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SUMMARY

Four different scenarios for discarded bed mattresses are analyzed using an LCA (Life Cycle Assessment) to identify the scenario with the least environmental impact. This scenario was identified as Scenario 2, Open Loop Recycling of all recyclable materials, using the Dutch RetourMatras method, however, with a Closed Loop Recycling for the PUR foam. In this scenario, the collected mattresses were sorted and shipped to a shredding company, RetourMatras, in the Netherlands for further shredding and sorting, whereafter the re-bonded post-consumer PUR foam was made available to the market, a.o. to the partner in this project, Bramming Plast Industri (BPI).

Keywords: Discarded bed mattresses LCA, mattress waste management scenarios

Goal of the LCA screening

About 650.000 used bed mattresses are discarded every year in Denmark, generating appr. 15-16.000 tons of waste that mostly ends in waste incinerators across the country (Hauge et al., 2024). Danish municipalities strive to enhance recycling efforts and mattress producers in utilizing secondary materials, but limited options for collecting and recycling mattresses challenge these goals. This project has succeeded in creating a temporary infrastructure for collecting and recycling discarded mattresses, hence supporting these goals.

The LCA data presented here compares potential environmental impacts of four different waste-handling scenarios for discarded mattresses. Partners in the project - Odsherred Municipality, ARGO, ARC, The Capital Region of Denmark, Vejle Municipality, Vestforbrænding, the City of Copenhagen, Danfoam/Tempur-Sealy, and BPI may use the LCA results for better decision-making.

The LCA investigates change expected to affect not just the immediate system but also related areas, production capacity, and the mattress market. The study is done as a consequential LCA, following the ILCD Guidelines (International Life Cycle Data System).

As an initial conclusion we can state that *our data suggests that the recycling scenarios are better than the incineration scenarios,* but as always, there are limitations. The three main limitations are

- Lack of primary data. This study heavily relies on other studies, small-scale tests, or laboratory-scale tests. This also includes the material composition, where proxies from EASETECH have been used.
- The market response is not accounted for, which will most likely have a substantial impact on the results, esp. considering the uncertainties of the future market for bonded foam.
- Capital equipment has been excluded.

In the following section, the four scenarios are described.

Description of Scenarios

Baseline scenario: Scenario 1a and 1b

Some municipalities sort metal and wood before incineration while other municipalities do not. For this reason, two scenarios constitute the baseline - 1a and 1b.

Scenario 1a (Baseline)

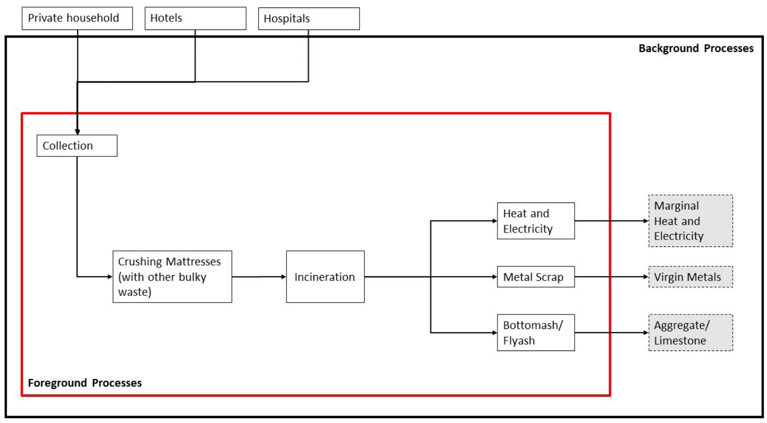

Fig. 1: Illustration of the foreground and background processes of the baseline scenario

Scenario 1a (baseline): Incineration of mattresses with energy recovery and recycling of metal (after incineration)

The mattresses (both box mattresses and soft mattresses) are crushed with other bulky waste. They are then incinerated with energy recovery. After the incineration, iron scrap and aluminum are removed from the bottom ash. The recoverable metal is recycled as scrap metal in Sweden. The bottom ash and fly ash are utilized as road aggregate in Denmark and limestone in Germany.

Scenarie 1b

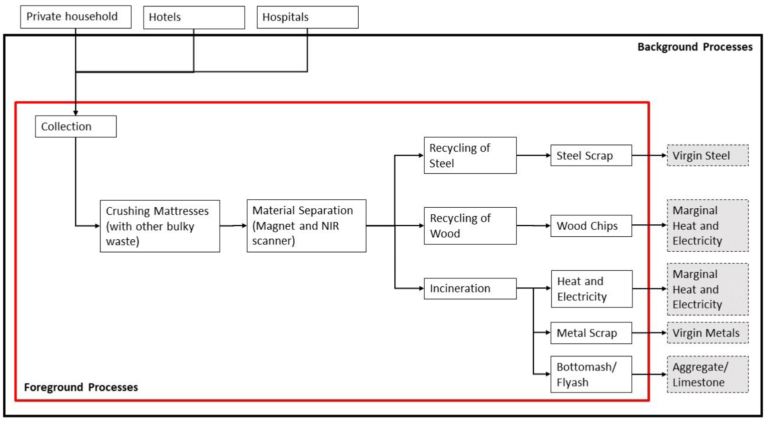

Fig. 2 Illustration of the foreground and background processes of scenario 1b

Scenario 1b (baseline): Incineration of mattress with energy recovery and recycling of metal (before incineration)

The mattresses (both box mattresses and soft mattresses) are crushed with other bulky waste. Any removable metal is removed via magnets and recycled as scrap metal. Any removable wood is removed via NIR scanners and recycled into particleboard. The remaining materials are then incinerated with energy recovery. After the incineration, any leftover metal is removed from the bottom ash. The recoverable metal is recycled as scrap metal in Sweden. The bottom ash and fly ash are utilized as road aggregate in Denmark and limestone in Germany.

Scenario 2: Open Loop Recycling of all recyclable materials (Using the RetourMatras method), however, Closed Loop Recycling for foam.

After collection and transportation to a transfer station, mattresses are sorted based on their condition, type, and components to determine the appropriate disassembly methods.

The soft mattresses are transported to a material separation facility in the Netherlands. The disassembly process begins by removing any textile covers by cutting the mattresses on three sides and peeling off the textile. This is then baled. If the mattress contains metal springs (e.g., spring mattresses), these are extracted from the mattress manually. The foam or padding layers are cut into strips and baled. The separated components are sent to other appropriate reprocessing facilities or incineration:

- Metal springs are processed in a shredding machine where it is separated from the plastic pockets. Thereafter it is brought back into the metal market as scrap metal.
- Foam is chemically recycled into re-polyol for use in new mattresses (up to half of the polyol needed for new PUR foam can be re-polyol).
- Clean and recyclable textile covers are processed into industrial cloths.
- Latex is converted into bonded foam to be used for thermal insulation.

For soft mattresses (spring or foam mattresses), the sorting rate for the material separation process is up to 80% (Møller, 2022) (RetourMatras, 2022). The remaining ≥20% that is not fit for recycling is incinerated (with the same conditions as Scenario 1a and 1b).

The box mattresses are crushed, and the wood, textile, and metal separated via NIR scanners and magnets respectively. The separated

Scenarie 2

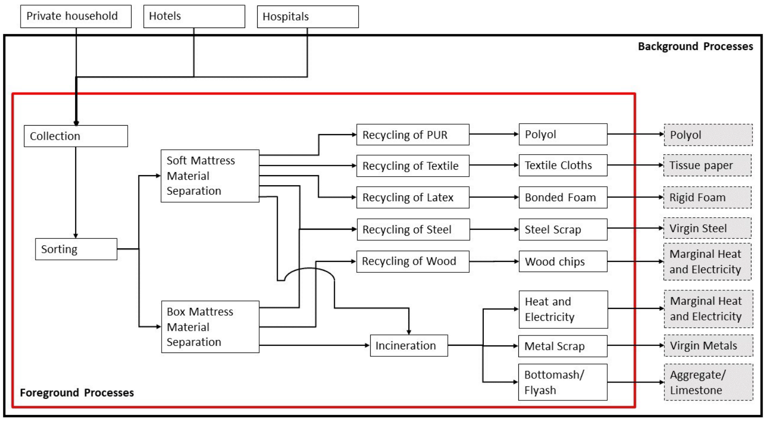

Fig. 3 Illustration of the foreground and background processes of scenario 2

components are sent to other appropriate reprocessing facilities or incineration:

- Metal springs are brought back into the metal market as scrap metal.
- Wood is recycled into particleboard.

For box mattresses, the sorting rate is up to 68% (Møller, 2022) (RetourMatras, 2022). The remaining ≥32% that is not fit for recycling is incinerated (with the same conditions as Scenario 1a and 1b).

Scenario 3: Open Loop Recycling of all recyclable materials (Using the RetourMatras method), (Note: only applies to soft mattresses).

Scenario 3 has the same material separation; however, the recycling and substitution differ. Instead of Closed Loop recycling for the foam, it is Open Loop recycled:

Scenarie 3

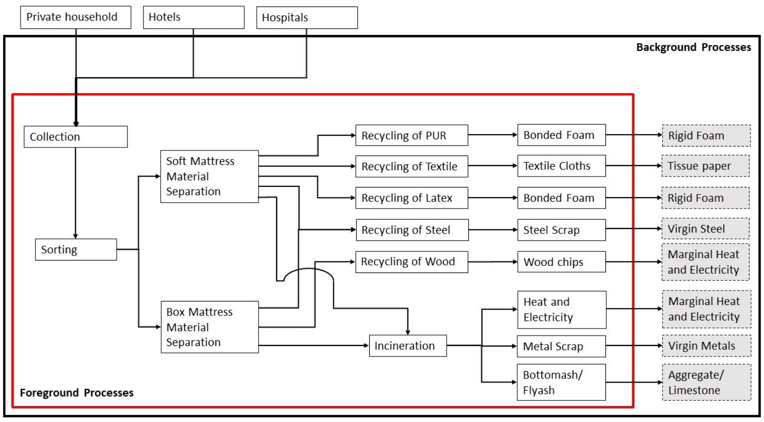

Fig. 4 Illustration of the foreground and background processes of scenario 3

- Metal springs are processed in a shredding machine where it is separated from the plastic pockets. Thereafter it is brought back into the metal market as scrap metal.

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Environmental impact categories	Unit	Scenario 1a	Scenario 1b	Scenario 2	Scenario 3
Climate change	kg CO2-eq	3.5E+02	1.9E+02	-2.9E+02	-2.7E+02
Ozone depletion	kg CFC-11 eq	-6.8E-06	-7.9E-06	-2.5E-05	-2.1E-06
Human toxicity: carcinogenic	CTUh	4.1E-07	-2.7E-06	-9.9E-06	-1.0E-06
Human toxicity: non-carcinogenic	CTUh	-3.5E-05	-3.8E-05	-7.4E-05	-2.8E-05
Particulate matter formation	Disease incidences	-6.56E-05	-7.7E-05	-6.7E-05	-7.3E-05
Ionising radiation: human health	kBq U-235 eq.	2.1E+01	1.4E+01	6.1E+00	1.8E+01
Photochemical oxidant formation: human health	mol H+ eq	-3.5E+00	-4.3E+00	-5.1E+00	-4.0E+00
Acidification	mol N eq	-3.7E+00	-4.3E+00	-4.6E+00	-5.0E+00
Eutrophication: terrestrial	kg N eq.	-1.6E+01	-1.8E+01	-1.7E+01	-1.6E+01
Eutrophication: freshwater	kg P eq.	-1.0E+00	-1.1E+00	-1.1E+00	-1.0E+00
Eutrophication: marine	kg N eq	-9.9E-01	-1.2E+00	-1.5E+00	-1.1E+00
Ecotoxicity: freshwater	CTUe	-7.6E+04	-7.9E+04	-1.4E+05	-6.6E+04
Land use	-	-9.6E+04	-9.4E+04	-7.4E+04	-6.8E+04
Water use	m3 water eq	-4.1E+02	-4.7E+02	-3.7E+02	-5.5E+02
Material resources: metals/minerals	kg SB eq	-3.4E-03	1.9E-03	-1.2E-02	7.2E-03
Energy resources: non-renewable	MJ	-1.6E+03	-2.4E+03	-3.9E+03	-2.8E+03

Table 1: The characterized results for all scenarios, where the red color indicates the highest value in the impact category and the green the lowest value (hence best)

- PUR foam is processed into bonded foam to be used for thermal insulation. However, it can also be used for packaging/shock absorption (protection of e.g., hifi-equipment, etc.), sound and vibration insulation (industrial machine encapsulation, DIY-market, etc.), comfort products (selected parts for furniture, mattresses, etc.), carpet underlay and other floor underlay applications.
- Clean and recyclable textile materials are processed into industrial cloths.
- Latex is converted into bonded foam to be used for thermal insulation.

As in scenario 2, soft mattresses (spring or foam mattresses), have a sorting rate for the material separation process of up to 80%. The remaining ≥20% that is not fit for recycling is incinerated (with the same conditions as Scenario 1a and 1b).

Results

The analysis shows clear preferences in the results:

- Scenario 2 showed the lowest environmental impacts in 10 categories, while contributing to environmental savings in all other categories.
- Scenario 1a has the lowest potential environmental impacts in 1 out of 16 impact categories (LU) and the highest in 7.
- Scenario 1b has the lowest potential environmental impact in 3 out of 16 impact categories (PMF, EuT, EuF) and the highest in none.
- Scenario 2 has the lowest potential environmental impacts in 10 out of 16 impact categories (CC, OD, HTc, HTnc, IRhh,POFhh, EuM, EcF, MRmm and ERnr) and the highest in 2.
- Scenario 3 has the lowest potential environmental impacts in 2 out of 16 impact categories and the highest in 7.

However, the potential impacts in some impact categories are very similar. It is not possible to conclude which scenario has the lowest potential impact when uncertainties in these impact categories are considered.

Recovery and Recycling Rate

The different recovery, recycling, and substitution efficiencies for Scenario 2 and 3 can be seen below in Table 2.

The materials in Table 2 show very different total recycling efficiencies and overall displacement, the latter representing the aggregated avoided impact from end-of-life recycling/substitution.

The foam has the lowest overall displacement due to recovery efficiency, as no foam is recovered from the box mattresses, and due to the technical substitution. In particular, the density of the bonded foam influences the technical substitution, as it is substantially higher than the substituted products such as glass wool and EPS. Thus, more material is needed to fulfill the same function. Furthermore, only up to 50% of the polyol used in new mattress foam can be recycled foam. Otherwise, the new foam will lose functionality.

The project is financed by IFD under InnoMission4 and the Novo Nordisk foundation

MATERIAL EFFICIENCIES	INPUT PR FU [KG] A	OUTPUT PER FU [KG] B	INITIAL SORTING RATE C	RECOVERY EFFICIENCY D	RECYCLING EFFICIENCY E	OVERALL RECYCLING EFFICIENCY F (=B/A)	SUBSTITUTION RATE G	OVERALL DISPLACEMENT H (=G*F)
PUR FOAM (SCENARIO 2)	307	127	94%	44%	100.0%	41%	50%	21%
PUR FOAM (SCENARIO 3)	307	120	94%	44%	95%	39%	62%	24%
LATEX FOAM	55	22	94%	44%	95%	39%	62%	24%
METALS	153	110	94%	99%	77%	72%	100%	72%
WOOD	344	250	94%	85%	91%	73%	100%	73%
TEXTILES	126	37	94%	34%	90%	29%	100%	29%

Table 2 The efficiencies of the modeled recycling system for the different materials.

Sensitivity analysis

Although the recycling scenarios appeared to have the lowest potential environmental impacts compared to the incineration scenarios, the perturbation analysis showed that Scenarios 2 and 3 had many sensitive parameters. If a parameter was considered both sensitive and uncertain, it was deemed highly important. These high-importance parameters include, a.o, the recycling efficiencies for the PUR and Latex foam, the substitution factors for steel, textile, polyol, and bonded foam, and the separation efficiencies in both the soft and box mattress recovery facilities. It is recommended that these parameters be investigated to decrease the uncertainty of the values.

The scenario analysis showed that the choice of energy mix had a substantial influence on the results and ranking of scenarios and, thus, on the conclusions of this study. This study based the energy mix on the increase and decrease of energy technologies from 2011 to 2021, therefore basing the long-term marginal energy mix on past changes. This makes the choice of future marginal technologies susceptible to current trends, as less utilized energy technologies might experience sudden increases or decreases in use that will not continue. The choice of marginal mix had an especially large influence on Scenarios 1a and 1b as these scenarios rely more on energy recovery. Other sensitive assumptions were the choice of data source for the glycolysis process and the location of the disassembly facility for soft mattresses. It is recommended that the study be updated when more data for the glycolysis process becomes available, especially when testing the process on a large scale, as the LCI data might change. Also, the efficiencies might change if a wider variety of mattress types and states of mattresses (i.e., to which degree they are clean and dry) might be included in the recycling system. It is also recommended that the study be updated if the location of the disassembly facility changes.

Conclusions

This study investigated current and potential waste management options for discarded bed mattresses in Denmark.

The following points can be concluded from this LCA screening.

- Results are highly dependent on the recycling pathway, i.e., whether the foam is recycled into polyol or bonded foam. This means that future decisions regarding the potential waste management is likely to have a large influence on the results.
- An environmental benefit of recycling mattresses with the currently proposed system and currently used data appear; however, these results have substantial uncertainties.
- The market response for rebonded post-consumer PUR foam is unclear. Substantially increasing the recycling of bed mattresses may result in supply exceeding demand (esp. for the PUR foam). As the market response is not included in the substitution, the results should be interpreted as representing the environmental impacts if the specified amount of material is successfully displaced.

Uncertainties especially pertain to the lack of primary data and market response. If the study is updated with more primary data, the results may lead to different conclusions.

The following recommendations for further work are given

- Investigate the market response to increased amounts of rebonded post-consumer PUR foam
- Potentially consider other uses for rebonded post-consumer PUR foam
- Most importantly, updating the study when more primary data is available

Literature

DTU Sustain. (forthcoming). *Life Cycle Assessment of End-of-Life Bed Mattresses - Evaluating the Environmental Impact of 'Mattresses – Reuse and Recycle Systems, a Pilot to Scale*

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