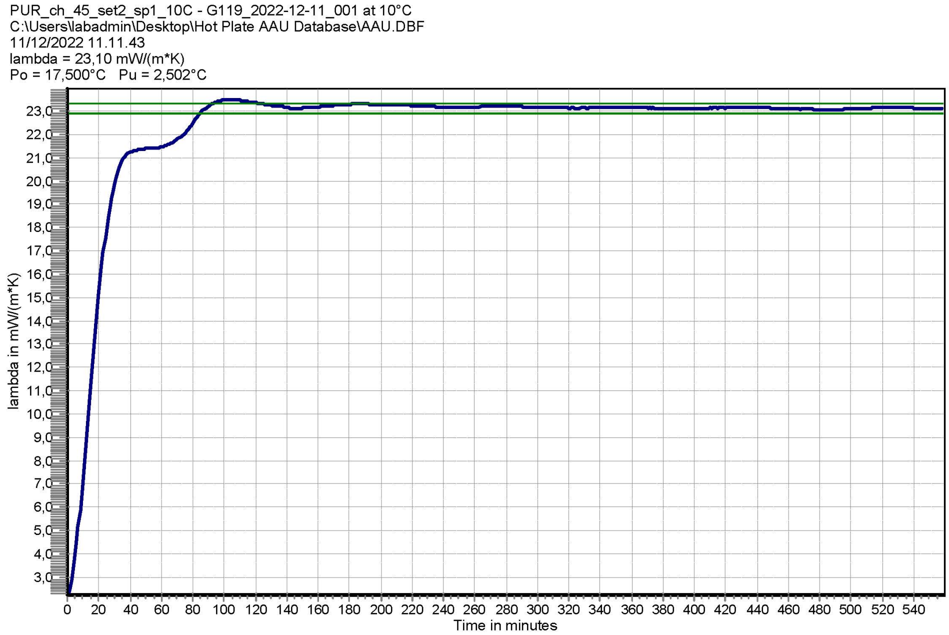

Figure K.20. Coarse granulated 45% PUR sample 1 thermal conductivity measurement

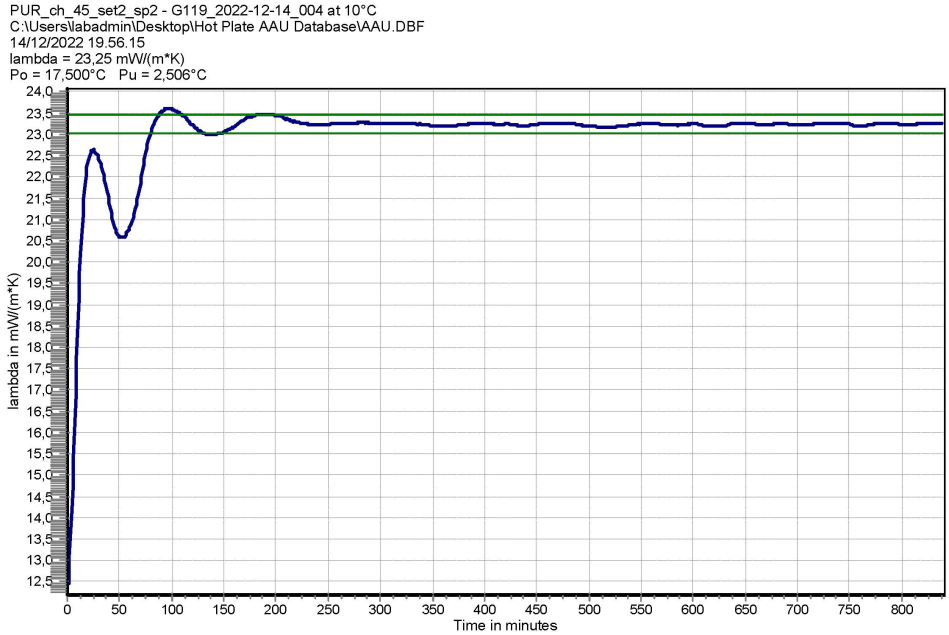

Figure K.21. Coarse granulated 45% PUR sample 2 thermal conductivity measurement

Appendix L Results of LCC for the renovation of the case building

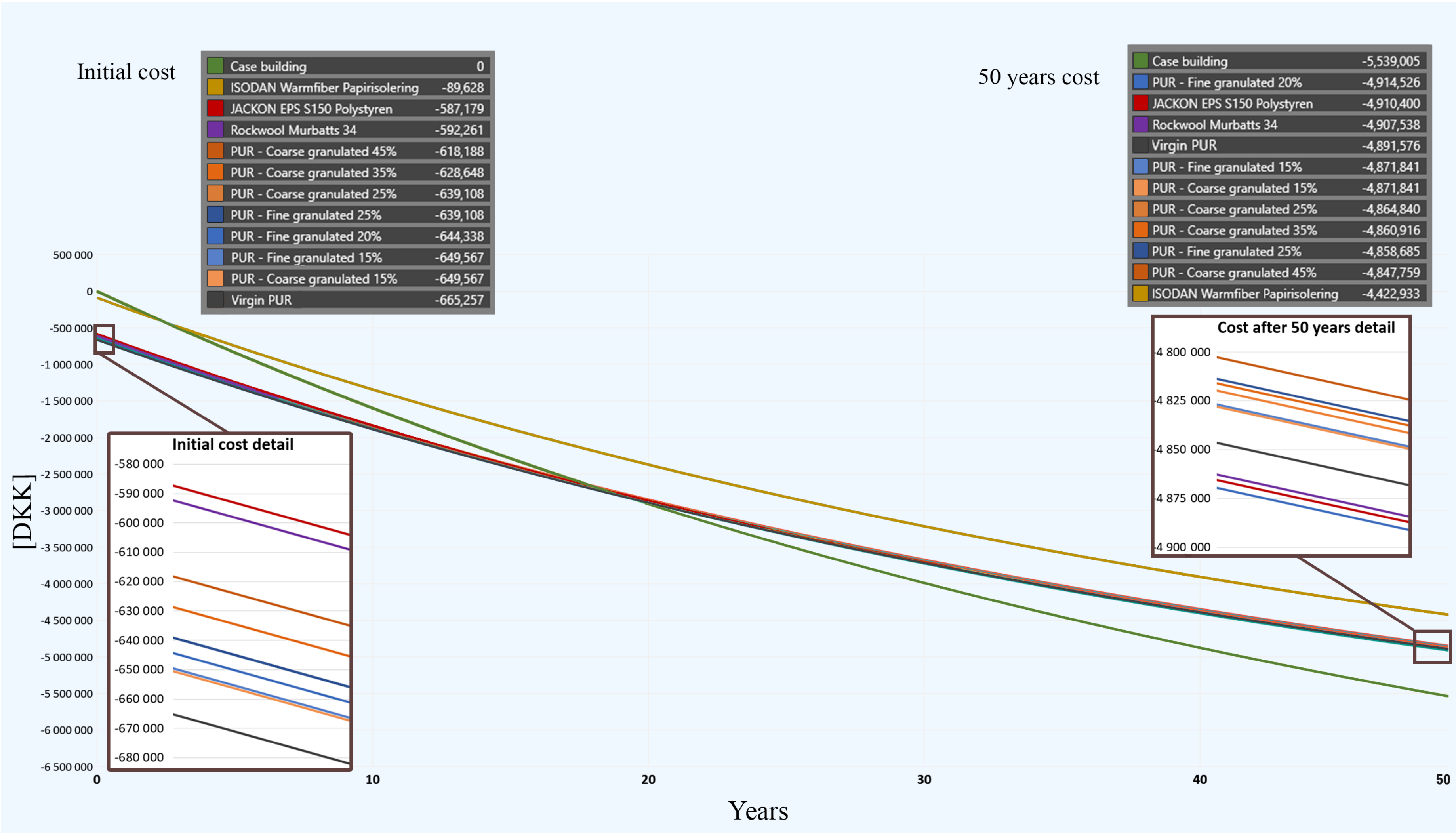

Figure L.1. Results of LCC over the period of 50 years

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