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TOTEM potential

PART 1: ESTIMATION OF THE POTENTIAL OF TOTEM FOR ENVIRONMENTAL IMPACT REDUCTION

Study commissioned by public waste agency of Flanders

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Executive summary

Buildings have a significant impact on the environment. This impact is due to both operational energy use and the use of construction materials. The online TOTEM tool allows to calculate and optimise the environmental impact of buildings in Belgium. The first version of the tool was released in 2018. The three regional authorities (OVAM, IBGE-BIM and SPW), who designed the tool, have the ambition to further develop it and have already taken various steps in that direction, including the present TOTEM potential study. This study has two main objectives:

- to estimate the potential reduction in environmental impact of buildings that could be achieved by using the TOTEM tool during the design phase and therefore the potential of TOTEM to help achieve policy goals (Part 1);
- to assess the potential of the TOTEM methodology to improve the environmental performance of non-building related construction works (mainly civil engineering works) (Part 2).

In this part of the study (Part 1), the environmental impact reduction potential for buildings is studied by means of a limited literature review in combination with a set of case study analyses. More specifically, the study focuses on the order of magnitude of the impact reduction, the relative importance of material optimisation compared to optimisation of the energy performance and the differences in optimisation potential between new construction and renovation.

In order to investigate the different optimisation strategies, three case studies were selected. For *Case 1*, a newly constructed multi-residential building, the focus of assessment is the optimisation potential through material selection (different structural systems, alternative finishing materials, ...). For *Case 2*, a terraced house from 1920, the assessment focuses on the improvement potential through renovation. For *Case 3*, a new semi-detached house, the focus lies on the improvement potential through optimisation of the energy performance. For each building, a reference composition (representative of current practice for the given building type) and several variants (in line with the studied optimisation strategy) are defined. The cradle-to-grave life cycle analyses of the cases are performed with the software SimaPro, following the MMG methodology (which forms the basis for the TOTEM tool).

The first case study shows that, for a new building, an optimisation strategy based on material selection only can lead to a reduction of about 30% of the material related impact or about 15% of the total impact (materials + energy use for HVAC). This reduction will, however, be largely influenced by the initial material selection, as well as by the freedom left to the designer (e.g. financial and technical possibilities). In addition, the results confirm the findings from literature that finishing materials can play an important role in the optimisation strategy. They are sometimes major contributors and usually several alternatives are possible. However, it should be kept in mind that finishing materials are likely to be changed over the lifetime of the building and therefore a higher level of uncertainty exists.

In line with the conclusions from the literature review, the renovation case study (case 2) indicates that the highest reduction potential for older (poorly insulated)

buildings lies in the improvement of the energy performance. The material related impact for an energetic renovation is usually relatively low, but the improvement potential in terms of energy use is high. For the renovation of the terraced house from 1920, a 50% reduction of the life cycle impact is achieved by optimising the type of installations and insulation level compared to a strategy that would only fulfil the minimum legal requirements in terms of energetic renovation. The results also show that EPB-software and TOTEM can and should be used complementary. Whereas the E-value provides guidance in terms of lower total environmental impact (lower E-levels generally lead to lower environmental impact), the results show that there is also room for optimisation within a given E-value.

The third case study shows that even for low energy buildings (respecting the current requirements in terms of energy performance), there is a potential for impact reduction through optimisation of the insulation level and choice of installations. The extent of the optimisation potential will depend on the performance of the starting point, but for buildings built according to minimum legal requirements it can be of the same order of magnitude as the reduction potential through material selection. However, based on present case studies, the life cycle impact (over 60 years) of the most optimised new dwelling (insulated up to passive standard) in Case 3 is still significantly higher than the life cycle impact of the optimised energetic renovation (to E-level of 30) in Case 2.

The results from the study also indicate that the impact of installations can be relatively high. As installations influence the impact related to the energy use of the building it must be ensured that the embodied impact of (insulation) materials and installations (modules A, B4, C), and operational energy use (B6) are considered together to allow for holistic optimization.

Additionally, the literature review indicates that for new (low energy) buildings the reduction potential through optimized building design (lay-out, percentage of windows, height of ceilings, …) can be at least as important as the reduction potential through material selection or improvement of the energy performance of the building. Therefore, a geometric optimization should be the first step of any environmental optimization process.

Finally, the last chapter of the study provides some recommendations for improvement of the functionalities of TOTEM that could facilitate or enhance the optimisation process. These functionalities concern a visualisation of the relative contribution of individual materials to the total environmental impact of the building using a network diagram or to a given life cycle phase or impact indicator; the possibility to make comparisons on material level for specific materials by reporting the monetarised impact of materials per functional unit directly in the TOTEM library; the introduction of technical installations into the TOTEM library; the visualisation of the benefits from using or exporting electricity produced by PV panels; the inclusion of additional finishing materials into TOTEM; and the addition of module D (or alternative information) to take into account potential benefits of recycling and reuse. Also, it could be interesting to investigate alternative units for representing the results (e.g. impact/GFA, total impact, impact/inhabitant).

Samenvatting

Gebouwen hebben een belangrijke impact op het leefmilieu omwille van het operationeel energieverbruik en het gebruik van bouwmaterialen. De online TOTEM tool laat toe om de milieu-impact van gebouwen in België te berekenen en te optimaliseren. De eerste versie van de tool werd gelanceerd in 2018. De drie regionale overheden (OVAM, BIM en SPW), die de tool uitgewerkt hebben, willen deze verder ontwikkelen en hebben hiertoe al verschillende stappen ondernomen, waaronder deze TOTEM Potentieelstudie. Deze studie omvat twee grote doelstellingen:

- het inschatten van de potentiële reductie in milieu-impact van gebouwen door het gebruik van de TOTEM tool tijdens de ontwerpfase en zo ook het potentieel van TOTEM om beleidsdoeleinden te bereiken (Deel 1)
- het inschatten van het potentieel van de TOTEM methodologie om de milieuprestaties van niet-gebouwgerelateerde bouwwerken (vooral infrastructuurwerken) te verbeteren (Deel 2).

In dit deel van de studie (Deel 1), wordt het potentieel inzake milieu-impactreductie van gebouwen bestudeerd aan de hand van een beperkte literatuurstudie en een aantal casestudieanalyses. Meer specifiek focust de studie op de grootteorde van de impactreductie, op het relatieve belang van materiaaloptimalisatie in vergelijking met de optimalisatie van de energieprestatie en de verschillen in optimalisatiepotentieel tussen nieuwbouw en renovatie.

De case studies werden specifiek geselecteerd om drie verschillende optimalisatiestrategieën te onderzoeken. In Case 1, een nieuw multi-residentieel gebouw, ligt de focus op het materiaaloptimalisatiepotentieel (verschillende structurele systemen, alternatieve afwerkingsmaterialen, …). Case 2, een rijwoning uit 1920, bekijkt het verbeterpotentieel door renovatie. Bij Case 3, een nieuwe halfopen woning, ligt de focus op het verbeterpotentieel door optimalisatie van de energieprestatie. Voor elk gebouw wordt een referentiesamenstelling gedefinieerd, die de huidige praktijk voor dat type gebouw vertegenwoordigt. In lijn met de optimalisatiestrategie worden vervolgens meerdere varianten per case vastgelegd. Alle varianten worden gemodelleerd en geanalyseerd met behulp van LCA om de resulterende impactreductie te berekenen. De *cradle-to-grave* levenscyclusanalyses worden uitgevoerd volgens de MMG-methodologie (die aan de basis ligt van de TOTEM-tool) en gebruik makend van de software SimaPro.

De eerste casestudie toont aan dat een optimalisatiestrategie gebaseerd op materiaalselectie voor een nieuw gebouw kan leiden tot een reductie van ongeveer 30% van de materiaalgerelateerde impact of ongeveer 15% van de totale impact (materialen + energieverbruik voor HVAC). Deze reductie is echter sterk afhankelijk van de initiële materiaalselectie en van de vrijheid van de ontwerper (vb. financiële en technische mogelijkheden). Bovendien bevestigen de resultaten de bevindingen uit de literatuur dat afwerkingsmaterialen een belangrijke rol kunnen spelen in de optimalisatiestrategie. Zij hebben soms een grote bijdrage en meestal zijn er verschillende alternatieven mogelijk. Hierbij moet in acht genomen

worden dat afwerkingsmaterialen waarschijnlijk gewijzigd worden tijdens de levensduur van het gebouw en daarom bestaat hierover een grotere onzekerheid.

In overeenkomst met de conclusies uit de literatuurstudie, toont de renovatiecase (case 2) aan dat het hoogste reductiepotentieel voor oudere (slecht geïsoleerde) gebouwen vooral ligt in de verbetering van de energieprestatie. De materiaalgerelateerde impact voor een energetische renovatie is meestal relatief laag, maar het verbeterpotentieel inzake energieverbruik is hoog. Voor de renovatie van de rijwoning uit 1920 kan een reductie in levenscyclusimpact van 50% bereikt worden door optimalisatie van het type installatie en het isolatieniveau in vergelijking met een strategie, die enkel voldoet aan de minimale wettelijke vereisten aangaande energetische renovatie. De resultaten tonen ook aan dat de EPB-software en TOTEM kunnen en zouden moeten complementair gebruikt worden. Terwijl het E-peil een gids is voor een lagere totale milieu-impact (een lager E-peil leidt doorgaans tot een lagere milieu-impact), tonen de resultaten aan dat er ook ruimte is voor optimalisatie binnen een gegeven E-peil.

De derde casestudie toont aan dat er zelfs voor lage-energiegebouwen (die voldoen aan de huidige vereisten inzake energieprestatie) een potentieel tot impactreductie is via optimalisatie van het isolatieniveau en de keuze van de technische installaties. De grootteorde van het optimalisatiepotentieel hang af van de prestatie op het startpunt, maar voor gebouwen, die gebouwd zijn volgens de minimale wettelijke vereisten, kan dit van dezelfde grootteorde zijn als het reductiepotentieel via materiaalselectie. Echter, gebaseerd op de huidige casestudies, is de levenscyclusimpact (over 60 jaar) van de meest geoptimaliseerde nieuwe woning (geïsoleerd tot op passiefstandaardniveau) in Case 3 nog steeds aanzienlijk hoger dan de levenscyclusimpact van de geoptimaliseerde energetische renovatie (tot E-peil 30) in Case 2.

De studie toont ook aan dat de impact van technische installaties relatief groot is. Gezien de impact ten gevolge van het materiaalgebruik (isolatie), de technische installaties en het operationeel energieverbruik met elkaar gelinkt zijn, moeten deze samen beschouwd worden om te komen tot een holistische optimalisatie.

Bovendien toont de literatuurstudie aan dat voor nieuwe (lage-energie) gebouwen het reductiepotentieel via een geoptimaliseerd gebouwontwerp (lay-out, percentage ramen, plafondhoogte, …) minimum even belangrijk kan zijn als het reductiepotentieel via materiaalselectie of via verbetering van de energieprestatie van het gebouw. Daarom zou een geometrische optimalisatie de eerste stap moeten zijn binnen elk optimalisatieproces vanuit milieuoogpunt.

Het laatste hoofdstuk van deze studie geeft tenslotte enkele aanbevelingen ter verbetering van de functionaliteiten van TOTEM die het optimalisatieproces zouden kunnen vergemakkelijken of verbeteren. Deze functionaliteiten omvatten een visualisatie van de relatieve bijdrage van de individuele materialen aan de totale milieu-impact van het gebouw met behulp van een netwerkdiagram of aan een bepaalde levenscyclusfase of impactindicator; de mogelijkheid om vergelijkingen te maken op materiaalniveau voor specifieke materialen door het weergeven van de gemonetariseerde impact van de materialen per functionele eenheid direct in de TOTEM bibliotheek; het opnemen van technische installaties in de TOTEM bibliotheek; de visualisatie van de voordelen van het gebruik of het exporteren van elektriciteit geproduceerd met behulp van PV-panelen; de opname van bijkomende afwerkingsmaterialen in de TOTEM bibliotheek en de toevoeging van module D (of alternatieve informatie) om potentiële voordelen van recyclage of hergebruik mee in rekening te kunnen brengen. Tot slot kan het ook interessant zijn om alternatieve eenheden voor de weergave van de resultaten (vb. impact/BVO, totale impact, impact/gebruiker) te onderzoeken.

Résumé exécutif

Les bâtiments ont un impact élevé sur l'environnement. Cet impact s'explique à la fois par la consommation d'énergie opérationnelle du bâtiment mais aussi par l'utilisation des matériaux de construction. L'outil en ligne TOTEM permet de calculer et d'optimiser l'impact environnemental des bâtiments en Belgique. La première version de cet outil a été lancée en 2018. Les trois services publics régionaux (OVAM, IBGE-BIM et SPW) qui ont conçu l'outil, ont l'ambition de le développer encore d'avantage. Ils ont d'ailleurs déjà pris diverses mesures en ce sens, dont la réalisation de la présente étude Potentiel de TOTEM. Cette étude a deux objectifs principaux :

- Estimer la réduction de l'impact environnemental des bâtiments qui pourrait potentiellement être atteinte en utilisant l'outil TOTEM au cours de la phase de conception et ainsi évaluer le potentiel de TOTEM pour aider à atteindre les objectifs politiques (partie 1) ;
- Evaluer le potentiel de la méthodologie TOTEM pour améliorer la performance environnementale des travaux de construction qui n'ont pas pour objet des bâtiments (principalement les travaux de génie civil) (Partie 2).

Dans cette première partie de l'étude, le potentiel de réduction de l'impact environnemental des bâtiments est étudié par l'intermédiaire d'une revue limitée de la littérature combinée avec des études de cas spécifiques. En particulier, l'étude se concentre sur l'ordre de grandeur de la réduction de l'impact, sur le potentiel d'optimisation d'une stratégie axée sur le choix des matériaux par rapport une stratégie axée sur la performance énergétique, et le potentiel d'optimisation de la construction neuve par rapport à la rénovation.

Les cas d'étude ont été sélectionnés de façon à pouvoir étudier trois stratégies d'optimisation différentes. La première étude de cas (*cas 1*), qui a pour objet un bâtiment multi-résidentiel neuf, se focalise sur le potentiel de réduction via une sélection réfléchie des matériaux (variation du système structurel, modifications des matériaux de finitions, ...). La deuxième étude de cas (*cas 2*), qui se concentre sur le potentiel d'optimisation lié à la rénovation, a pour objet une maison mitoyenne de 1920. Finalement, la troisième étude (*cas 3*), qui a pour objet une nouvelle maison jumelée, étudie principalement le potentiel de réduction via une optimisation de la performance énergétique du bâtiment. Pour chaque bâtiment étudié, une composition de référence (représentant la pratique actuelle) et différentes variantes (en lien avec l'objectif de l'étude) sont définies. Les analyses du cycle de vie (cradle-to-grave) de ces différents cas sont réalisées conformément à la méthodologie sous-jacente à l'outil TOTEM (MMG), mais à l'aide du logiciel SimaPro.

La première étude de cas montre que, pour un nouveau bâtiment, une stratégie d'optimisation uniquement basée sur la sélection des matériaux peut entrainer une réduction d'environ 30% de l'impact lié aux matériaux ou d'environ 15% de l'impact total (matériaux + utilisation de l'énergie pour la HVAC). Cette réduction dépend cependant fortement de la sélection initiale des matériaux, ainsi que de la liberté laissée au concepteur (par exemple, les possibilités techniques et

financières). De plus, les résultats confirment les conclusions issues de la littérature stipulant que les matériaux de finition peuvent jouer un rôle important dans la stratégie d'optimisation. Ils sont parfois des contributeurs majeurs pour lesquels plusieurs alternatives existent. Cependant, il faut garder à l'esprit que les matériaux de finition sont susceptibles d'être modifiés au cours de la durée de vie du bâtiment et par conséquent qu'il existe un niveau d'incertitude plus élevé concernant ces matériaux

Conformément aux conclusions de la revue de la littérature, l'étude de cas sur la rénovation (*cas 2*) montre que le potentiel de réduction le plus élevé pour les bâtiments les plus anciens (mal isolés) réside dans l'amélioration de la performance énergétique. L'impact lié aux matériaux lors d'une rénovation énergétique est en général relativement faible, alors que le potentiel d'amélioration en termes de consommation énergétique est élevé. Dans le cas de la rénovation de la maison mitoyenne de 1920, une réduction de 50% de l'impact du cycle de vie est atteint en optimisant le type d'installation et le niveau d'isolation par rapport à une stratégie qui remplirait seulement les exigences légales minimales en termes de rénovation énergétique. Les résultats montrent également que le logiciel PEB et l'outil TOTEM peuvent et doivent être utilisés de façon complémentaire. Alors que les niveaux E fournissent des indications pour réduire l'impact environnemental total (des niveaux E plus faibles entrainent généralement un impact plus faible), les résultats montrent qu'il est aussi possible d'optimiser l'impact pour une valeur E donnée.

La troisième étude de cas montre que même pour les bâtiments basse énergie (respectant les exigences actuelles en termes de performance énergétique), il y a un potentiel de réduction de l'impact environnemental via l'amélioration du niveau d'isolation et le choix des installations. L'ampleur du potentiel d'optimisation dépendra de la performance initiale de la construction, mais pour les bâtiments construits selon les exigences légales minimales en vigueur, il peut être du même ordre de grandeur que le potentiel de réduction lié au choix des matériaux. Toutefois, sur la base des études de cas présentées, l'impact du cycle de vie (60 ans) de la nouvelle habitation la plus optimisée (isolée selon la norme passive) dans le *cas 3* est encore nettement supérieur à l'impact de la rénovation énergétique optimisée (niveau E égal à 30) dans le *cas 2*.

Les résultats indiquent aussi que l'impact des installations techniques peut être relativement élevé. Pour permettre une optimisation holistique du bâtiment il est par ailleurs important d'optimiser conjointement l'impact des matériaux (d'isolation), des installations techniques et l'énergie opérationnelle du bâtiment.

De plus, la revue de littérature indique que pour les bâtiments neufs (basse énergie), la réduction de l'impact environnemental pouvant être obtenue via une conception optimisée du bâtiment (lay-out pourcentage de parties vitrées, etc.) est au moins aussi importante que celle pouvant être obtenue via une sélection réfléchie des matériaux ou l'optimisation de la performance énergétique.

Finalement, le dernier chapitre fournit quelques recommandations pour l'amélioration des fonctionnalités de TOTEM qui pourraient faciliter ou améliorer le processus d'optimisation. Ces améliorations concernent la visualisation, à l'aide d’un arbre des procédés, de la contribution relative de chaque matériau par rapport à l’impact environnemental total du bâtiment, une phase donnée du cycle de vie ou un indicateur d’impact spécifique ; la possibilité d'effectuer des comparaisons au niveau des matériaux pour des matériaux spécifiques en indiquant l'impact monétarisé des matériaux par unité fonctionnelle directement dans la bibliothèque TOTEM ; l'introduction d'installations techniques dans la bibliothèque TOTEM ; la visualisation des avantages de l'utilisation ou de l'exportation de l'électricité produite par les panneaux photovoltaïques ; un plus grand choix de matériaux de finition dans la bibliothèque de TOTEM ; et l'ajout du module D pour tenir compte des avantages potentiels du recyclage et de la réutilisation. Il pourrait également être intéressant d'étudier la possibilité d’utiliser d’autres unités pour la représentation des résultats (par exemple, impact/surface brute au sol, impact total, impact/habitant).

1. Context of the study

Buildings have a significant impact on the environment. An important part of this impact is due to the operational energy use. Therefore, in recent years numerous initiatives have been taken to make buildings more energy efficient. However, as buildings become more energy efficient the absolute and relative impact of building materials increases. Moreover, a lot of precious (primary) resources are used to produce those materials. Therefore, designers need reliable information concerning the life cycle impact of building materials, in order to make more environmentally friendly choices during the design process.

To meet the demand of the Belgian building sector, three regional authorities (OVAM, BIM and SPW) decided to collaborate on the development of an online tool to calculate and optimize the environmental impact of buildings in Belgium. As a result of this collaboration, the first version of the TOTEM tool was released in 2018. The regions have the ambition to further develop the tool and have already taken various steps in that direction, including the present project.

The present study has two main objectives. The first objective is to estimate the potential reduction in environmental impact of buildings that could be achieved by using the TOTEM-tool during the design phase, and therefore the potential of TOTEM to help achieve policy goals. The results of this research are presented in this report (Part 1).

A second objective is to assess the potential of the TOTEM methodology to improve the environmental performance of non-building related construction works (mainly civil engineering works). This research is presented in a separate report (Part2).

1.1 Vision and general approach

The TOTEM methodology allows to gain insight into the environmental impact of buildings, and therefore, it works as a leverage to further reduce it. By extension TOTEM could also be used to reduce the impact of other construction works

The study considers the current building practice and the possible environmental impact reduction within the system boundaries of TOTEM. In this framework, it evaluates (based on case studies) the reduction potential through material selection and/or optimization of the energy performance of buildings. As the strategies for/ and size of impact reduction can differ between new construction and renovation (where normally the loadbearing structure is largely kept), and vary depending on the building typology, case studies are chosen in order to cover this range of situations. Findings from the case studies are completed with insights from literature.

Based on the analysis of the environmental optimization potential of buildings, attention points for improvement or orientation of the TOTEM tool are also formulated.

1.2 Project team

The Laboratory of Environmental performance of the BBRI has a broad experience in environmental evaluation of construction materials, building elements and entire buildings using Life Cycle Analysis (LCA), and a good knowledge of the European and Belgian legislation regarding this subject. More specifically, the BBRI is/was always actively involved in the different developments of the TOTEM tool.

2. Objective and approach

The general objective of Part 1 is to gain insights into the potential reduction of the environmental impact of buildings that can be achieved by using a tool like TOTEM during the building design phase.

More specifically following elements are studied:

- Order of magnitude of the impact reduction
- Relative importance of the impact reduction achievable through material optimization compared to the reduction achievable through optimization of the energy performance.
- Optimization potential of new construction versus renovation

Firstly, existing studies are screened to collect insights into the environmental performance of buildings, their optimization potential, main sources of impact and optimization strategies (section 3). The main objective of this screening is to complement the results from the limited number of cases analyzed within the present study (section 4), and therefore also enable to check the plausibility of the obtained results.

Secondly a set of case studies, representative of various situations (new construction, renovation, different building types) are selected (section 4). For each case study, various optimization strategies are defined and analyzed in order to evaluate the resulting impact reduction (section 5). The defined strategies focus either on the material selection or the energy performance of the building.

Finally, after general conclusions are drawn concerning the optimization potential of buildings (section 6) an overview is also given of functionalities that would facilitate or enhance the optimization process in TOTEM (section 7).

3. Existing literature concerning optimization potential of buildings

The following sections give an overview of the main conclusions drawn from various studies [1][2][3][4] concerning the environmental performance of buildings, their optimization potential, main sources of impact and optimization strategies. Those studies have been selected based on their objective, usability within the present study, and the number of buildings considered. Although [2] and [3] do not draw conclusions concerning the optimization potential of buildings as such, the reported statistical distribution of the environmental performance of buildings was used to (grossly) estimate it.

3.1 Sustainable Building. The development of an evaluation method

The goal of the PhD research “Sustainable Building. The development of an evaluation method (2010)” [1], was to develop a method for the environmental and economical assessment of residential buildings based on a life cycle approach. The developed environmental assessment method is very close to the TOTEM methodology as the former was used as basis for the development of the latter. Also, the environmental data that was implemented in the developed tool is very similar to the TOTEM data (i.e. ecoinvent data adapted to the Belgian context).

The developed method was applied to 16 dwellings which are representative of the Belgian building stock (apartment buildings, detached, semi-detached and terraced houses representative of the periods before 1945, between 1945 and 1970, between 1791 and 1990 and between 1991 and 2007). For each dwelling type many variations were analysed in terms of material selection and energy performance (+-830 000 simulations/dwelling).

Although this publication is relatively old, it was still included in the present study because it is the only study available which analyses such a high number of building cases representative of the Belgian building stock, based on a methodology and data very similar to what is used in TOTEM.

Optimization potential

The results from the environmental analysis, assuming a 60 years reference study period, lead to following conclusions regarding the optimization potential of dwellings:

- The comparison of the life cycle impact of each dwelling variant built according to standard practice in 2010 with the pareto optimum obtained for the same dwelling, indicates that the optimization potential through **measures related to the choice of materials and technical installations, insulation level and airtightness**, ranges from **9 to 35%** of the life cycle impact (including materials, technical installations and energy for heating, ventilation and sanitary warm water production).

- A comparison of the optimum results obtained across the various building types, shows that that the **optimization potential through dwelling characteristics** (e.g. lay-out, size and window area) is much larger (almost **60%**). However, there is no absolute preference identified between the four major dwelling types analysed. This proves that the environmental impact is determined by a combination of parameters (size, type, insulation level, choice of materials, etc.)
- Wood and wood-based products lead to a higher external cost than alternative materials. However, this is mainly due to the high monetary value considered within this study for the impact category land use forest occupation (it was deemed equal to land use occupation agricultural). Considering the same monetary values as TOTEM [5] would lead to different results concerning this particular matter. Indeed, the results obtained with the TOTEM tool indicate that, based on the current monetary values [5], land use occupation forest does not contribute significantly to the monetised score of wood products.
- Although **renovation** measures were not investigated within the study, it makes a first estimation of the optimization potential through renovation by comparing the sum of the in-use and EOL environmental impact of the existing dwellings (built according to standards set in the period they represent, e.g. before 1945, between 1945 and 1970, etc.) with the life cycle impact of the optimized newly built dwelling. Based on this estimation, the optimization potential of **buildings built before 1970** equals on average **62%**. For buildings built between 1970 and 1990 it equals **20%**.

Main contributors

The study also looked at the relative importance of **transport of inhabitants, non-building related electricity use** (for home appliances) and **operational water use** (module B7 according to EN 15978 [6]). Based on those results, those three parameters contribute significantly to the life cycle impact of the building. Indeed, for the optimized buildings, the operational water use represents on average about 30% of the life cycle impact of materials and operational energy use for HVAC, non-building related electricity use about 50%, and the transport of inhabitants can represent more than twice the impact of materials and energy for HVAC.

If we exclude the impact from transport of inhabitants, the most contributing factors for dwellings built according to 2010 standards are in order of importance: heating, non-building related electricity use, production of materials, and operational water use. **For low energy buildings, electricity use and material selection should therefore be the focus**. Concerning the latter, the study concludes that finishing materials should be part of the optimization strategy as they can contribute significantly to the impact of materials. However, no order of priority for optimization could be set concerning the building elements. Indeed, it will depend both on the ratio of the element in the building (m^2 element/m^2 building), but also on the individual optimization potential of the element (the study gives an overview of the optimization potential of various elements).

Finally, although the analysis on building level did not include much variation in choice of installations, the study includes a comparison of installations on element level. This analysis considers the life cycle impact of the installations and the corresponding energy use for a well-insulated (K20) detached dwelling. Based on those results, the heat pump seems the most interesting alternative for heating and hot water production. It is followed by the condensing gas boiler. Concerning the ventilation systems (A, B, C, D), the study indicates that all systems lead to similar life cycle environmental impacts.

3.2 Research 'Principes en parameters Milieuprestatie Gebouwen (MPG)'

The study "Eindrapport Onderzoek 'Principes en parameters Milieuprestatie Gebouwen (MPG)' Op basis van ervaringen in 2012 – 2016" [2] analyses the results from an important number of building LCA's performed between 2012 and 2016 according to the Dutch method for LCA of buildings [7] . It concerns LCA's performed in practice (as part of real building projects), as well as variants calculated for reference buildings. In all cases, it concerns new buildings that are designed to meet or surpass Dutch building regulations. This study was performed for the Dutch Ministry in preparation of the introduction of maximum values for the environmental performance of new buildings in the Netherlands in 2018. The results are expressed in an MPG score, which is a monetised environmental score of 11 impact categories (according to the "Bepalingsmethode milieuprestatie gebouwen en GWW werken") expressed per square meter gross floor area (GFA) per year.

The main objectives of the study were the following:

- Draw conclusions concerning the environmental performance of buildings (which performance can realistically be expected?)
- Identify design parameters that (significantly) influence the environmental impact of buildings. Those can form the basis for the establishment of rules of thumb for the design of environmentally friendly buildings.

The main findings of the study are presented hereunder. It is important to note that the MPG does not include the energy consumption of the building in use. So, unless stated otherwise, the results hereunder always refer to the life cycle environmental impact of materials and installations (excluding the energy consumption during the use phase of the installations). At the time of the analysis the Dutch methodology did not specify a reference study period for buildings. However, most tools specify a default value (which could be adapted by the user) of 75 years for dwellings and 50 years for utility buildings[1]. Finally, the set of

[1] In 2019, those defaults values are required by the national method [15]. However, users can deviate from those values using the method exposed in [16].

analysed results were obtained using various versions of the "Bepalingsmethode milieuprestatie gebouwen en GWW werken" and the "Nationale milieudatabase".

Expected environmental performance- optimization potential

Based on calculations performed for more than 1000 variants of the RVO referentiewoningen, the environmental performance shown in Table 1 can be expected. An analysis of more than 200 "real" building projects confirmed the plausibility of those results. The results for the office buildings are based on the analysis of the results from 174 recent building projects.

Table 1. Expected environmental performance (MPG score) of buildings based on [2] and optimization potential deducted from those values.

	MPG score [2] for percentile			Optimization potential from percentile		90%/10% percentile (*)
Type of building	10%	50% (median)	90%	50% to 10% (*)	90% to 10% (*)	
Terraced house	0,27	0,39	0,54	31%	50%	2,0
Semi-detached house	0,31	0,45	0,67	31%	54%	2,2
Detached house	0,36	0,54	0,96	33%	63%	2,7
Appartment	0,26	0,38	0,55	32%	53%	2,1
« Gallery » home	0,3	0,42	0,58	29%	48%	1,9
All dwelling types	0,3	0,44	0,66	32%	55%	2,2
Office buildings	0,36	0,48	0,79	25%	54%	2,2
(*) values calculated based on the results reported in [2]						

Based on those results, the optimization potential is high (the ratio 90th over 10th percentile varies from 1.9 to 2.7). Also, assuming that the 50th percentile corresponds to average practice, a **30%** reduction in environmental impact seems reasonably feasible (difference between the 50% and 10% percentile). The results also indicate that **similar results can be excepted for office buildings and residential buildings**. The study however mentions that the results from the office buildings included some much higher extreme values (values above 90% percentile) than the residential buildings. Moreover, detached houses show a higher variation (difference between 90% and 10% percentile) than other types of dwellings. This could be explained by higher variations in shape factors for those buildings (e.g. surface of façade/floor surface).

Design parameters that influence the environmental impact of buildings

Based on the results collected from practice it was difficult to deduct significant correlations between design parameters and environmental performance as the various cases were different in many aspects (no systematic variation of one aspect at the time). Therefore, as part of the study, different variants were calculated for the RVO-reference dwellings[2], where parameters were varied one by one. Based on those calculations, following design parameters have a significant influence on the environmental impact of buildings:

- Gross floor area (GFA)→the MPG score will increase as the GFA decreases. This is especially true for very small dwelling, as various services are relatively independent of the floor area (e.g. installations) and the ratio of envelope area/floor area is relatively high.
- Number of stories →for apartment buildings the MPG score decreases as the number of stories increases because the common facilities (e.g. lifts, foundations, ...) can be spread over a higher number of dwellings. However, the rate of decrease is lower as the number of stories increases because of the need for a more robust structure
- Floor height →10% increase in floor height results in 2 to 3% increase in MPG score
- Area of façade →the MPG score increases as the area of façade per GFA increases (i.e. cubic buildings are more material efficient).
- Window area →as windows usually have a higher impact than closed elements, an increase in window area will lead to a higher MPG score

The service life of the building also influences the MPG score:

- above 75 years the impact of the service life is limited as many materials need to be replaced anyway (only the structure remains unchanged)
- under 75 years, the MPG score increases quickly as the service life decreases. In that case it is important to choose materials with a relatively low environmental impact and pay attention to circular principles.

Finally, the results from the more than 1000 variants of the RVO reference buildings show that **technical installations represent on average 35% of the material impact** (construction materials + installations), and that almost **half of this contribution is due to PV panels**. The impact from installations could be reduced by including the material related impacts into the decision-making process related to the determination of the energy concept of the building (e.g. weighting the impact of extra insulation against the impact of more developed installations) [8].

3.3 Environmental Improvement Potential of Residential Buildings (IMPRO)

The IMPRO study "Environmental Improvement Potential of Residential Buildings" from 2008 [4] had as goal to analyse the environmental improvement potential of European residential buildings. To achieve this goal, 72 building models were defined (53 existing buildings, 19 new building types) which together represent

[2] https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/nieuwbouw/energieprestatie-epc/referentiewoningen-epc

about 85% of the EU25 buildings. Those where then subjected to a hotspot analysis in order to define and study the effect of different optimization strategies. The hotspot analysis considers various life cycle impact indicators (global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), photochemical ozone creation potential (POCP), non-renewable primary energy (NRPE)); however, as similar trends were obtained for the different impact categories, **GWP and NRPE** were considered as good proxy indicators to assess the environmental performance of buildings. Therefore, only those two indicators were considered for the determination of the optimization potential. A reference study period of **40 years** was used for both the existing and new dwellings as this was estimated reasonable for the first and limited the uncertainty inherent to the long term for the second. Moreover, this timeframe was assumed to be consistent with what policy measures can cover.

Based, on the LCA hotspot analysis, the study concluded that for the **existing** buildings the **use phase** is the main source of environmental impact (for all impact categories considered, namely GWP, ODP, AP, POCP, NRPE). Consequently, the impact of various optimization strategies (selected based on a hotspot analysis considering the relative contribution of the various building elements to the use phase (including heat transfer through the elements) were analysed for the existing building stock. For the single-family houses in Middle European countries, the main strategies identified were the **insulation of the roof (to U=0.16W/m^{2}K) and the façades (to U=0.12W/m^{2}K)**. If the combination of those two measures were applied to all building models considered within this group (single family house, Middle Europe), the study concludes that this would result in a reduction of about **50% of the greenhouse gasses over the next 40 years** compared to the base case. However, the achieved reduction **varies greatly depending on the insulation level of the building model considered** (e.g. from 8% reduction for existing buildings with U_{wall}=0.27W/m^{2}K and U_{roof}=0.24W/m^{2}K to 61% reduction for existing buildings with U_{wall}=2.7 W/m^{2}K and U_{roof}=3.2W/m^{2}K). Moreover, it is important to note that the study considers that various renovation measures also take place for the base case within the 40 years horizon, so the achieved reduction is realistic. Indeed, the study assumes that for example, the existing roof tiles and battens will only last another 25 years (residual lifetime) and that at the time of their replacement the owner will take advantage of the occasion to also insulate the roof.

In the IMPRO study, the results obtained for the **new** building models, indicate that for new buildings the **use** phase is also the most significant life cycle phase **followed by the construction phase** (depending of the indicator considered, the construction of the building (including production of materials) represents from about 10 to 25% of the life cycle impact). The contribution of the end-of-life phase is insignificant.

As the energy performance of new buildings is already relatively good, and covered by the Energy Performance of Building Directives, **improvement measures were, despite the high contribution of the use phase, only defined for the construction phase** of the building and more specifically the production of the **walls**. Indeed, although based on a hotspot analysis the basement and foundations and the floors and ceilings also contribute significantly to the construction phase, they are considered to have little room for optimization (for the basement and foundations mainly because of loadbearing requirements). Based on the hotspot analysis, windows and roof were considered less important and therefore not tackled.

The analysis considered only a limited number of alternative materials for the (interior and exterior) walls, namely breeze concrete, sand-lime, wooden construction, cored (hollow) bricks, reinforced concrete, and did not change the materials for the ceilings and floors accordingly. Moreover only 4 new buildings were selected from the sample to study the effect of the alternative materials. Based on this limited analysis, it is concluded that for new buildings "significant environmental improvements can be expected only when the substitution leads to the use of wood products instead of more conventional products (concrete, reinforced concrete, brick))." The optimization potential on EU level could however not be evaluated within the study. Indeed, the study indicates that further investigation, considering amongst others thermal mass requirements, would be needed to evaluate whether this construction mode suits different weather and local conditions in Europe. Additionally, conditions of forest management should be further investigated as they have an important influence on the carbon balance of the forest (carbon neutrality cannot be assumed for wood from unsustainably managed forest) and possibly on the biodiversity.

3.4 Towards guidance values for the environmental performance of buildings (France)

The French study "Towards guidance values for the environmental performance of buildings: application to the statistical analysis of 40 low-energy single family houses' LCA in France" [3] analyses the Life cycle impact (according to EN 15978) of 40 new low energy (<50kWh/m^{2}y of primary energy use according to the RT2012 thermal regulation) single family houses. The sample is elaborated in order to be representative of the French market in terms of main constructive systems (wood, steel frame, concrete blocks, brick, aerated concrete). The study considers the impact of materials and installations, water consumption, energy use for heating, domestic hot water, lighting, ventilation and auxiliaries (HVAC) for a reference study period of 50 years and the following indicators : acidification potential (AP), global warming potential (GWP), non- renewable primary energy use (NRPE), radioactive (RW) and non-hazardous waste (NHW), net fresh water consumption (WC) .

Main contributors

Results indicate that the embodied impact (related to building products and building integrated technical installations) of low-energy buildings is significant. Indeed, it represents more than 70% of the life cycle impact for the indicators AP and GWP and between 40 and 50% of the indicators NRPE, and RW. The remaining impact for those indicators is mainly occasioned by the building related energy use, as the contribution of the operational water use is negligible. On the contrary, the operational water use represents about 90% of the indicator Net fresh-water consumption (WC). Moreover, the non-hazardous waste indicator is mostly determined by the mass of waste produced by the materials (and more specifically the building structure) at end-of-life.

Concerning the embodied impact, the study also evaluates the relative contribution of materials (building structure, finishing and interior elements) versus technical installations. Based on those results, all components (installations, building structure, interior elements) contribute significantly to the material + equipment impact. The finishing and interior elements have the highest contribution for the indicators NRPE, AP and RW, and the building structure has a higher impact on GWP. A sensitivity analysis shows that considering a longer reference study period (100 years), results in a reduction of life cycle impact per square meter per year, mainly because the impact of the structure can be amortised over a longer period (the impact of the structure expressed per year decreases by more than 40% for all indicators considered). For the interior elements the reduction is smaller (from 2 to 18%) as they have a limited service life. Finally, installations show very limited reductions as their service life is often limited to 25 years.

Optimization potential

This study [3] also analyzed the variability of the results within the sample. Based on those results (Table 2), the variability of the total life cycle impact (expressed per square meter per year) obtained for the various buildings is relatively high (depending on the indicator considered, there is an order of magnitude of about 1.7 (NRPE) to 3,5 (WC) between the 10% and 90%percentile). The high variability indicates that the optimization potential for low energy buildings is significant. Indeed, if the 10% percentile is considered the most optimized score, buildings in the 90% percentile can achieve a reduction between about 75% (WC) and 50% (NRPE) depending on the indicator considered. Moreover, buildings that are already on the median can still achieve a reduction between about 25% and 45% (Table 2). As the buildings within the sample have various lay-outs, sizes, orientation, etc. the observed variation in environmental performance is not exclusively related to the selection of materials, energy carriers, and/or energy performance of the buildings.

The study did not only look at the variability between buildings, but also the variability between specific contributors (materials, installations, operational energy use). Although the contribution of the materials and installations is significant for GWP, RW, NRPE, their variability for those indicators is smaller than that of the operational energy use (e.g. there is an order of magnitude of 9 between the tenth and ninetieth percentile of the operational energy use related contribution to GWP, and only an order of magnitude of 2 for the material + equipment related contributions). On the contrary for AP, both the contribution and the variability of materials and equipment is higher than that of operational energy use.

Finally, a scatterplot analysis indicates that (at least for GWP) there is no systematic correlation between the choice of the constructive system and the life cycle impact of the building. However, the buildings using natural gas seem to form a cluster at the upper part of the cloud (higher GWP). On the other hand, for the other energy carriers, no obvious clusters could be drawn.

Table 2. Estimated optimization potential based on the statistical values obtained from the sample of 40 new low energy French dwellings (percentiles are deducted from figure 4 of [3] , the optimization potential is calculated based on the percentiles).

Indicator	10% percentile	50% percentile (median)	90% percentile	reduction from 50% to 10% percentile (*)	reduction from 90% to 10% percentile (*)
NRPE ($kWh/m^2NFA/y$)	63	87	118	28%	47%
WC ($l/m^2NFA/y$)	900	1500	3500	40%	74%
GWP ($CO2eq/m^2NFA/y$)	7	12,5	18	44%	61%
NHiW ($kg_{eq}/m^2NFA/y$)	20	35	60	43%	67%
AP (kg $SO2_{eq}/m^2NFA/y$)	0,04	0,055	0,08	27%	50%
RW ($kgeq/m^2NFA/y$)	0,0015	0,0025	0,0045	40%	67%
(*) values calculated based on the results reported in [3]					

3.5 General conclusions from the literature study

The reviewed studies have different objectives and the results are based on different assumptions and methodological choices (reference service life, data sources, system boundaries, indicators, etc.). However, following general conclusions can still be drawn from the literature review:

- The order of magnitude of the optimization potential largely depends on the initial performance of the building (before optimization), the indicators considered and the extend of the optimization strategy (e.g. materials, energy, building, design parameters).
- The variability of building performances indicate that the optimization potential (through material selection, energy performance, and design parameters) of "badly" performing buildings is very high (above 50%), but also for buildings on the median the optimization potential is significant (around 30%) [2][3].
- For new (low energy) buildings, the relative contribution of materials is significant [1][3][4]. The material related impact can be optimized trough

material selection but also considerably through design parameters (e.g. height of ceilings, ratio of façade area over floor area, building type) [2][1][9].

- For existing buildings, the optimization strategy should focus on the improvement of the energy performance of the buildings. The improvement potential is especially high (above 50% of impact from materials and energy use) for old (very poorly/not insulated) buildings [1] [4].
- Installations (especially PV panels) contribute significantly to the material related impact of buildings [2][3]. The optimization of installations can however only be done in conjunction with the operational energy use.
- Given their relatively important contribution, it is worthwhile to consider finishing materials as part of any optimization strategy focusing on material selection [1][3].
- Although they are not commonly taken into account in building LCA, the electricity use for appliances, transport of building users and operational water can also contribute significantly to the life cycle impact of a building [1][3].

4. Selection of case studies

In order to consider different typologies and situations (new construction versus renovation, optimization strategy focused on material selection versus energy performance) following case studies were selected:

1. Multi-residential building (**new** construction)
2. **Renovation** of an existing terraced house from 1920
3. Semi-detached house (**new** construction)

As summarized in Table 3, the first case study focuses on the optimization potential through material selection only, and the remaining cases focus on the reduction potential through optimization of the energy performance of the building (insulation level and choice of technical installations).

Table 3. Overview of case studies and corresponding areas of study

	Type of building activity	
Focus of optimization strategy	New construction	Renovation
Materials	Multi-residential building (case 1)	/
Energy (insulation level and choice of installation)	Semi-detached house (case 3)	Terraced house built in 1920 (case 2)

The case studies are described in more details in the following section. Cases two and three were derived from a VEA study [10], and used also for the OVAM study "Climate goals for the building sector – A potential for circular construction (2019)".

5. Analysis and optimization of the environmental performance

5.1 General approach

For each case study we start from a reference composition which represents current practice for the given building type (i.e. commonly used materials/building solutions are selected). Starting from this reference case, different optimization strategies (focusing on materials or energy) are then defined and analyzed with LCA (using the TOTEM methodology).

5.2 Scope of the LCA

The life cycle analyses are performed following the MMG-methodology [11]. This methodology also forms the basis for the online TOTEM tool (www.TOTEM-building.be).

However, in consultation with OVAM the calculations are performed within the specialised LCA-software SimaPro. One advantage of using SimaPro is that it allows to incorporate the material related impacts of the technical installations (e.g. for heating, sanitary hot water production, ventilation systems and PV panels), which are presently not included in TOTEM. Furthermore, in SimaPro the impacts related to different energy consumption profiles can be calculated based on the EPB-data. The TOTEM tool only allows for the calculation of the impact related to heating according to the degrees-days method, with consideration of a condensing gas boiler. Finally, SimaPro allows for more freedom in the materialisation of the specific building parts (e.g. thickness of insulation), and it allows to dig deeper into the LCA-results (hot-spot identification based on network analysis).

Table 4 summarises the scope and main parameters of the life cycle analyses carried out within this study.

Table 4. Scope of the life cycle analyses carried out within this study

Software	SimaPro v8.5.2.0
Database (Life Cycle Inventory)	Ecoinvent v3.4, allocation cut-off by classification
Reference study period (RSP)	60 years
Reference service life (RSL) of materials	As in TOTEM [12]. The number of replacements is calculated as the nearest integer value of (RSP/RSLmaterial-1).
Allocation and system boundaries	According to NBN EN 15978 [6]. The analysis considers the following modules:

	▪ A1-A3 Product stage (raw materials supply, transport, manufacturing) ▪ A4 Transport of materials to the building site ▪ A5 Installation of materials on the building site ▪ B4 Replacements ▪ B6 Operational energy use (heating, domestic hot water (SWW) supply, cooling and ventilation, auxiliaries and electricity use for appliances)→ assessed **only for cases 2 and 3.** ▪ C1-C4 Demolition, transport, waste processing and disposal of materials Elements excluded in all case studies: electric wiring, kitchen, bathroom, toilets, indoor plumbing, lighting
Scenarios	▪ Scenarios for transport (module A4), and end-of-life of materials (modules C1-C4) are representative for the Belgian context [11]. ▪ Service life of materials are taken from [12] ▪ When included in the study, the operational energy use (module B6) is calculated using the EPB methodology for residential buildings in Flanders (2015).
Life Cycle Impact Assessment (LCIA)	MMG method 2014, update December 2017 (v1.05) [5]. See summary in Annex 1
Electricity mix	For the operational energy use, an electricity mix representative of the Belgian market (= national production + imports) for the year 2014 is used (latest mix available in Ecoinvent v3.4). This mix is kept constant for the entire reference study period.

5.3 CASE 1: Multi-residential building (new construction) – material optimization

5.3.1 Description of the building and specific system boundaries

The starting point of the study is a 4-level apartment building with following characteristics:

- Gross floor area: 2410m^2 including:
    - 2050 m^2 total saleable floor area (= indoor gross floor area above ground)

  - 200 m^2 outdoor gross floor area above ground (outdoor staircases, lifts and outdoor platforms)
  - 160 m^2 gross underground area (cellar, technical space, hallways)
- 25 living units
- Depending on their position in the building, apartments have a K-value (insulation level) between 22 and 29

The composition of the main building elements is summarized in Table 5. The analysis also includes additional elements like zinc gutters, lintels, reinforced concrete foundations, outdoor piping (PVC sewage and infiltration pipes), and a concrete rainwater tank (10 m^3 capacity). In addition to the exclusions mentioned in section 5.2, the installations for heating, cooling and ventilation are also excluded from the analysis.

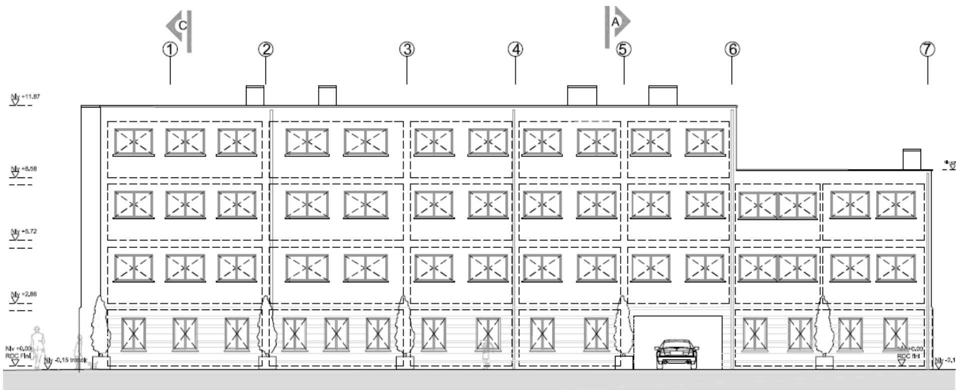


Figure 1. CASE 1: multi-residential building (new construction) from the Opticost study

5.3.2 Approach

The sand-lime brick building (Table 5) is first analysed with LCA (in SimaPro) in order to identify the main **material** contributors (hotspot analysis). Considering in first instance that the construction mode is fixed (structure in masonry), different alternatives are analysed (in TOTEM) for the most impacting materials. Whenever possible, those are replaced by an alternative with a lower environmental impact. The environmental impact of the obtained “optimized” building is then compared with the reference (sand-lime brick) building in order to evaluate the potential for impact reduction through material optimization within a given construction mode (masonry). Finally, the impact reduction is also evaluated in case the construction mode is variable. In all cases the energy performance of the building and the general lay-out (floor plan, % of windows, etc.) are kept constant. Moreover, the energy use of the building is not taken into account.

Table 5. CASE 1: Description of main building elements

Exterior walls

- Gypsum plaster (1cm)
- Sand lime bricks 15cm
- +-2/3 ETICS (EPS 15cm) and 1/3 facing bricks combined with 10cm PUR

Flat roof

- Precast reinforced concrete panels (5cm) with 15cm reinforced concrete
- slope concrete
- vapor foil bitumen
- PIR insulation 10 cm
- bitumen roof covering

Interior walls (loadboaring)

- Sand-lime brick (30x15x15, glued)
- Gypsum plaster on both sides + paint

Interior walls (non-loadbearing)

- Gypsum blocks with finishing putty + paint

Floors

- Floor on grade :
  - Reinforced concrete slab 25cm
  - In-situ blown PUR 4cm
- Storey floors :
  - Precast reinforced concrete panels (5cm) with 15cm reinforced concrete
  - Concrete screed
- Floor finishing (1618m^2): +-3/4 Ceramic tiles, 1/4 laminate flooring

Basement walls

- precast concrete walls 22-30cm +10cm XPS on outer walls
- Hollow concrete block walls (9cm)

Stairs

- Indoor : prefab reinforced concrete
- Outdoor : Steel

Windows and doors

- PVC windows with double glazing and aluminum windowsills
- Outer doors : PVC
- Inner doors: frames in massif wood, leaves in wood

5.3.3 Hotspot analysis

Figure 2 represents a network analysis of the initial design of the building (with sand-lime brick structure). The cut-off is set at 3% which means that only processes that are responsible for 3% or more of the (material related) life cycle impact of the building are visible[3]. Based on this analysis the main contributing elements are the floors, the walls, the roof and the outer windows and doors. On the other hand, the foundations and outdoor piping (gutters, sewage, drainage) represent less than 5% each. However, concerning the foundations, the floor on ground slab is included in the floor element.

The network analysis also shows that about 75% of the material related impact of the building is occasioned by less than 10 materials, namely: reinforced concrete (steel +concrete=14% when excluding the part that is used for the infill of the precast concrete floors), precast concrete floor panels with concrete infill (+-18%), floor screed (1.28%), ceramic floor tiles (+-8%), wall paint (+-8%), sand-lime brick walls (+-10%), PVC window frames (+-7%), inner doors (3%), and steel used for the outdoor staircase and platforms (almost all the impact from the stairs +-5%). The optimization process will focus mainly on those materials. Only the inner doors are not discussed in the following sections as those were not present in the TOTEM Tool at the time of the analysis.

5.3.4 Optimization process, without changing the construction mode (masonry)

Reinforced concrete

The network analysis shows that the main impact from the on-site poured concrete is cement. However, the concrete already uses CEM III cement (with blast furnace slag), so the impact of the concrete cannot be optimized by the use of another cement type (which would have been the case if CEMI (Portland cement) would have been used).

As the impact of the concrete itself cannot be lowered by the use of a lower-impact cement, an alternative is to look at the possibility of replacing the concrete by other materials. However, an analysis of the different parts where the concrete is used, shows that little optimization is possible here. Indeed, the concrete poured onsite ($683m^3$) is mainly used for:

- Infill of the precast concrete floors ($271m^3$)→possible alternatives will be looked at on floor level
- Foundation ($257m^3$): raft (in floor elements) + edges (in foundation itself) →structural element, so this cannot be optimized without the consultation of a structural engineer

[3] Processes representing less than 3% can still be visible if one process that contributes to them (and other processes) represent more than 3%

- Concrete walls around the interior and exterior elevators (44m^3)→ difficult to optimize without the intervention of a structural engineer/fire safety expert
- Infill for precast concrete walls used for basement walls (49m^3)→thinner walls are already used where possible (20cm instead of 30cm) and some underground (inner) walls are in hollow concrete blocks. So, from a structural/water tightness point of view it is difficult to optimize the usage of concrete for this application.

The impact of the reinforced concrete could maybe also be reduced by looking at the possibility to lower the amount of reinforcing steel or use slender elements. However, this is unlikely to be done by the person who does the LCA assessment as it requires the intervention of a structural engineer.

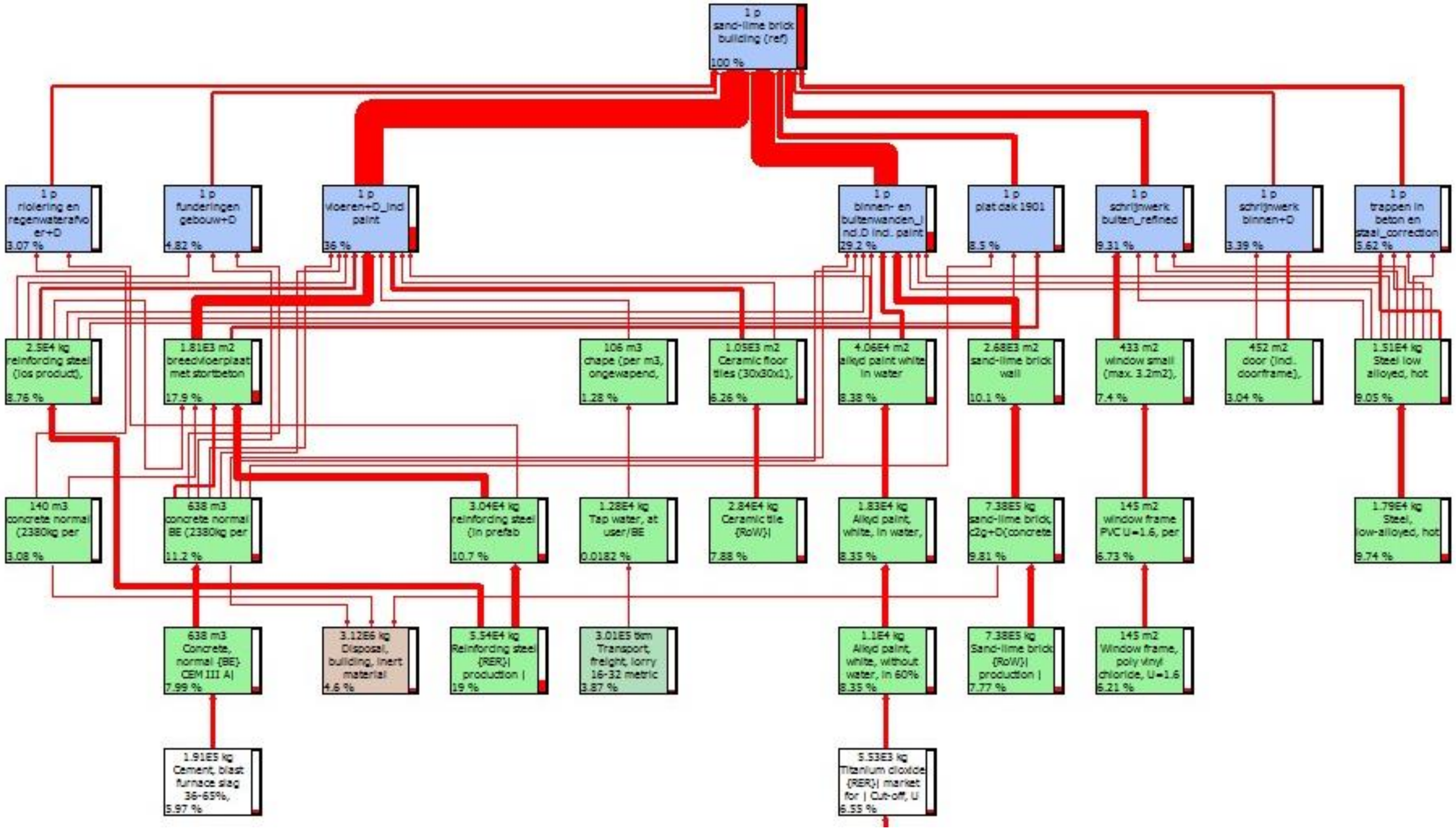


Figure 2. CASE1: Network analysis of the sand-lime brick building (cut-off at 3%)

In conclusion, the only "easy" strategy to reduce the contribution of the reinforced concrete for this building consists in finding an alternative for the precast concrete floor elements (the concrete poured on top of the elements represent about 40% of the concrete used onsite).

Precast concrete floor elements

Different floor alternatives were compared in TOTEM by making a fictive inner floor element composed of different floor components. The obtained pie chart of this element allows to identify the floor option with the lowest impact (which is the one with the lowest relative contribution to the element).

Based on this analysis, the use of precast prestressed TT elements or concrete beams with concrete block infills instead of the actual precast concrete floor elements would lead to the highest impact reduction. However, TT elements are not commonly used in apartment buildings because of their important height (minimum 33cm) and lower acoustical insulation (only the (thin) horizontal part of the T-elements contribute to the acoustical insulation). On the other hand, concrete beams with blocks are more commonly used for smaller spans and may not procure enough acoustical insulation for use in a multi-residential building.

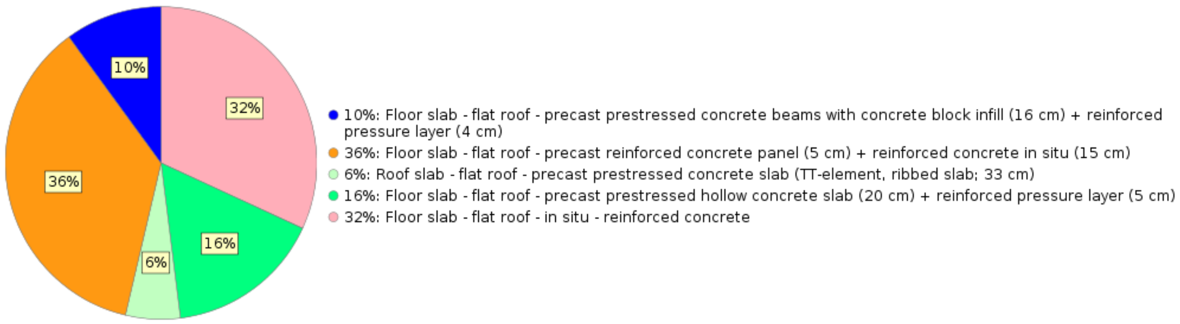


Figure 3. Comparison of different structural floor elements in TOTEM (Accessed December 2018; results may vary in later versions of the tool)

Therefore, the most realistic optimization strategy is to **replace to precast reinforced concrete panels by hollow concrete elements with a 5cm pressure layer**. This choice still allows to reduce the impact of the structural floor element by about 50% and thus leads a 9% reduction of the material impact of the building.

Sand lime-brick walls

Figure 4 represents the relative contribution of different masonry walls to a fictive wall element in TOTEM. The element was created in the category "inner wall loadbearing" in order to exclude the impact of the material choice on the energy demand of the building. Based on a first analysis the insulating clay bricks were the most interesting from an environmental point of view. However, they have a lower thermal resistance than autoclaved aerated concrete blocks. In order to make a fair comparison a layer of EPS equivalent to the difference in thermal resistance between the aerated concrete and the insulating clay bricks was therefore added to the fictive element. As the sum of the contribution of the EPS and the clay bricks is lower than the contribution of the aerated concrete, the sand-lime bricks are replaced by insulating clay bricks in the optimized building. This change however leads to only a very small improvement on building level (1%) as the difference between both blocks is relatively small. Although the insulating clay bricks also have a little better lambda value than the sand-lime bricks; the difference is too small to allow a reduction in insulation thickness (the difference between both blocks represents less than 1cm of EPS).

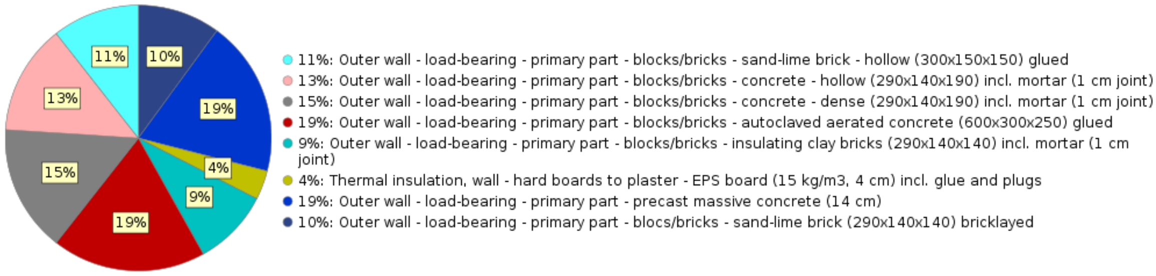


Figure 4. Comparison of different masonry walls in TOTEM (Accessed December 2018; results may vary in later versions of the tool)

Window frames

As there were some errors with the window frames in TOTEM at the time of the analysis, the comparison between the different types of window frames was performed in SimaPro considering a reference study period of 60 years and using the same % of glass and frame, reference service life of materials (30 years for wood and PVC, 60 years for Aluminium), and scenario's as in TOTEM. For the wooden window frames, the analysis considers that 3 new layers of water-based alkyd paint are applied on the outside of the frame every 6 years (1 kg paint/14m^2 frame/layer).

Based on this analysis (Figure 5), the PVC window frames were replaced by painted wooden window frames. This change results in a reduction of the impact related to the windows of about 25%, thus to a reduction of about 2% of the material impact on building levels.

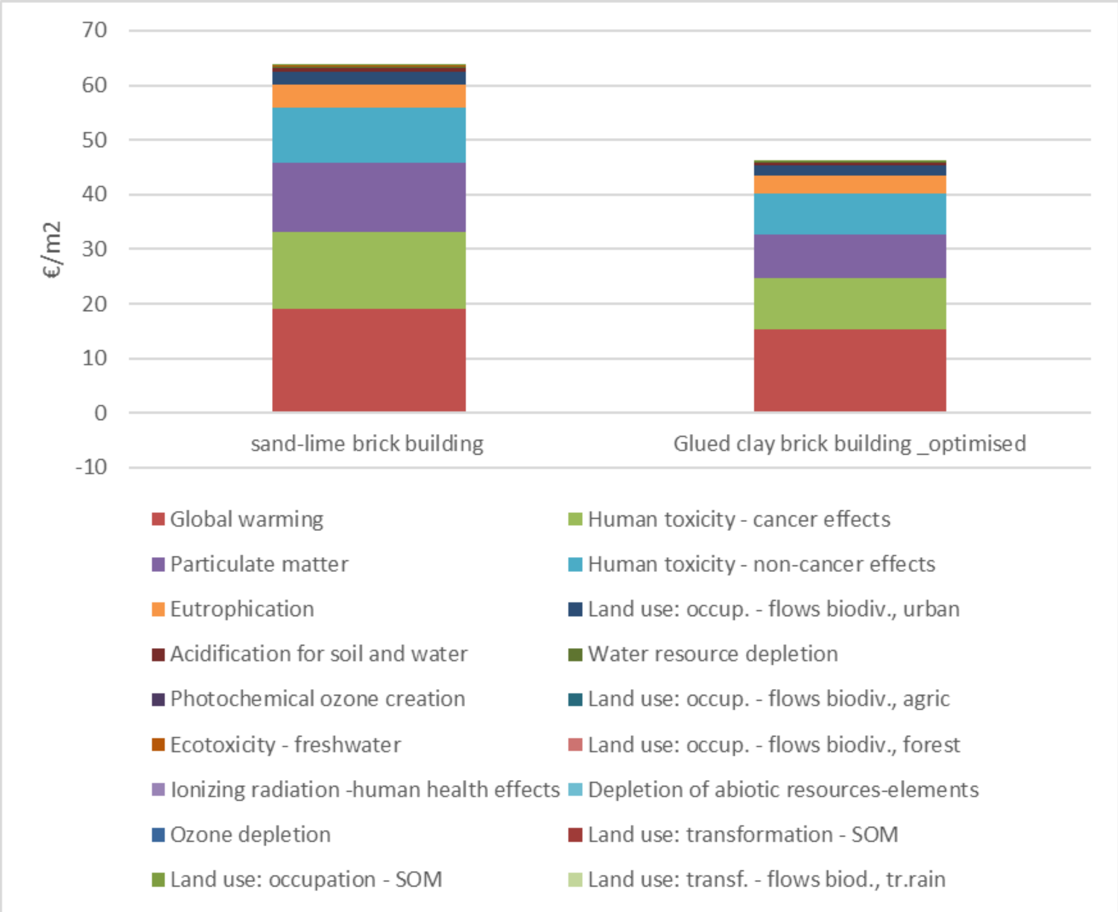


Figure 5. Environmental impact of different window frames (calculated with SimaPro), reference service life for Aluminium window frame=60 years, wooden and PVC window frames=30 years.

Ceramic tiles

Based on a comparison in TOTEM of different floor coverings (Figure 6), 80% of the surface covered with ceramic tiles was replaced by hard wood parquet. The reason for not covering all the surface with hard wood is that we assumed that it would not be useable in all areas (e.g. bathroom, kitchen).

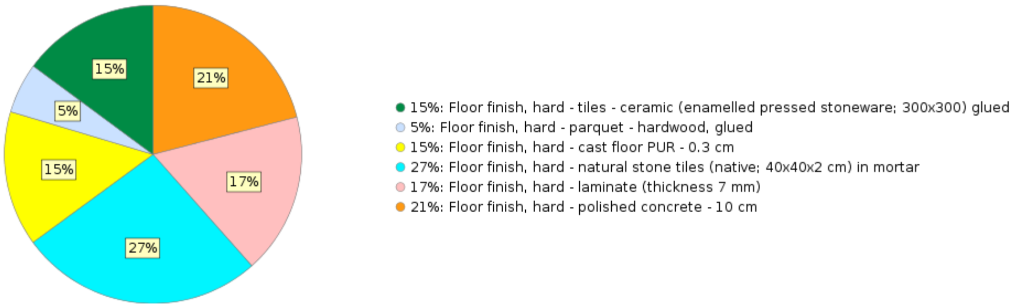


Figure 6. Comparison of floor coverings in TOTEM (Accessed November 2018; results may vary in later versions of the tool)

Acrylic paint

Figure 7 shows the relative impact of different wall finishes. The loam plaster can be used alone. The other finishes have to be combined with gypsum plaster (i.e. loam plaster could be used as an alternative for acrylic paint on gypsum plaster). Based on those results, the acrylic paint (on gypsum plaster) was replaced by lime paint (on gypsum plaster).

As it could be a logical reflexion when opting for lime paint to also opt for lime plaster as a base, the impact of the latter (calcareous plaster for indoor use applied in 3mm thickness, as predefined in TOTEM) was also compared with gypsum plaster (1mm) in TOTEM, but the results indicated that it would not be beneficial to replace the gypsum plaster by calcareous plaster[4].

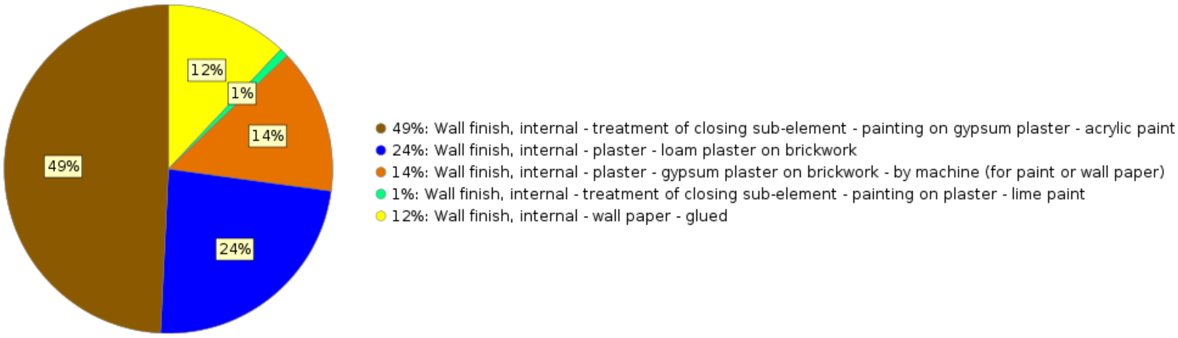


Figure 7. Comparison of different wall finishes in TOTEM (Accessed December 2018; results may vary in later versions of the tool). The loam plaster can be used alone. The other wall finishes have to be used in combination with gypsum plaster.

Cement based screed

Figure 8 indicates that amongst the materials included in the TOTEM library, the cement-based screed is the support structure for floor finish with the lowest impact. Therefore, it was not replaced.

[4] Further analysis of the underlying processes shows that the « calcareaous plaster for indoor use » as defined in TOTEM (december 2018) contains a certain percentage of cement. Therefore, this worksection should be revised in further versions of TOTEM to better represent a « natural » calcareous plaster for indoor use.

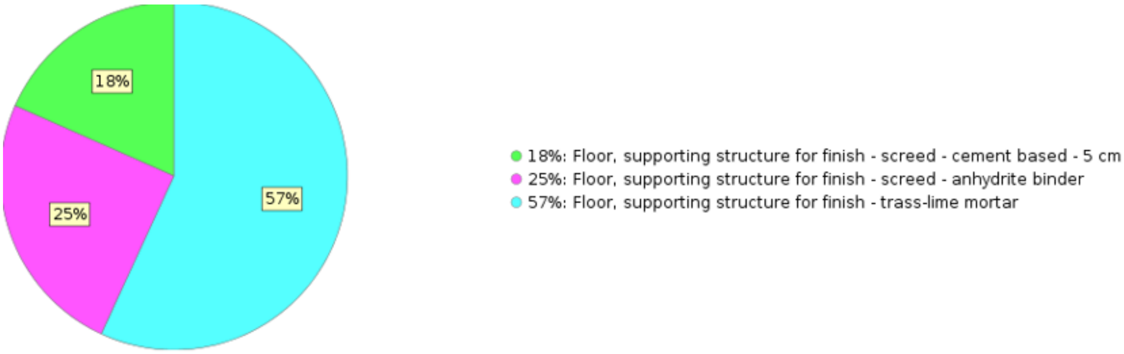


Figure 8. Comparison in TOTEM of different floor screeds (Accessed December 2018; results may vary in later versions of the tool)

Insulation floor on grade

The insulation of the floor on grade with in-situ blown PUR represents only 1.44% of the material impact. Based on a comparison of different floor slab insulations (Figure 9), the 10cm PUR layer was replaced by 11cm EPS. Although the impact of the insulation is reduced by about 60%, on building level this represents a reduction of less than 1% of the material impact.

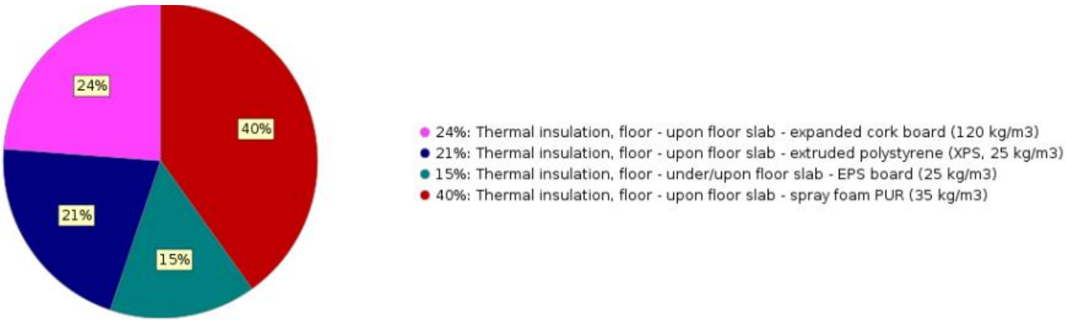


Figure 9. Comparison in TOTEM of different floor insulation materials (Accessed December 2018; results may vary in later versions of the tool)

5.3.5 Conclusion optimization potential of masonry building

Table 6 summarises the optimization steps from the sections above. This optimization strategy, which focused only on the material selection, resulted in a reduction of about 27% (17€/m^2) of the total material related impact of the building.

By lack of a complete EPB evaluation the energy use for HVAC was estimated based on an extrapolation of the EPB results from individual living units. Including the impact of this estimated energy use (+-50€/m^2), the optimization potential of the building based on material selection would be around 15%.

The most important reductions were achieved by the optimization of the floor elements, the floor coverings and the paint. For the latter, it is however unlikely that it will be chosen at design stage (the apartments are likely to be sold without paint on the walls). Moreover, there is no guarantee that the owner will use the same type of paint during maintenance (every 10 years). Sometimes, the selection of the floor coverings for the apartments is also left to the building owners and therefore unknown at the design stage.

Table 6. Summary of the optimization strategy for CASE 1 (multi-residential building, new construction, material optimization only)

Initial material choice	Contribution to the total material impact (60 years) (A)	Alternative choice	Reduction (%) of individual material impact (B)	Reduction of total material (%) (A)x(B)
Precast concrete floors	18%	Hollow concrete floors	50%	9,00%
Sand-lime bricks	10%	Insulating clay bricks	10%	1,00%
Window frames PVC	7%	Window frames wood	25%	1,75%
Ceramic tiles	8%	Hard wood flooring	84%	6,72%
Acrylic paint	8%	Lime paint	98%	7,84%
Insulation floor on ground (PUR foam)	1,4%	EPS	63%	0,91%
			Total	27%

As can be seen from Figure 10, the optimization strategy leads to a reduction of all indicators that contribute significantly to the monetised score. The non-aggregated results also indicate that the only indicators for which the optimization strategy lead to an increase in impact are land use occupation SOM and land use occupation forest (because of the use of hard wood flooring). However, based on the monetised scores the contribution to those indicators are negligible. Therefore, we can conclude that the optimization strategy does not cause any significant impact shift between the considered impact categories.

The optimization strategy focused on materials contributing to 75% of the impact. Although not all could be optimized (e.g. reinforced concrete used for foundations) it led to a reduction of about 27%. Assuming that for the materials that contribute to the remaining 25% a similar reduction could be achieved, the maximum achievable reduction through material selection would be around 35% (27%+27/75 x 25%) or 22€/m^2. However, this additional optimization step would be very time consuming. Indeed, it would require tackling a lot of materials that contribute each to less than 3% of the total impact.

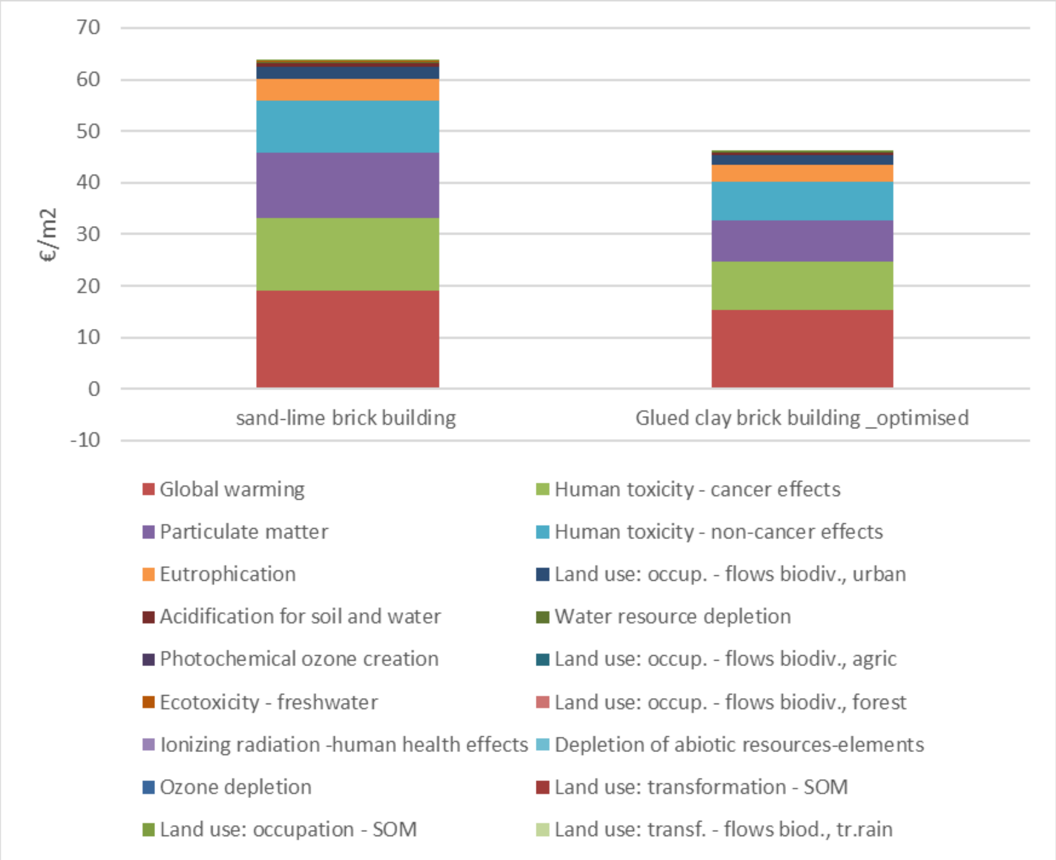


Figure 10. CASE 1: comparison of the initial and optimized material impact with the same construction mode (masonry)

5.3.6 Comparison with other construction modes

The previous analysis supposed that the construction mode (masonry) was fixed. In this second part, different alternative construction modes (concrete skeleton with sand-lime brick infill, CLT panel building and wooden skeleton) are analysed in order to evaluate whether higher reductions can be achieved when allowing the construction mode to change. The variants all have the same lay-out (building plan), energy efficiency-level, and look (e.g. same floor and façade coverings, window frames in PVC, paint,…) as the reference sand-lime brick building. The foundations and basement, windows, doors, and stairs are also identical for all variants. The floor elements and non-loadbearing inner walls were chosen in function of the structure in order to have realistic cases (e.g. gypsum blocks are replaced by light partition walls in the new variants). The finishing materials were kept equal wherever realistic (e.g. same façade (ETICS or bricks) and floor coverings) but adapted to the structure when needed (e.g. walls in masonry are all finished with gypsum plaster, but the wood skeleton walls are finished with gypsum plaster boards). Insulation thicknesses were adapted in order to achieve similar energy performances (e.g. the wood skeleton is filled with rockwool, so the thickness of the EPS for the ETICS is reduced from 15 to 6cm).

The comparison of the impact from the sand-lime brick, the concrete skeleton, the wood skeleton and the CLT building (Figure 11), shows that if we had first focused on the construction mode we would probably have chosen the wood skeleton building as starting point for the optimization strategy. . Therefore, we also applied the optimization strategy on the wood-skeleton building in order to evaluate whether it could have resulted in an even lower environmental impact than the optimized masonry building (glued clay brick building).

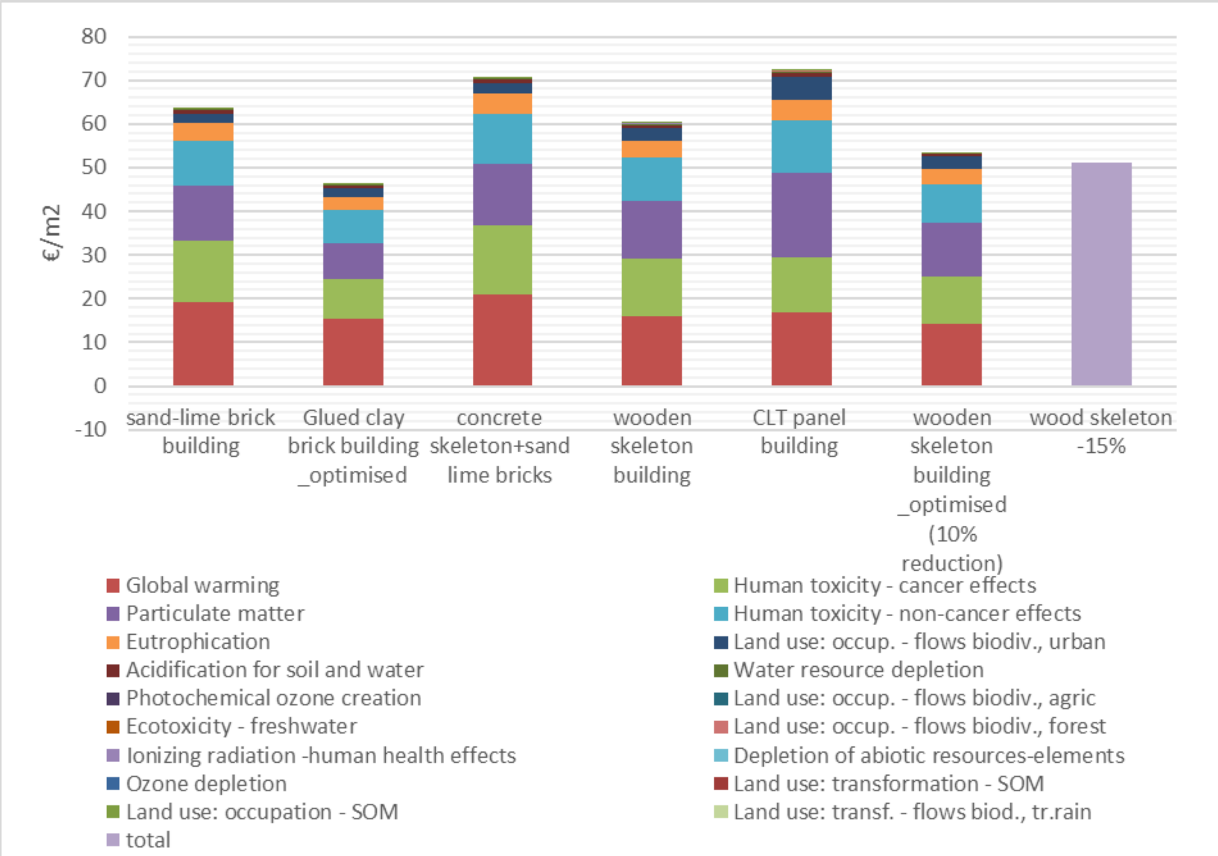


Figure 11. CASE 1: Comparison of different construction modes

The network analysis (with 2.5% cut-off) of the wood skeleton building is presented in Figure 12. Based on those results, the main contributors and the corresponding optimization strategies are the following

- Gypsum plaster/fibre boards (+-13%) → The impact from the gypsum boards is high because double layers are often needed for acoustical and/or fire safety reasons and all those boards are replaced once within the 60 years reference study period. No (lower impact) alternatives were found for this contributor. Indeed, not many options exist, and the one that was analysed (OSB-board finished with loam plaster) resulted in a higher impact (using the TOTEM tool) than the gypsum board and paint combination. The question can however be asked whether it is realistic to assume that all the gypsum plaster boards will be replaced once in the 60 years study period.
- Paint (+-9%) → replace by lime paint (see 5.3.4)
- PVC window frames (+-8%) → replace by wooden window frames (see 5.3.4)

- Ceramic tiles (+-7%) → replace for 80% by hard wood flooring (see 5.3.4)
- Outdoor steel stairs and platforms (+-6%) → not optimized within the study as it would need a whole redesign of the building
- Reinforced concrete for foundations and basement walls (+-14%).→ not optimized (see 5.3.4).
- Wooden roof structure (+-3%) → replacing the wooden roof structure by TJI beams would allow to decrease its contribution by about 50%. Given the small contribution of the wooden roof structure, the resulting improvement on building level would however be small. The results shown in Figure 11 do not include this improvement strategy.
- Inner doors +frame (+-3%) → no alternatives were studied at the time of the study (2018) as this element was not yet in TOTEM.

The above mentioned improvements (except the wooden roof structure) reduce the material related impact of the wood skeleton building by about 10% (compare wood skeleton building and optimized wood skeleton building in Figure 11). Tackling also the roof structure, and the doors, and a few other smaller contributors, an additional 5% could eventually be reached relatively easily. Considering a 15% reduction the total score of the wood skeleton building would be about 10% higher than the optimized masonry building. However, the contribution of the optimized wood skeleton building to climate change, ozone depletion potential and ionising radiation would be about 10% lower than the optimized masonry building.

In conclusion, for this building (and starting point), allowing the construction mode to vary at first would not have led to a higher reduction than what was achieved by optimization within a given construction mode (masonry building). Indeed, although initially the wood skeleton building had a slightly lower impact (+-3.5€/m^2) than the sand-lime brick building, the optimization potential of the latter was about twice as high (about 27% of the material related impact or 17€/m^2) as that from the wood-skeleton building (about 15% or 9€/m^2).

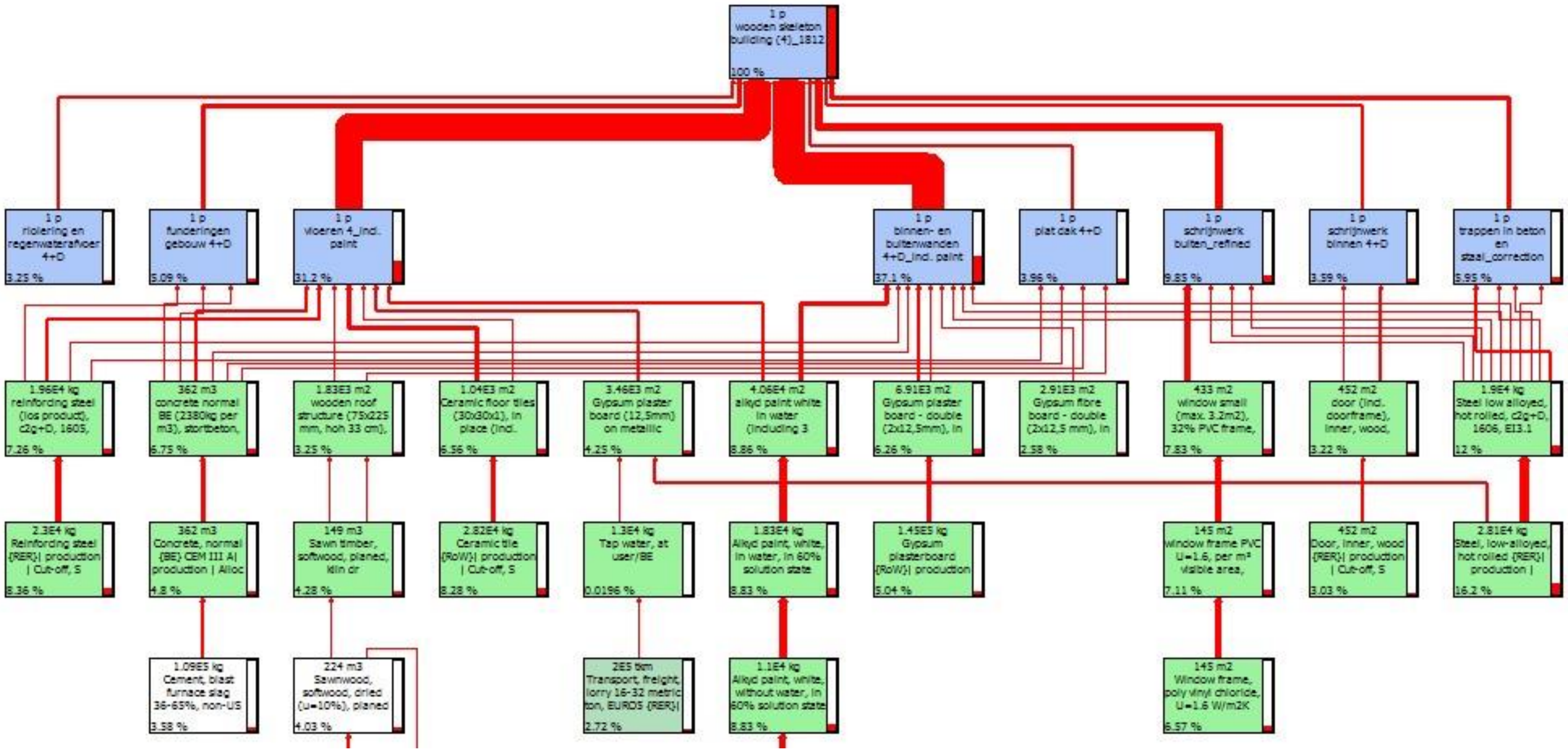
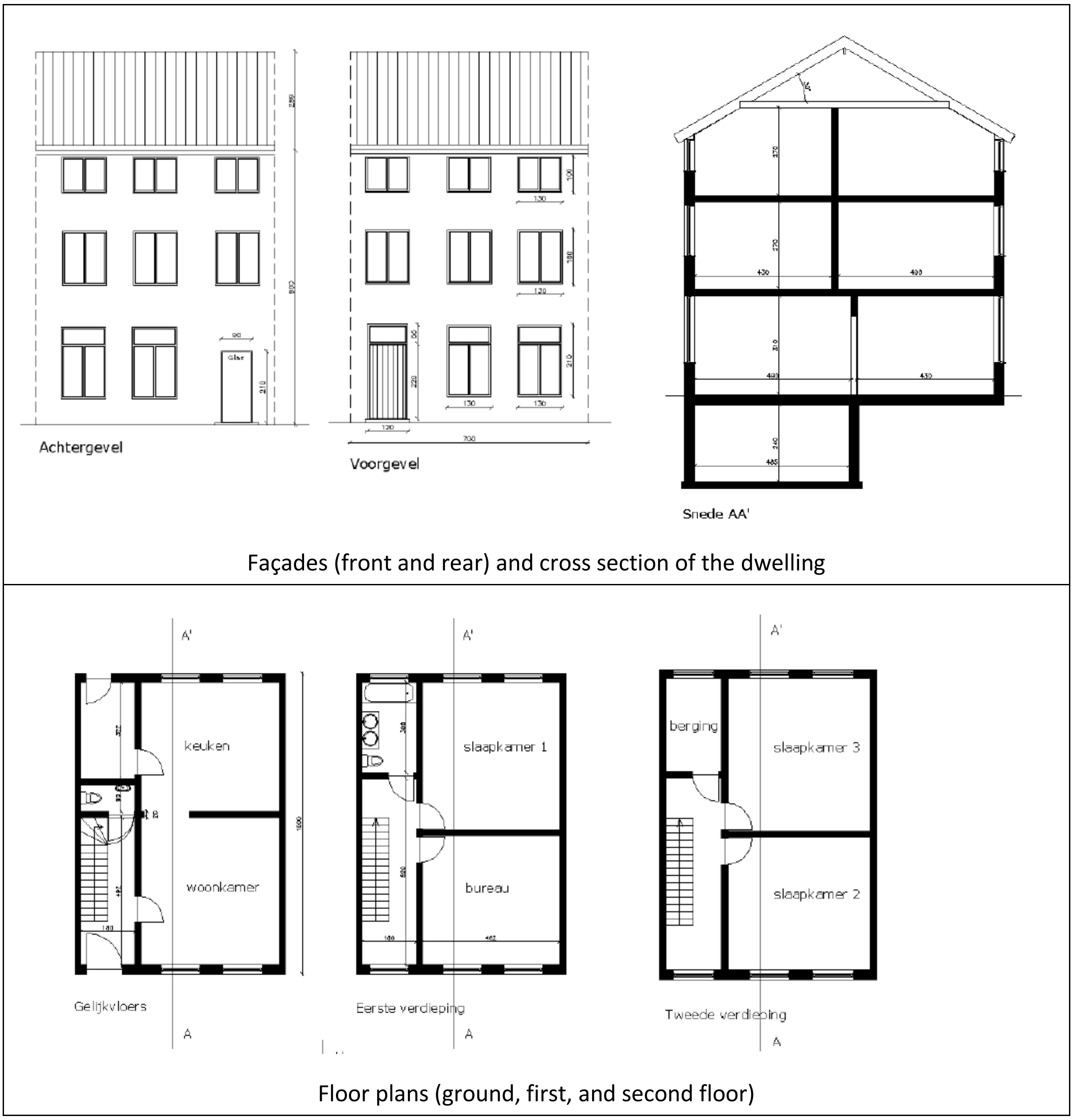


Figure 12. Network analysis of the wood skeleton variant (cut-off at 2.5%)

5.4 CASE 2: Terraced house (renovation) – optimization of the energy performance

5.4.1 Description of the building

The renovation case study concerns a terraced house (mansion), which was built in 1920. It consists of three floors, a cellar and an attic. Figure 13 gives an overview of the façades, across section and the floor plans. Table 8 provides an overview of the characteristics of the reference house, as it was built in 1920. More details on this dwelling are given in the VEA study (2013) [10]



Façades (front and rear) and cross section of the dwelling

Floor plans (ground, first, and second floor)

Figure 13. Visualisation of the terraced house. Images from [13]

Table 7. Overview of the characteristics of the terraced house (mansion), as it was built in 1920.

Terraced house (mansion, 1920)	
Protected volume	631.4 m³
Floor area	210 m²
Pitched roof	Non-insulated wooden roof
External walls	Non-insulated brick wall (30 cm)
Floor above cellar	Non-insulated concrete floor
Floor on ground	Ceramic tiles on sand bed
External windows	Wooden profiles with single glazing
Heating	Local heating with gas fires
Sanitary hot water	Local gas geyser
Ventilation	System A
Renewable energy	None

5.4.2 Approach and renovation scenarios

The study is elaborated from the viewpoint of a building designer that would have the mission to improve the energy performance of an existing building and would use LCA to determine what, from an environmental point of view, would be the most interesting renovation scenario. The reason for not taking the existing situation as the starting point is that TOTEM will not be used if no renovation is planned. Moreover, it would be unrealistic to assume that the building could be used another 60 years without replacing the windows or the heating system by better performing options.

As the case study focuses on the optimization potential through improvements of the energy performance of buildings, different renovation scenarios, allowing to reach different (energy) ambition levels (minimal, E60 and E30), have been determined for this terraced house. The minimal renovation corresponds to the replacement of the windows, the replacement and insulation of the roof (seen the age of the roof-structure it was assumed that it would not be realistic to keep it) and the installation of central heating with a condensing gas boiler. For the higher ambition levels different alternatives were studied, where higher E-levels were achieved by focussing either on more insulation or more sophisticated installations (PV panels and/or heat pump). Table 8 summarizes the energetic characteristics of this dwelling prior to renovation and describes the various renovation scenarios. It also includes the corresponding operational energy use and a short description of the renovation measures in terms of materials considered.

Concerning the impact of materials, the LCA considers the full life cycle impact of newly added materials. Existing materials are generally not considered because their production was already attributed to the previous life cycle and their replacement (only for materials kept in place) and EOL will occur in all scenarios (and can therefore be omitted from the comparison). However, in order to enable fair comparisons between the cases, one replacement of the existing gypsum on the walls of the street side façade is taken into account for the minimum renovation, E60inst_gas and E60_inst_HP scenarios, as the remaining scenarios include the replacement of the newly added gypsum plasterboards on PUR.

Table 8. Terraced house: Overview of renovation measures related to the different scenarios, including overview of materialisation and energy performance.

	Existing situation	Renovation scenarios							Materialisation of the renovation measure
		Min. (E100)	E60inst_gas	E60inst_HP	E60_mat	E30_HP	E30gas_ U=0,24	E30gas_ U=0,16	
U-Roof (W/m²K)	1,7 (no insulation)	**0,24**	0,24	0,24	0,24	0,24	0,24	**0,16**	New roof insulated with glass wool between the structure
U-façade (street side) (W/m²K)	1,7	-	-	-	**0,24**	**0,24**	**0,24**	**0,16**	Insulation from the inside: glued PUR +gypsum plasterboard panel
U-façade (back) (W/m²K)	1,7	-	-	-	**0,24**	**0,24**	**0,24**	**0,16**	ETICS system with EPS
U-window (W/m²K)	2.36/5.8	**1.6/1.1**	1.6/1.1	1.6/1.1	1.6/1.1	1.6/1.1	1.6/1.1	**1.6/1.0 (g=0.5)**	Double glazing with aluminium profile
U-Floor above cellar (W/m²K)	0,85	-	-	-	-	**0,24**	**0,24**	**0,16**	PUR boards glued under the floor
Ventilation system	/	/	**C3**	**C3**	**C3**	**C3**	**C3**	**D with heat recovery**	Ventilation unit and ducts
Heating system	**Local gas fires**	Combi condensing gas boiler		Air-water heat pump (COP3.5, high temperature radiators)	Combi-condensing gas boiler	Air-water heat pump (COP3.8, low temperature radiators (SPF=3.0))	Combi condensing gas boiler		New installation + distribution pipes and radiators adapted to energy demand
Sanitary warm water (SWW) production	**Local gas geyser**								

	Existing situation	Renovation scenarios							Materialisation of the renovation measure
		Min. (E100)	E60inst_gas	E60inst_HP	E60_mat	E30_HP	E30gas_ U=0,24	E30gas_ U=0,16	
				+ storage tank for SWW		+ storage tank for SWW			
PV (kWp)	0	0	4	2.5	0	2.5	3.9	2	Mono-SI panels mounted on the roof
E-level	202	100	60	60	59	30	30	30	
K-level	132	74	74	74	45	39	39	32	
Final energy use for heating (kWh/y/m²)	267 (gas)	116 (gas)	90 (gas)	23 (electricity)	48,9 (electricity)	12,7 (electricity)	40,1 (electricity)	29,1 (electricity)	
Final energy use for SWW (kWh/y/m²)	18,9 (gas)	18,9 (gas)	18,9 (gas)	6,7 (electricity)	18,9 (gas)	6,7 (electricity)	18,9	18,9	
Final energy use for auxiliaries (kWh/y/m²)	0	2,6	3,5	2,6	3,5	2,6	3,5	4,4	
Final energy use for cooling (kWh/y/m²)	0	0,35 (electricity)	0,7 (electricity)	0,7 electricity)	2,4 (electricity)	3,2 (electricity)	3,2 (electricity)	0,3 (electricity)	The impact of a cooling installation is not taken into account
Final energy use for non-building related	3000	3000	3000	3000	3000	3000	3000	3000	

	Existing situation	Renovation scenarios							Materialisation of the renovation measure
		Min. (E100)	E60inst_gas	E60inst_HP	E60_mat	E30_HP	E30gas_ U=0,24	E30gas_ U=0,16	
energy (kWh/y)									
Electricity produced by PV (kWh/y)	**0**	0	2913	1821	0	1821	2840	1457	Avoided impact from corresponding amount of electricity sold on the Belgian market

5.4.3 Methodology related to PV panels

In case of scenarios including rooftop photovoltaic panels, the electricity produced by the panels is calculated. As certain scenarios are gas-based, it is assumed for all scenarios that the produced electricity is entirely exported to the Belgian electricity grid. As a result, a "benefit" or "avoided impact" can be specified for the scenarios using PV: this "avoided impact" corresponds to the impact of a corresponding amount of energy sold on the Belgian market. According to the European standard NBN EN 15978 [6] the avoided impact (benefit) from exported energy is reported in module D as a negative value.

To allow for the evaluation of the direct use of electricity produced by photovoltaic panels within the building (even for scenarios without electricity use for heating and domestic hot water supply), the non-building related energy use of home appliances (which is normally not considered in building LCA) is also included in this study. This electricity use is set at 3000 kWh/year for each building type (mean value used for a family with 4 persons in Flanders). The environmental benefits of using electricity produced by PV panels directly within the building shows when subtracting the avoided impact of electricity produced by PV panels (reported in module D) from the impact of the non-building related energy of home appliances.

5.4.4 Results

Figure 14 represents the life cycle impact of the newly installed materials (MAT), HVAC installations (INST), and the energy use/production of the renovated building over 60 years. The thick black line in the graph represents what the impact of the building would be if all electricity was used in the building (and therefore would reduce the electricity imported from the grid for home appliances).

Based on those results following observations can be made:

- For the minimal renovation scenario (E100), the relative contribution of materials is very small compared to the impact of energy use. Therefore, at this level, the reduction potential through optimization of the energy performance of the building is much higher than through material selection.
- Since the object of the assessment is a renovation case, the absolute impact of materials is also relatively small (around 10 €/m^2). If we extrapolate the results from the previous section (+-30% reduction achievable based on material selection only) the maximum reduction that could be achieved purely through material selection would be around 3€/m^2.
- The contribution of installations can be relatively high. However, as they have an important impact on the energy use of the building they cannot be optimized separately.
- Assuming that Min (E100) is the starting point and that the E-value is not fixed, then the maximal reduction that can be achieved (within the defined variants), by optimization of the energy performance of the building and its

installations, is around 50% (57€/m²). Indeed, the total impact of Min (E100) is about twice as high as that of E30LWWP.

- With the exception of E30gas_U=0.24, lower E-levels generally lead to lower environmental impact (E100>E60>E30). However, significant differences can be observed between alternatives with the same E-level. Consequently, there is also room for optimization within a given E-value (E30, E60). Nevertheless, the optimization potential based on energy performance tends to become smaller as the E-value decreases (about 40 €/m² (30%) difference between the worst and the best E60 alternative and 14€/m² (+-15%) between the E30 alternatives).
- Concerning the specific renovation measures, the results show that, for a given E-level, it is more interesting to insulate more than to install PV panels (i.e. E60_inst_gas>E60mat and E30gas_U=0.24>E30gas_U=0.16). Indeed, the increase in impact from installations caused by the PV panels is of the same order of magnitude as the reduction in electricity consumption.
- Compared to the gas boiler, the heat pump leads to a small increase in the impact from installations. This is partly due to the fact that a higher service life is assumed for the gas boiler (20 years) than for the heat pump (15 years), and therefore the heat pump is replaced once more over the 60 years study period than the gas boiler. However, for this level of energy demand for heating, the increased impact from installations is largely compensated by the higher efficiency and therefore lower impact from heating of the heat pump.

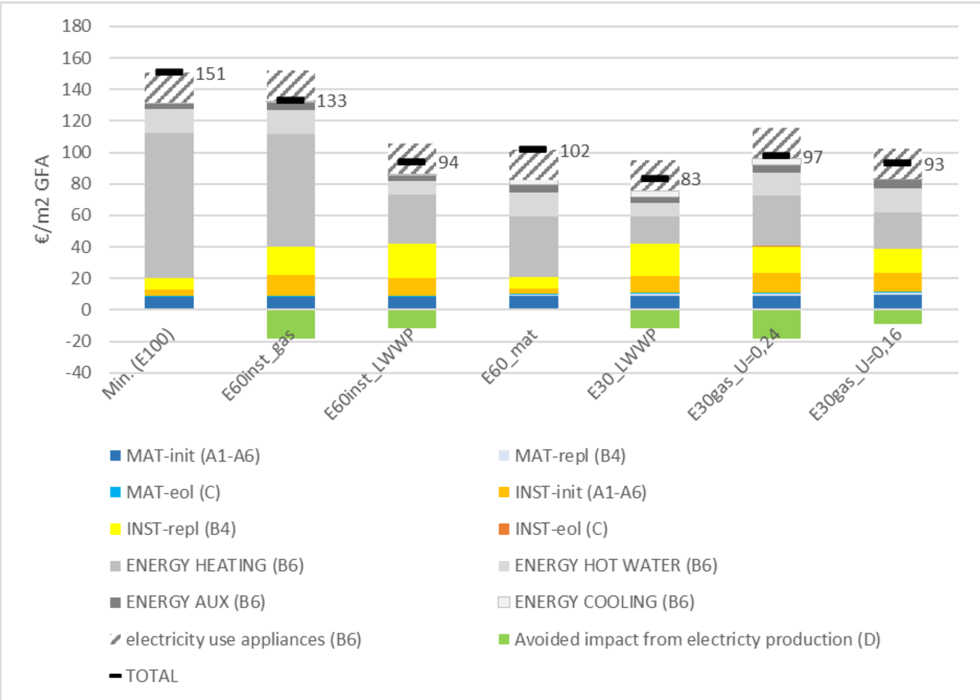
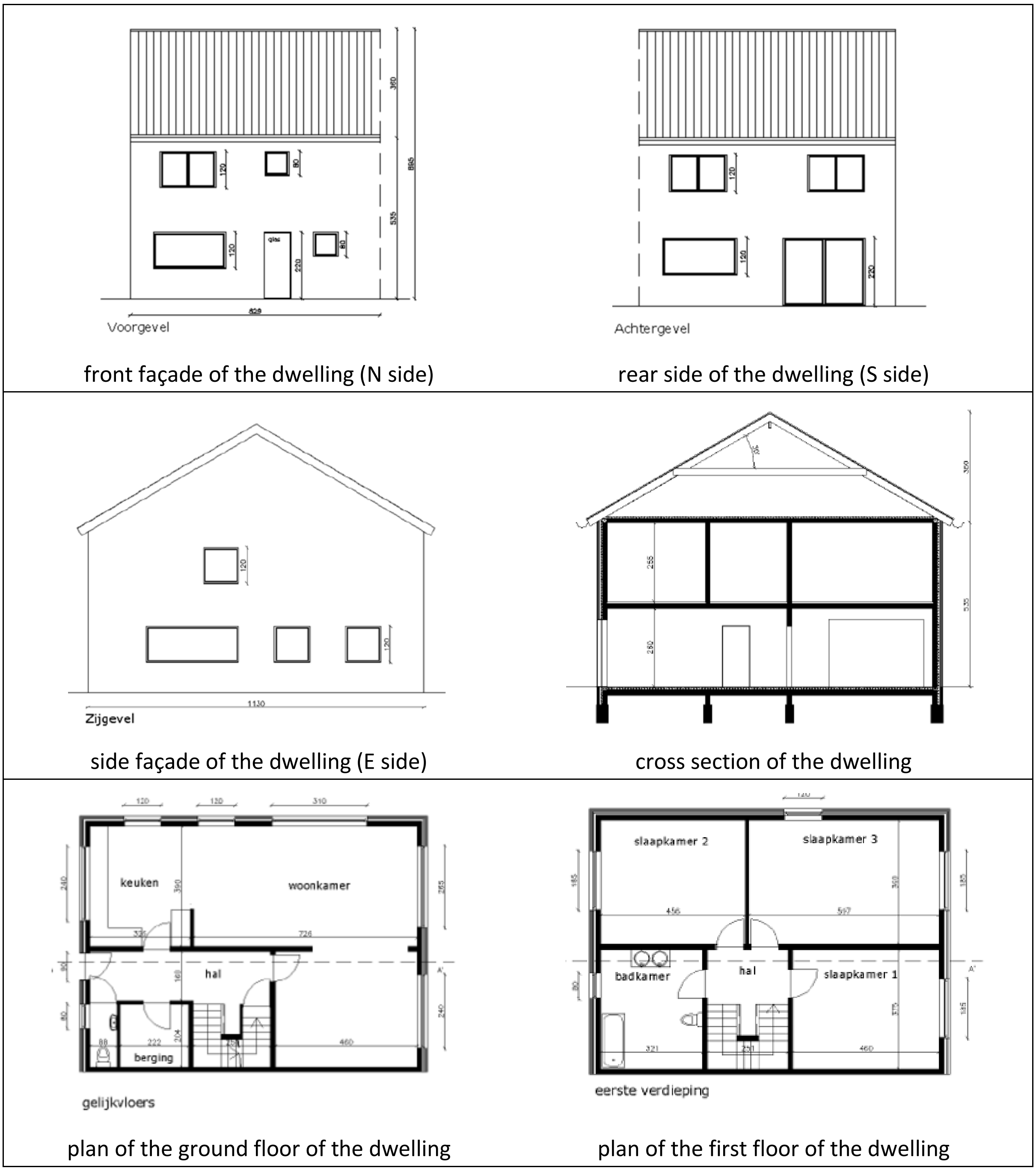


Figure 14. CASE 2: Comparison of the life cycle impact (60 years) of different renovation scenarios. The line (Total) represents the sum of modules A, B, C and D or the case where all electricity would be used onsite and therefore module D would be zero, but the import of electricity for appliances would be smaller.

5.5 CASE 3: Semi-detached residential building (new construction) – optimization of the energy performance

5.5.1 Description of the building

The considered semi-detached house is supposed to be newly built in 2020. Figure 15 gives an overview of the three façades of the dwelling, as well as a cross section and a floor plan of the ground floor and the first floor. Table 9 provides an overview of the composition of the different components of the house. More details on this dwelling are given in the VEA study [10].



front façade of the dwelling (N side) | rear side of the dwelling (S side) | side façade of the dwelling (E side) | cross section of the dwelling | plan of the ground floor of the dwelling | plan of the first floor of the dwelling

Figure 15. Visualisation of the semi-detached dwelling (2020). Images from [10].

Table 9. Overview of the composition of the different components of the semi-detached dwelling (2020).

Semi-detached dwelling (2020)	
Protected volume	548 m^3
Floor area	187,36 m^2
Pitched roof	Non-insulated roof with ceramic roof tiles, PE sub-roof and wooden rafters and purlins
Attic floor	PUR insulation boards, PE vapour barrier, hollow core slabs with concrete pressure layer, gypsum plaster
Storey floor	Ceramic floor tiles or laminate floor finishing, cement-based screed, mineral wool acoustic insulation, hollow core slabs with concrete pressure layer, gypsum plaster
Ground floor	Ceramic floor tiles, cement-based screed, PUR insulation boards, in situ reinforced concrete floor slab
External walls	Cavity wall with facing bricks, PUR insulation boards, clay brickwork, gypsum plaster
Party wall	Cavity wall with mineral wool insulation, clay brickwork and gypsum plaster
Internal walls	Clay brickwork with gypsum plaster on both sides
Foundations	In situ reinforced concrete sole foundation
External windows and doors	Aluminium frames with double or triple glazing
Internal doors	Wooden doors
Staircase	Wooden steps with wooden railing
Heating	Central heating system with combi condensing gas boiler or air-water heat pump
Sanitary hot water	Combi with gas boiler or with heat pump
Ventilation	System C3 with demand control or system D with heat recovery
Renewable energy	Mono-Si PV panels mounted on pitched roof

5.5.2 Scenarios

Different scenarios, allowing to reach different (energy) ambition levels have been determined for this semi-detached newly built house (Table 10).

Table 11 summarizes the characteristics of the dwelling for the various scenarios, as well as the corresponding operational energy use. Higher U-values are reached by simply increasing the insulation (not changing the insulation type or construction method).

Table 10. Overview of scenarios for CASE 3: new-built semi-detached house (focus on energy)

Ambition level	Measures
E30 minimal	The building is conceived according to the minimal requirements set by regulation (EPB requirements 2020) for new construction (E30). Two scenarios are evaluated considering different technical installations. In both cases a certain amount of PV panels are added to reach E30: Min E30gas (1) Insulation of building envelope following current legislation* (2) Heat production using a combi condensing gas boiler Min E30HP (1) Insulation of building envelope following current legislation* (2) Heat production using an air-water heat pump
E30/E25 passive	The building is aiming for the passive standard by focussing on higher insulation levels of the building envelope. Two scenarios are evaluated considering different technical installations (but same insulation level): Passive E30gas (1) Deep insulation to U=0.13W/m²K for building envelope and triple glazing (2) Heating production using a combi condensing gas boiler Passive E30HP (1) Deep insulation to U=0.13W/m².K for building envelope and triple glazing (2) Heating production using an air-water heat pump No PV panels are needed to reach an E-level of 30. In combination with the heat pump, the high insulation level even leads to an E-level of E25
E0 passive	This alternative is the same as Passive E30 HP, but with the addition of PV panels to reach E0
* U=0.24 W/m².K for building envelope; U=1.5 W/m².K and Ug=1.0 W/m².K for windows	

Table 11. Characteristics of the newly built semi-detached dwelling (2020) for various scenarios.

	Minimal E30 gas	Minimal E30 HP	Passive E30 gas	Passive E25 HP	Passive E0 HP
Attic floor (U-value, W/m².K)	0,24	0,24	0,13	0,13	0,13
External walls (U-value, W/m².K)	0,24	0,24	0,13	0,13	0,13
Party wall (U-value, W/m².K)	0,6	0,6	0,6	0,6	0,6
Ground floor (U-value, W/m².K)	0,24	0,24	0,13	0,13	0,13
External windows (U-value for profiles and glass, W/m².K)	1,4/1,0	1,4/1,0	1,4/0,6	1,4/0,6	1,4/0,6
Ventilation system	System C3	System C3	System Dwtw3	System Dwtw3	System Dwtw3
Heating system	Combi condensing gas boiler (25 kW production, SPF 0,94) + HT radiators	Air-water heat pump COP 3.8 (5,6 kW production, SPF 3,67) + LT radiators	Combi condensing gas boiler (25 kW production, SPF 0,94) + HT radiators	Air-water heat pump COP 3.8 (3,7 kW production, SPF 3,67) + LT radiators	Air-water heat pump COP 3.8 (3,7 kW production, SPF 3,67) + LT radiators
Sanitary warm water (SWW) production	Combi with gas boiler	Heat pump boiler with hot water storage vessel	Combi with gas boiler + shower heat recovery	Heat pump boiler with hot water storage vessel	Heat pump boiler with hot water storage vessel
PV panels (kWp)	2,5	0,5	0	0	4,2
E-level	30	30	29	25	-1

	Minimal E30 gas	Minimal E30 HP	Passive E30 gas	Passive E25 HP	Passive E0 HP
K-level	30	30	20	20	20
Final energy use for heating (kWh/m².y)	40,1 (gas)	10,3 (electricity)	16,1 (gas)	4,1 (electricity)	4,1 (electricity)
Final energy use for SWW production (kWh/m².y)	21,5 (gas)	7,7 (electricity)	17,5 (gas)	7,7 (electricity)	7,7 (electricity)
Final energy use for auxiliaries (kWh/m².y)	3,45 (electricity)	2,57 (electricity)	4,35 (electricity)	3,47 (electricity)	3,47 (electricity)
Final energy use for cooling (kWh/y/m²)	106,8	106,8	91,8	91,8	91,8
Final energy use for non-building related energy (kWh/y)	3000	3000	3000	3000	3000
Electricity produced by PV panels (kWh/y)	1796	359	0	0	3017

5.5.3 Results

Figure 16 compares the environmental impact generated by the new construction over 60 years, considering the scenario's described in Table 11. The energy produced by PV panels is treated as described in 5.4.3. The presentation of the results is identical to case 2.

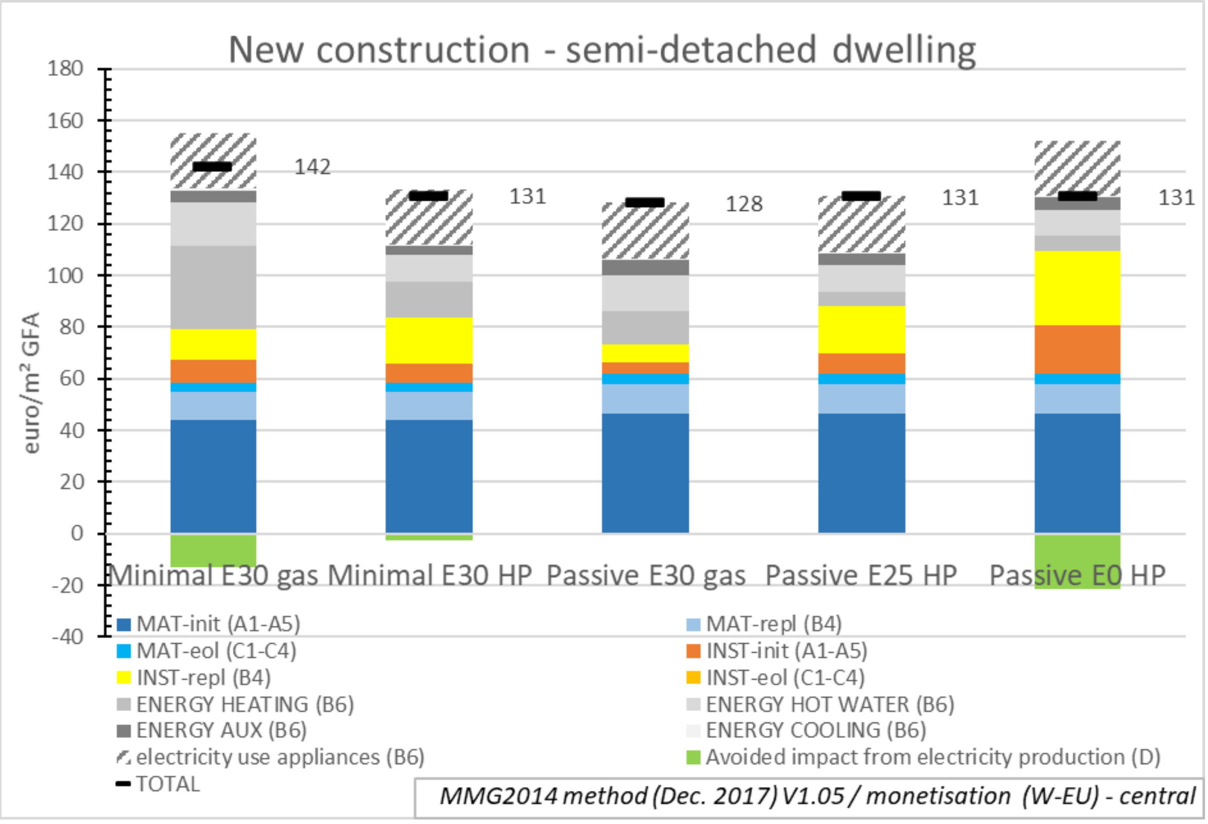


Figure 16. CASE 3 Comparison of the life cycle impact (60 years) of different variants for a new construction. The line (Total) represents the sum of modules A, B, C and D or the case where all electricity would be used onsite and therefore module D would be zero, but less electricity would need to be imported to feed appliances.

Based on Figure 16 the following conclusions can be drawn:

- For all variants (all relatively energy efficient), the impact related to the materials used (= embodied impact) is equal to or larger than the impact of the building related energy use (B6 excluding appliances). Therefore, it would be reasonable at this point to include optimization strategies focusing on material selection. Indeed, supposing that a reduction of 30% of the material impact is achievable through material selection, optimization strategies focusing on material selection could lead to a reduction of about 18€/m^2 (=30% x 60euros/m^2).
- Nevertheless, although the 2020 requirements in terms of energy performance are already high, the results indicate that with Minimal E30 gas as starting point, the environmental impact can still be reduced by strategies focusing only on the insulation level or choice of installations.

- Indeed, with Minimal E30 gas as the starting point for the optimization, the optimization process based solely on the choice of installations and insulation level still leads to a reduction of about 14€/m² (+-10% of the total impact including energy use for appliances). This is about of the same order of magnitude as the optimization potential through material selection.
- The most efficient energy related reduction strategies identified are the replacement of the condensing gas boiler by a (more efficient) heat pump or the increase of the insulation level to passive standard. Combining both strategies; however, does not seem to lead to any additional reductions. Indeed, at the insulation level to passive standard, the energy demand for heating is already so small that the increase in impact from installations induced by the heat pump (mainly because of its shorter service life) is of the same order of magnitude as the induced decrease in impact from heating and hot water production. Which alternative (gas or heat pump) scores better in the end will at this point be very case specific and influenced by underlying assumptions (e.g. concerning the service life of both installations, the specific type of condensing gas boiler, specific heating demand etc.)
- Increasing the insulation level of the Minimal E30gas alternative to passive standard leads to a net benefit of about 15€/m², which is of the same order of magnitude as the benefit achieved in case 1 through material selection (section 5.3.5). Indeed, the material related impact of the variants insulated to passive standard is only slightly higher than the material related impact of scenarios insulated to the minimum EPB requirements of 2020 (less than 5€/m² or about 8% increase in impact of materials between Minimal E30gas and Passive E30 gas). However, the extra insulation results in important savings in terms of energy use for heating with gas (+-20€/m²).
- PV panels have an important influence on the E-value. However, they do not influence the total impact significantly.

6. General conclusions

Both the results from literature and the performed case studies indicate that there can be high variations in environmental performance of buildings. Therefore, the optimization potential of buildings is significant.

The first case study (new apartment building-optimization strategy focusing on the material selection) shows that an optimization strategy based on material selection only (focusing only on materials contributing to at least 3% of the material impact) can lead to a reduction of about 30% of the material related impact (reduction of about +-17€/m²), or about 15% of the total impact (materials + energy use for HVAC). This reduction will however be very much influenced by the initial material selection and the freedom left to the designer (e.g. financial aspects were not considered within the present study). Moreover, the results confirm the findings from the literature study (see 3.5) concerning the fact that finishing materials can be an important part of the optimization strategy. They are sometimes major contributors and usually many alternatives are possible. However, it is important to note that the optimization potential of finishing materials with a short service life may be overestimated. Indeed, the results assume that the choice made during design stage will be maintained throughout the service life of the building (e.g. the same type of paint will be used every 10 years). However, in reality the building owner may decide otherwise.

In line with the conclusions from the literature review (see 3.5), the renovation case study indicates that the highest reduction potential for old (poorly insulated) buildings lies in the improvement of the energy performance. The material related impact for an energetic renovation is usually relatively low, but the improvement potential in terms of energy use is high. For the renovation of the terraced house from 1920, a 50% reduction of the life cycle impact (almost 60€/m²) was achieved by optimizing the type of installations and insulation level compared to a strategy that would only fulfill the minimum legal requirements in terms of energetic renovation (replacement of windows and heating system and replacement and insulation of the roof). The results also show that EPB and TOTEM can be complementary. Indeed, although the E-value points in the right direction (lower E-levels lead to lower environmental impact), there is still room for optimization within a given E-value.

Based on the third case study (newly built family house – optimization strategy focusing on the energy performance), even for low energy buildings (respecting actual requirements in terms of energy performance) there is a potential for impact reduction through optimization of the insulation level and choice of installations. The extent of the optimization potential will depend on the performance of the starting point, but for buildings built according to minimum legal requirements it can be of the same order of magnitude as the reduction potential through material selection. However, based on present case studies, the life cycle impact (over 60 years) of the most optimized new dwelling (renovation to passive standard) is still significantly higher (45€/m² GFA) than the life cycle impact of the optimized energetic renovation (to E-level of 30).

Existing (3.5) and present case studies (5.4, 5.5), indicate that the impact of installations can be relatively high. As installations influence the impact related to the energy use of the building it must be ensured that the embodied impact of insulation materials, installations (modules A, B4, C) and operational energy use (B6) are considered together to allow for holistic optimization.

Finally, existing studies (3.5) indicate that for new (low energy) buildings the reduction potential through optimized building design (lay-out, percentage of windows, height of ceilings, ...) can be at least as important as the reduction potential through material selection or improvement of the energy performance of the building. Therefore, a geometric optimization should be the first step of any environmental optimization process. [14]

7. Recommendations for functionalities of TOTEM

Currently, TOTEM does not allow to visualize the relative contribution of individual materials to the total environmental impact of the building. However, in some cases this may lead to additional insights that may improve the optimization process. Indeed, some materials may have a small contribution to many elements and therefore not seem relevant on element level. However, their impact on building level may be significant. Unlike a pie-diagram, a network as shown in Figure 2 also enables to trace in which elements the materials are used.

Additionally, being able to see the relative contribution of materials to a given life cycle phase or indicator would facilitate the interpretation (e.g. why is the impact of replacements so high or why does this element contribute more to toxicity than the other variant?), and therefore the optimization process. It would also enable to detect errors more easily.

Although it is not advisable to make comparisons on material ("component") level, the possibility to do it would facilitate the optimization process for cases where materials can be replaced without influencing the rest of an element (e.g. paints, floor coverings, windows). Indeed, for the moment the only "official"[5] way to compare different material options in TOTEM (December 2019) is to create different versions of an element (e.g. with different floor coverings) and compare them. However, this is time consuming, and relatively restricted as only 4 elements can be compared at once. One option to facilitate this comparison without really introducing a compare function at material level would be to report the monetarized impact of materials per functional unit directly in the library (e.g. extra column in the table providing an overview of the materials).

The results from the study show that installations have a significant impact on the environmental performance of buildings (both on the material impact and the energy use). Therefore, it advisable to include them in TOTEM (as already planned). However, to allow for a holistic optimization, the embodied impact of (insulation) materials, installations, and operational energy use should be linked and calculated together. For PV panels, this implies that TOTEM should have a functionality that enables to visualize the benefit from using or exporting the produced electricity.

Finishing materials contribute significantly to the material related impact of buildings. Therefore, it is interesting to include them in TOTEM. However, if at some point the use of TOTEM becomes compulsory and limit values are set, there should be a reflection concerning the inclusion of finishing materials with a short service life in the end-score of the building. Indeed, there is a high uncertainty concerning their replacement (by an identical material) in the future. Moreover, some of those materials are not selected during the design stage.

For the moment, circular solutions cannot really be valorized in TOTEM, as the end-of-life of materials depends only on the nature of materials (e.g. burnable insulation) and is not influenced by the way they are installed (e.g. glued or

[5] The method used in 5.3.4 is not a conventional way of working with Totem

mechanically fixed). The addition of module D would provide some information on the potential benefits of recycling and reuse. However, it is not necessarily a good indicator for the circularity of a building as the benefits reported in module D are mainly influenced by the avoided impact of primary production. Moreover, module D information provided by EPD's is usually also only representative of one specific installation process.

The literature study showed that geometric optimization of the building can lead to important reductions in environmental impact. Presently, the results in TOTEM (on building level) are expressed per square meter gross floor area (GFA). However, although this unit can be useful to compare different building projects (e.g. for the establishment of benchmarks), for geometrical optimization this may not be the most adequate unit. Indeed, the building concept with the lowest (total) environmental impact may not be the one with the lowest impact per GFA. As the most suitable unit will depend on the goal and scope of the study, it could be interesting to provide some alternatives (e.g. impact/GFA, total impact, impact/inhabitant) to the user. Ideally, the user should also be able to switch from one unit to another in the course of the study. Expressing the impact per year would only make sense if the user would be allowed to change the reference study period.

Finally, the existing studies indicate that water consumption during the use phase can be an important contributor to the building impact (especially for the indicator Net freshwater use). As water use can be influenced by design choices (e.g. measures taken to enable the use of rainwater) it would be worthwhile to investigate whether the inclusion of water use in TOTEM would make sense.

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Annex 1 Monetised global indicator

Table 12 gives an overview of the individual impact categories considered in the monetised environmental score and the corresponding monetarisation factors [5].

Table 12. Impact categories included in the monetised score and their corresponding monetarisation factor

Impact category	Unit	Monetarisation factor [€/unit]
Global warming	kg CO2 eq	0,05
Ozone depletion	kg CFC 11 eq	49,10
Acidification for soil and water	kg SO2 eq	0,43
Eutrophication	kg (PO4)3- eq	20
Photochemical ozone creation	kg Ethene eq	0,48
Depletion of abiotic resources - elements	kg Sb eq	1,56
Depletion of abiotic resources - fossil fuels	MJ, net calorific value	0
Human toxicity - cancer effects	CTUh	665.109
Human toxicity - non-cancer effects	CTUh	144.081
Particulate matter	kg PM2,5 eq	34
Ionising radiation - human health effects	kg U235 eq	9,70E-04
Ecotoxicity - freshwater	CTUe	3,70E-05
Water scarcity	m^3 water eq	0,067
Land use: occupation - soil organic matter	kg C deficit	2,70E-06
Land use: occupation - biodiversity		
- urban	m^2yr	0,30
- argricultural	m^2yr	0,006
- forest	m^2yr	2,20E-04
Land use: transformation, soil organic matter	kg C deficit	2,70E-06