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Sustainability of flat roofs: A LCA based scenario study

DIPLOMA THESIS

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Nova Gorica, 2009

Acknowledgments

First of all I thank my mentor, Dr. Laure Itard, for all her guidance and her advice on my work. The diploma would not be here today without her willingness to employ me as an intern at OTB Institute and providing me with a suitable project to work on, having trust in my abilities and knowledge. I also have to thank other OTB employees, and in particular Dr. Ad Straub, for every useful recommendation regarding this research.

Additionally, I am grateful to a number of individuals who were willing to help me go abroad and finish my studies in OTB institute at TU Delft. I would like to thank the professors and other staff of the Faculty of Environmental Sciences in Nova Gorica, to support my ambitions and all other professors and individuals that contributed their effort to enable my stay in The Netherlands.

Furthermore, the biggest "thanks" goes to my parents Marta and Gorazd; thank you for all your financial support and invariable understanding of my itchy feet.

Last, but not least I have to thank my dearest friends, especially Pedro for putting up with my long complaints about my diploma and all his support. You guys made my time in Delft, although hard working, an unforgettable experience!

Thank you all!

Summary

The building sector has an important impact on the environment and at the same time an unexploited potential for improving efficiency in order to ensure better sustainability. In this research, a complete life cycle assessment (LCA) of a building component – flat roof - is conducted using a model designed for this purpose. The environmental load calculations are based not only on material impact, but also on the load of maintenance activities and last but not least, on energy use. Results are presented on a case scenario and sustainability recommendations are made to assist the parties involved in making more informed decisions.

Key words: Sustainability, flat roof, LCA, scenario study

Povzetek

Gradbeni sektor ima pomemben vpliv na okolje in hkrati neizkoriščen potencial za izboljšanje učinkovitosti za zagotovitev večje okoljske trajnostnosti. V raziskavi je bila izvedena popolna analiza življenjskih ciklov ene izmed komponent zgradb – ravne strehe. Uporabljen je bil model, oblikovan posebej v ta namen. Izračuni okoljskega vpliva temeljijo na ocenah škodljivosti materialov, vzdrževalnih aktivnosti in nenazadnje tudi porabi energije, v odvisnosti od prejšnjih dveh. Rezultati so predstavljeni na realnem primeru, izdelana pa so tudi priporočila, katerih namen je pripomoči k okoljsko zavednim odločitvam vseh vpletenih.

Ključne besede: Trajnostnost, ravne strehe, LCA, študija scenarijev

Obsežen povzetek v slovenščini

Okoljska trajnostnost ravnih streh: študija življenjskih ciklov alternativnih izvedb ravne strehe

Diplomsko delo

UVOD

Trajnostni razvoj (Brundtlandova komisija, 1987*)* temelji na medgeneracijski in medvrstni etiki, kar pomeni, da razvojne potrebe prihodnjih generacij in drugih živečih vrst ne smejo biti ogrožene zavoljo današnjega načina življenja. Naša odgovornost je implementacija dejavnosti, ki so perspektivne na dolgi rok – za nas, za okolje in za prihodnje generacije.

Gradbeni sektor nudi izjemne možnosti za lajšanje bremena, ki ga ljudje s svojim načinom življenja predstavljamo okolju, saj zgradbe prispevajo kar 40% h končni porabi energije Evropske unije *(*Energy Performance of Buildings Directive, 2002) in za 30% vseh evropskih odpadkov (Europe's Environment: The Third Assessment, 2003). Smotrno načrtovanje gradnje je še posebej potrebno, saj povprečna življenjska doba zgradbe presega življenjsko dobo posameznika, kar pomeni, da bodo naše slabe odločitve vplivale na kakovost okolja tudi v času naših naslednikov. Ena izmed metod za presojo vplivov bivalnih prostorov na okolje je analiza življenjskih ciklov. Tovrstna analiza ne vključuje faze uporabe raziskovanega objekta, kar lahko v primeru presoje vplivov stavb privede do nepopolnih rezultatov. Faze uporabe pri stavbah namreč bolj odločujoče vpliva na okolje v primerjavi z manjšimi proizvodi (npr. aparat za kavo), za katere je bila metoda analize življenjskih ciklov pravzaprav ustvarjena. Oblikovana je bila hipoteza:

Celostna presoja vplivov gradbenega elementa, kakršna je ravna streha, je veliko kompleksnejša od presoje vplivov majhnih izdelkov. Poleg škodljivosti sestavnih delov mora zajeti tudi okoljsko breme vseh vzdrževalnih aktivnosti in vpliv izbranih materialov na porabo energije, saj ta dva faktorja pomembno vplivata na okoljsko trajnostnost strehe. Kot takšna imata hkrati tudi visok potencial za zmanjšanje okoljskega bremena.

Namen diplomske naloge je tako izvedba sistematične in celostne analize ravnih streh hiš z uporabo metode analize življenjskih ciklov, ki bo omogočala sprejemanje racionalnejših in okolju prijaznejših odločitev. Ta analiza je del obširnejše raziskave na OTB inštitutu v Delftu, katere cilj je podrobna analiza življenjskih ciklov celotnega objekta (sestavljenega iz več elementov, streha je le eden med njimi). Rezultati in razprave v tej diplomski nalogi so izključno moje delo, predpostavke pa smo postavili skupaj po temeljiti razpravi z ostalimi raziskovalci ter s pomočjo podjetja Bouwteam P&O, ki je hkrati tudi naročnik raziskave celotnega objekta.

Okoljsko trajnostnost ravne strehe je mogoče oceniti na podlagi različnih lastnosti. Ena od njih je okoljska (ne)spornost uporabljenih materialov. Različni materiali zahtevajo različne naravne vire za njihovo proizvodnjo, različne količine energije, njihova proizvodnja različno vpliva na zdravje ljudi ter na ekosisteme ipd. Kljub temu bi bila ocena vplivov na okolje samo v perspektivi uporabljenih materialov zelo omejena, saj so od njihove izbire odvisne druge pomembne lastnosti zgradbe - vzdrževalna dela (njihova pogostost) in energetska učinkovitost. Ocena vplivov je v tej raziskavi sestavljena iz ocene na treh stopnjah:

- ocena trajnostnosti materialov,
- ocena trajnostnosti vzdrževalnih del in
- ocena energetske učinkovitosti.

V diplomskem delu predstavljena analiza nudi vpogled v sledeča praktična vprašanja s pomočjo katerih je lahko raziskovalna hipoteza ovržena ali potrjena:

- Kateri materiali so okoljsko najmanj sporni?
- Ali predstavlja vzdrževanje veliko breme za okolje?
- Ali predstavlja poraba energije bistven delež vpliva stavbe na okolje?
- Ali obstajajo možnosti za izboljšanje?

TEORETIČNE OSNOVE

Za napredek na področju ocenjevanja okoljskih vplivov objektov je v zadnjem času v veliki meri odgovorna Evropska direktiva o energetski učinkovitosti stavb (Energy Performance of Buildings Directive, 2002). Vseeno pa le-ta predstavlja, kot pove že ime, predvsem korak naprej na področju energetske učinkovitosti, kar je samo eden od vidikov trajnostnosti. Poleg omenjene direktive obstaja za namen presoje vplivov objektov na okolje tudi vrsta komercialnih orodij (LEED v ZDA, BREAAM v Združenem kraljestvu). Tudi ta so v precej pogledih pomanjkljiva. Izdelana so predvsem za trg, zaradi česar je njihova odlika enostavna in hitra uporaba, kar lahko hitro privede do površnih rezultatov. Delujejo na principu seznamov kjer lastnosti, s katerimi objekt prispeva k čistejšemu okolju, prinašajo nagradne točke. Tovrstna orodja niso natančna, veliko je posploševanj, ocene vplivov, izvedene z njihovo uporabo, so precej površinske in kot take neprimerne za uporabo v znanstvene namene.

Za ocene vplivov objektov na okolje se v raziskovalne namene veliko uporablja prav analiza življenjskih ciklov (ang. life cycle analysis – LCA), zato je bila uporabljena tudi za pričujoče diplomsko delo. Tehniko je razvil živilski sektor v šestdesetih letih, njena priljubljenost pa vztrajno raste. Kot je določeno v ISO[1] standardu (ISO 14040, 1997) morajo biti v oceno življenjskih ciklov zajeti vsi okoljski vplivi, ki se pojavijo v življenju izdelka: od izkoriščanja virov in proizvodnje do uporabe in odlaganja. Prav tako so v standardu določene standardne faze tovrstne analize (razvidno s slike 1: definicija cilja in področja, analiza inventarja, ocena vplivov, vse faze se prepletajo s fazo interpretacije). Vse faze so vključene tudi v diplomski nalogi. Ocena vplivov temelji na metodi kategorizacije rezultatov v devet okoljskih kategorij[2], ki jih je leta 2001 zasnovala skupina raziskovalcev v Centru za okoljske znanosti v Leidnu (v nadaljnem besedilu CML) na Nizozemskem.

Uporaba analize življenjskih ciklov je v gradbeni industriji nekoliko otežena. Razlogov je več: stavbe so kompleksne, skoraj vsaka je unikat, sestavni deli niso proizvedeni masovno. Poleg tega oteži analizo tudi visoka pričakovana starost stavb, zaradi katere je težko predvideti, kaj se bo s stavbo zgodilo, ko bo odslužila, saj si težko predstavljamo, kako razvita bo takrat tehnologija. Zaradi dolge življenjske dobe so

[1] International Organization for Standardization, Mednarodna organizacija za standardizacijo
[2] Izraba abiotskih virov, globalno segrevanje, uničenje stratosferskega ozona, ekotoksičnost za sladke vode, ekotoksičnost za kopenske ekosisteme, fotokemična oksidacija, zakisljevanje, evtrofikacija, toksičnost za ljudi.

potrebni tudi vmesni posegi. Težava je, da čas ni definirana dimenzija v analizi življenjskih ciklov. Kakorkoli, v tem diplomskem delu smo s pomočjo modeliranja prikazali spremembe v okoljski trajnostnosti ravne strehe skozi čas.

Zaenkrat še ni vsesplošnega konsenza, kako se spopasti s pomanjkljivostmi uporabe LCA metode za presojo vplivov objektov. Kljub temu pa obstaja lepo število raziskav z omenjenega področja. Koforola et al. (2008) je tako analiziral celotno poslovno zgradbo, Blanchard et al. (1998) pa stanovanjsko. Prvi je upošteval uporabljene materiale kot tudi energetsko porabo v fazi uporabe objekta, a kot enkratne vsote ob koncu življenjske dobe objekta. Drugi je rezultate predstavil s pomočjo energetske cene celotnega življenjskega cikla. Podobno, le bolj podrobno, se je študije lotil Treloar et al. (2000), kjer so predstavljeni energetski stroški za vsak element objekta posebej, a še vedno v obliki enega rezultata ob koncu življenjske dobe objekta, medtem ko je cilj pričujoče diplome predstaviti dinamiko vpliva na okolje skozi celotno življenje objekta, vključujoč fazo uporabe. Temu se nekoliko približata Itard in Treloar (2007), ki primerjata okoljsko breme vzdrževalnih aktivnosti s ponovno gradnjo objekta. Rezultati so kategorizirani v devet okoljskih kategorij z uporabo že omenjene CML metode, ki je uporabljena tudi v tej študiji. Hkrati vključuje ta raziskava tudi komponento časa.

Močno se namenu naše raziskave, ki se v nasprotju s pravkar omenjenimi študijami osredotoča na okoljski vpliv komponente objekta in ne objekta kot celote, približa študija avtorjev Kosareo in Ries (2007), ki sicer iščeta najboljšo alternativo med tremi tipi streh, a v oceno ne vključita vzdrževalnih aktivnosti.

Kakorkoli, LCA raziskave so podvržene tudi določenim negotovostim, ki izvirajo iz pomanjkanja znanja o resnični vrednosti ali količini. Na zanesljivost rezultatov vpliva odvisnost LCA analize od podatkov iz različnih lokacij, virov, časa in namena ter subjektivne izbire metode za oceno (Bjorklund, 2002). V tabeli 1 so opisani vsi potencialni viri negotovosti v LCA analizi, prav tako je razvidno na kateri stopnji LCA analize se pojavijo. Med njimi so: nenatančnost podatkov, manjkajoči in nereprezentativni podatki, negotovost modela in izbir, prostorska in časovna odvisnost.

V diplomski nalogi je v drugem delu teoretičnih osnov dela predstavljena analiza inventarja, ki je po definiciji podlaga vsake ocene življenjskih ciklov. Komponente ravne strehe lahko razdelimo na tri enote glede na njihovo funkcijo v strehi: krovni sloj, vododržni sloj in sloj izolacije. Za vsako enoto je predstavljenih nekaj alternativ različnih materialov. Opisane so njihove značilnosti, s poudarkom na njihovi proizvodnji in morebitnih okoljskih problemih, ki jih povzročajo. Ker so bili za izvedbo raziskave potrebni različni tipi streh, je bilo potrebno omenjene materiale združiti v smiselne celote, ki smo jih poimenovali scenariji.

PRAKTIČNI DEL

Kot je bilo že rečeno, je bila LCA analiza temelj diplomskega dela. Za dejansko izvedbo je bilo potrebno izbrati še primerno programsko orodje. V našem primeru smo se odločili za program SimaPro 7.1, ki ga je razvilo nizozemsko podjetje PRé Consultants. Program natančno sledi strukturi LCA, opisani v ISO standardu 14040 (slika 1 in 9).

Po definiciji cilja in področja, ki zajema določitev mej sistema (slika 10) in kvalitete podatkov, ki bodo omogočali dovolj natančno analizo (tukaj specificiramo geografsko lokacijo ter časovni okvir), sledi analiza inventarja. V tej fazi pridobimo nabor materialov, ki bodo predstavljali sestavine strehe. Večina materialov je že na razpolago v podatkovni bazi EcoInvent, kar pomeni, da so raziskovalci že definirali vse naravne vire, tehnološke procese ter tudi vse vhodne in izhodne substance, potrebne za proizvodnjo tega materiala. Če materiala v podatkovni bazi še ni, obstajata dve rešitvi: modificiramo lahko obstoječi material ali pa definiramo novega. V fazi določitve izdelka (v našem primeru je bila to ravna streha, tipično sestavljena iz treh enot), katerega presoja vpliva nas zanima, so združeni sestavni deli – prej opisani materiali – dodani so jim manjkajoči procesi (transport do mesta namestitve in ravnanje z odpadki), kot je prikazano na sliki 12). Na diagramu so puščice dveh barv: črtkane predstavljajo izhodne substance, neprekinjene pa vhodne substance. Teh substanc je v primeru ravne strehe nekaj več kot 600. Na prvi pogled je težko razumeti (to sodi že v fazo interpretacije, slika 1), kaj to pomeni za okolje, zato je bilo v ta namen razvitih več metod za ocenjevanje vplivov. Uporabljena je bila metoda CML (Centre of Environmental Science of Leiden University), ki vsem izhodnim in vhodnim substancam utežijo s pretvorbenimi faktorji (kot npr. pri določanju toplogrednega potenciala), tako da so končni rezultati na voljo v le nekaj kategorijah – ta korak je v analizi življenjskih ciklov imenovan klasifikacija. Kategorije CML metode so opisane v tabeli 3.

Poleg negotovosti omenjenih v teoretičnih osnovah (tabela 1), so izkušnje pokazale precejšnjo odvisnost rezultatov od izbrane metode. Zaradi kompleksnosti metode je težko tudi ovrednotiti negotovost metode same in prav zato na področju metod, primernih za izvedbo LCA analize še ni standardizacije. Metod zagotovo ne manjka, različne organizacije so razvile različne metode. Metoda CML 2001 je bila izbrana predvsem po kriteriju razširjenosti in uporabljenosti. Presodili smo tudi, da je število okoljskih kategorij pri tej metodi primerno. Za enostaven rezultat bi bila namreč najbolj praktična ena okoljska kategorija, a bil rezultat zelo negotov. Več kot je kategorij, manj je negotovosti, vendar so tovrstni rezultate težko razumljivi. Tudi vsaka izmed devetih okoljskih kategorij CML metode ima svoje značilnosti. Bolj natančne so tako kategorije kot so globalno segrevanje, uničenje stratosferskega ozona ter fotokemična oksidacija, za katere so določeni intervali napak. Kategorije kot je npr. zakisljevanje so manj natančne. Potencial zakisljevanja je odvisen od števila protonov, katerih vpliv na okolje ni dobro znan ter močno zavisi od opazovanega okolja. Manj natančne so tudi kategorije toksičnosti, ki se še ne skladajo z ISO standardom (Haes et al., 1999). Težava je v velikem številu obstoječih kemikalij s potencialom za nešteto sinergističnih učinkov (Finnveden, 2000). Razvoj bolj natančnih podatkovnih baz ter prihodnje raziskave bodo nekoliko izboljšale nekatere pomanjkljivosti v LCA.

Ker je namen raziskave predstaviti okoljski vpliv ravne strehe, ki je sestavljena iz več elementov, je bilo potrebno izoblikovati scenarije. Scenariji so bili potrebni ker je izbira določene komponente strehe navadno odvisna od lastnosti ostalih komponent – npr. na zeleno streho se nikdar ne namesti gramoznega balasta. Pri tovrstnih praktičnih dejstvih nam je z nasveti pomagalo nizozemsko podjetje Bouwteam P&O. Pri oblikovanju scenarijev pa smo želeli upoštevati tudi okoljsko breme komponent. Nezaželeno je bilo, da se npr. v scenariju z zeleno streho uporabi zelo škodljiva sintetična vododržna plast. Zaradi tega je bila sprva izvedena ocena posameznih materialov znotraj določene enote. Torej: ocena okoljskega vpliva krovnih slojev, nato ocena vododržnih slojev in nenazadnje še ocena izolacijskih slojev (slike 13 - 15). Poleg izsledkov te preliminarne ocene vplivov so upoštevane tudi praktične izkušnje nizozemskega podjetja, s katerim je sodelovanje potekalo ves čas raziskave. Scenariji so sledeči (razvidni so tudi v tabeli 4):

- tradicionalni scenarij (gramozni krovni sloj, asfalten vododržni sloj in izolacija iz poliuretana) - takšno je bilo tudi stanje v referenčni stavbi, katere dimenzije smo uporabili v raziskavi. Ta scenarij je torej referenca za vse nadaljnje;
- EPDM[3] scenarij (betonski krovni sloj, EPDM vododržni sloj in izolacija iz polistirena);
- zelena streha (kompozicija zelene strehe kot na sliki 6, nima izolacijskega sloja);
- fotovoltaični scenarij (odbojna plast in nad njo nameščene sončne celice kot krovni sloj, PVC folija kot vododržen sloj, spodaj izolacija iz ovčje volne).

REZULTATI TER DISKUSIJA

Kot že rečeno, so ocene vplivov na okolje izvedene na treh stopnjah. Prva, okoljska trajnostnost materialov, temelji na zgoraj opisanih materialnih izbirah za vsak scenarij. Rezultati so pokazali (slika 20), da se EPDM scenarij v večini kategorij okoljsko primernejši od referenčnega scenarija, scenarij zelene strehe je nekje blizu referenčnemu, fotovoltaični scenarij pa slabše. Razlog za slabe rezultate fotovoltaičnega scenarija je jasen – sestava sončnih celic je kompleksna in sama po sebi okoljsko sporna, če ne upoštevamo električne energije, ki jo tovrstne celice generirajo na okolju prijazen način. Malce bolje, a še zmeraj relativno slabo (glede na to da gre za domnevno napredno tehnologijo), na okolje vpliva zelena streha. V večini kategorij se precej približa referenčnemu scenariju. Torej, najboljša izbira s stališča materialov je EPDM strešni scenarij.

Naslednja stopnja, na kateri smo ocenjevali okoljske vplive, je okoljska trajnostnost vzdrževanja. Sem so vključeni zgoraj opisani vplivi materialov, hkrati pa tudi aktivnosti, ki so potrebne za njihovo vzdrževanje. Ker vzdrževanje poteka v celotnem življenjskem obdobju zgradbe in ker so za različne materiale značilne njim lastne življenjske dobe, je bilo na tej stopnji v ocene potrebno vključiti tudi komponento časa. Vzdrževalne aktivnosti smo razdelili v skupine: letno vzdrževanje, popravila in zamenjave. Ocenili smo njihovo pogostost, deleže zamenjanih materialov in število za to potrebnih delavcev. Na podlagi pogovorov s podjetjem Bouwteam P&O, ki se ukvarja z vzdrževanjem stavb, smo določili približno kilometrino do gradbišča (tabela 5). Višina naklona premice v obdobju določenih vzdrževalnih del je enaka njihovi okoljski škodljivosti v določenem letu (slika 22). Za pomoč pri razumevanju so v prilogi C dodani še vsi nakloni premic, saj so pogosto razlike med nakloni tako majhne, da jih na grafih težko razločimo.

Če se osredotočimo na letno vzdrževanje, je iz vseh grafov (slike 23 - 31) razvidno, da povzroči fotovoltaični scenarij znotraj vseh okoljskih kategorij največ škode glede na letno vzdrževanje. Sledi scenarij zelene strehe, tradicionalni scenarij, zadnji pa je EPDM scenarij.

[3] Etilen propilen dien M-razredna guma

Naklon premice v obdobju popravila (le-to vpliva na okolje neposredno preko škodljivosti materiala, ki ga je potrebno nadomestiti, ter preko transporta, ki je odvisen od mase materiala) je najvišji pri zelenih strehah, sledi mu tradicionalen scenarij. Rezultat je razumljiv, saj je pri zeleni strehi predvidena zamenjava 10 % odstotkov vseh komponent, pri tradicionalni pa le 10 % gramoznega in asfaltnega vododržnega sloja. Scenarija EPDM in fotovoltaični scenarij sta po vplivu na okolje zaradi zamenjav nekje vmes. Scenarij EPDM bi imel vpliv, podoben referenčnemu scenariju, a ni tako zaradi betonskega krovnega sloja, ki je bolj škodljiv, predvsem pa težji (večja škoda zaradi transporta).

V tretji skupini vzdrževalnih del, zamenjavah, je okolju najmanj prijazen fotovoltaični scenarij z izjemo nekaterih okoljskih kategorij, kjer še slabše odreže zelena streha. Tako se zelena streha najslabše odreže v okoljskih kategorijah evtrofikacija in ekotoksičnost za sladke vode. Za oba pojava sklepamo, da sta posledica zamenjave prsti vsakih 10 let.

Glede na omenjene izsledke so oblikovana vodila za prihodnost. Na kratko lahko sklenemo sledeče:

- Smiselno se je izogniti težkim komponentam, ki terjajo velik davek na račun transporta. Bolj primerno je mehansko pritrjevanje vododržnega sloja na spodnjo strukturo.
- Priporočljivo se je izogniti komponentam, ki terjajo veliko vzdrževanja in nimajo jasnih prednosti za okolje (npr. odbojni sloj, morda tudi zelena streha).
- Bolj smotrno od preventivnega vzdrževanja, ki ga predpisujejo proizvajalci gradbenih komponent, bi bilo kurativno vzdrževanje (zamenjave in popravila samo kadar se kaj pokvari). Pojavlja se dvom, ali je tako pogosto vzdrževanje res potrebno.
- Letni pregledi so neizogibni, lahko pa bi zmanjšali njihovo okoljsko breme z boljšo organizacijo in povezanostjo podjetij, ki so odgovorna za določeno delo na strehi. Aktivnosti kot so čiščenja in letni inšpekcijski pregledi bi se lahko izvajale simultano.

Zadnja stopnja okoljskih vplivov, ki smo jo preučili, je bila energetska učinkovitost. Ta temelji na dejstvu, da hiša z energetsko učinkovitejšo streho privarčuje delež energije v primerjavi z referenčnim stanjem, seveda pa poleg energije upošteva že prej omenjena okoljska bremena materialov in vzdrževanja. K vplivom na okolje iz ocene trajnosti materialov in vzdrževanja smo tako agregirali še negativno vrednost energije, ki jo stavba privarčuje v primerjavi s tradicionalnim scenarijem. Torej se je vpliv v danem letu (razviden iz slik 23 - 31), v določenem letu znižal za količino energije, ki je bila prihranjena do tistega leta. Na ta način smo pošteno ocenili, katere strehe bodo po določenem časovnem obdobju (stanje smo opazovali na grafu po petdesetih letih, slika 34) okolju bolj prijazne.

Vse strehe so imele boljšo izolacijo od tradicionalne, torej višjo skupno R vrednost (tabela 6). V fotovoltaičnem scenariju je poleg boljše izolacije igrala vlogo tudi proizvodnja električne energije na strehi nameščenih fotovoltaičnih modulov. Rezultati (slika 32) kažejo, da fotovoltaičen scenarij prekaša ostale z ogromno prednostjo predvsem zaradi elektrike, ki jo proizvede. EPDM prav tako pokaže dobre rezultate, zahvaljujoč najbolj učinkoviti izolaciji med vsemi scenariji.

Zelena streha pa je tudi po petdesetih letih od namestitve v večini kategorij breme okolju. Izkaže se, da tovrstna streha brez dodatne izolacije ne nudi veliko boljše izolacije kot referenčni scenarij, poleg tega pa bolj kot referenčna degradira okolje na stopnji materialne sestave, predvsem na stopnji vzdrževanja. Res je tudi, da vsi potenciali in prednosti zelene strehe v tej raziskavi niso kvantificirani, saj to ni mogoče zaradi pomanjkanja znanstvenih podatkov o ostalih pozitivnih lastnostih (zadrževanje vode v času neurij, moč povečanja biodiverzitete na območju, zmanjševanje količine onesnaževal v zraku itd.). Skratka, tovrstnih streh ni mogoče označiti kot trajnostnostnih, dokler niso raziskane omenjene prednosti. V večini scenarijev je vsaj okoljska škoda letnih vzdrževalnih aktivnosti povrnjena s prihranki energije, to pa še najmanj drži za zeleno streho. Torej še vedno ostaja zaželeno, da se spoštuje nasvete, ki so bili oblikovani na podlagi izsledkov trajnostnosti vzdrževanja.

Opazili smo tudi, da pri fotovoltaičnem scenariju ne pride do sorazmerne izboljšave glede na porabo energije znotraj posamezne okoljske kategorije, če ga primerjamo z ostalimi tremi scenariji (tam so izboljšave sorazmerne). Sledeči trije scenariji se, kar se tiče energijske porabe, razlikujejo le v porabi zemeljskega plina (to je v večini primerov gorivo za ogrevanje stanovanjskih poslopij na Nizozemskem), ki je posledica izolacije sistema. PV scenarij, na drugi strani, z nameščeno fotovoltaiko tudi proizvaja elektriko, torej je manjša tudi poraba elektrike in ne samo poraba zemeljskega plina manjša kot v vseh ostalih treh scenarijih. Vpliv proizvodnje določene enote zemeljskega plina je v vsaki od okoljskih kategorij drugačen od vpliva proizvodnje elektrike, saj 1 ima kWh (kilovatna ura) energije različen okoljski vpliv v vsaki od okoljskih kategorij glede na vir pridobivanja energije (vsi vemo, da so nekateri viri energije bolj ali manj okoljsko sporni). Zaradi tega se tudi izboljšana okoljska trajnostnost PV strehe ne kaže sorazmerno z izboljšavami pri ostalih scenarijih.

Vodila glede na tokratne izsledke so sledeča:

- Fotovoltaične celice so za zdaj razumna naložba, četudi v državah, ki niso najbolj sončne, saj dokazano prispevajo k manjši degradaciji okolja, njihov negativni učinek (materialna sestava) je zelo hitro poplačan.

- Naložba v izolacijo je okoljsko zelo dobra ideja, vseeno pa moramo biti pozorni na njene omejitve (obstaja mejna R vrednost, nad katero energetski prihranki ne bodo več vidni zaradi prevelikih izgub zaradi neučinkovitega prezračevanja, zračenja skozi špranje v stenah ipd.)

- Zmotno je prepričanje, da je pri energetski učinkovitosti strehe pomembna samo izolacija. Izračuni so namreč dokazali, da lahko k temu opazno prispeva tudi vododržna plast.

- Poleg rabe izolacije in sončnih celic, bi lahko okoljski vpliv stavbe nadalje omilili s toplotnim izmenjevalnikom.

Natančnost rezultatov je, kot že rečeno, odvisna od mnogih faktorjev. Negotovost metode je prikazana na slikah 17 in 21 z uporabo metode Monte Carlo. Poleg negotovosti metode same je na rezultate vplivala tudi kvaliteta podatkov. Nekateri med njimi temeljijo na pogovorih z gradbenim podjetjem, njihovimi izkušnjami in prakso, drugi so spet zajeti iz tiskanih virov. Med njimi včasih prihaja do očitnih razhajanj – še posebej ko gre za pogostosti vzdrževanja in življenjske dobe materialov. V soglasju z raziskovalci inštituta OTB so bili na podlagi vseh razpoložljivih virov izbrani najbolj reprezentativni in hkrati natančni podatki. Tovrstne negotovosti rezultatov nismo prikazali, saj jo je zelo težko ovrednotiti.

ZAKLJUČEK

Uspešno je bil dosežen namen diplomskega dela, rezultati predstavljajo sistematično znanstveno analizo ravnih streh hiš z uporabo metode analize življenjskih ciklov. Že v diskusiji se izsledki navezujejo na praktična vprašanja, zastavljena v uvodnem delu. Tako smo ob opazovanju rezultatov na treh nivojih ugotovili naslednje:

- okoljska trajnostnost materialov:
  Balast in odbojni sloj sta veliko breme za okolje. Smotrna rešitev so sončne celice. Med vodoodržnimi sloji se najbolje odrežeta EPDM folija in PVC. Izolacijo je potrebno izbirati predvsem na podlagi R vrednosti;

- okoljska trajnostnost vzdrževanja:
  Potrebna je racionalna organizacija, saj je njihov vpliv na okolje daleč od zanemarljivega;

- energetska učinkovitost:
  Energetski prihranki imajo pomemben potencial za izboljšanje okoljske trajnostnosti ravnih streh. Izboljšava strešne izolacije ali namestitev fotovoltaičnih celic lahko v določenem časovnem obdobju v celoti poplača vsa okoljska bremena povzročena s prenovo in vzdrževanjem celotne strehe. Tako je prvenstvena naloga oblikovanja novih bivalnih prostorov zagotavljanje večje energetske učinkovitosti.

Glede na povzetek izsledkov lahko v celoti potrdimo tudi hipotezo. Rezultati so namreč pokazali, da je breme vzdrževalnih aktivnosti res primerljivo z bremenom, ki ga povzročijo izbrani materiali. Prav tako se okoljsko breme izboljša v primeru implementacije energetsko učinkovitejših materialov, kar pomeni, da je potrebno pri ocenjevanju vplivov na okolje upoštevati tudi ta vidik.

Raziskava predstavlja celostno oceno vpliva na okolje in dokazuje, da je vključitev vseh življenjskih obdobij v oceno vplivov ključnega pomena. Visoka okoljska škoda določenega scenarija na stopnji trajnostnosti materialov ni povezana s škodo na stopnjah trajnostnosti vzdrževanja in energetske učinkovitosti, na primer, nek material lahko okolje močno degradira zaradi toksinov povezanih z njegovo proizvodnjo, vendar pa je veliko bolj vzdržljiv od ostalih in vpliva na manjšo porabo energije sistema ter tako predstavlja najmanjše breme za okolje. Načinov za izboljšanje prakse na področju materialov ter vzdrževanja ravnih streh je precej, za njihovo učinkovito optimizacijo pa so potrebne celostne presoje vplivov, ki zajemajo vsa pomembna okoljska bremena povezana z določenim tipom gradnje.

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1 INTRODUCTION

Sustainability is based on intergenerational (Brundtland Commission, 1987) and intraspecial ethics, meaning that the development needs of the future generations and any other living species should not be compromised. During a long course of evolutionary history human race outdid the others. A short insight into a natural system shows that, unlike the human system, this system is still backward oriented, thus meaning that the current state is nothing but a consequence of past events. The human system on the other hand is future oriented. Current state of it is dependent on future development. Therefore, the notion of global responsibility to employ practices which are prosperous in the long term should be respected universally.

Buildings account for more than 40 % of EU's final energy consumption during operational phase (Energy Performance of Buildings Directive, 2002) and for 30% of all Western Europe's waste (Europe's environment: The Third Assessment, 2003) due to construction and demolition. If the energy consumption and waste generation continue rising according to the current trend, quality of environment will continue to deteriorate thereby increasing the affiliated economical, health, safety and environmental threats. Particularly, ensuring the sustainability in the building sector will greatly influence future generations, since the average life span of a building stretches further than human life expectancy. Thus, environmental design, construction and management practices are needed in advance to ensure the long term sustainability of buildings. The responsibility to fulfil the environmental sustainability criteria in building sector is shared by various parties such as architects, material engineers, civil engineers, maintenance workers and last, but not least, the home owners and/or occupants. This might be a difficulty, because of the shared responsibility when it comes to environmental impact, but it also illustrates the numerous opportunities for improvement of environmental performance of that sector, such as eco-friendly of design, material choice, maintenance management, influencing occupant behaviour and many more.

Lately, national legislation has been improved in most EU member states, as a consequence of Energy Performance Building Directive (EPBD) implementation. Furthermore, the building sustainability labelling tools such as Leadership in Energy and Environmental Design (LEED), developed by US Green Building Council (Green Building Rating System, 2004) or Building Research Establishment Environmental Assessment Method (BREEAM), developed by UK communities and local government (The Code for Sustainable Homes, 2008) and other nationally developed instruments are widely popular in promoting greater market success of sustainable housing. However, the setback of the EPBD is that it currently focuses only on energy performance, which can be in many ways distant from environmental performance. Similarly, the labelling tools employ checklists to assess how sustainable a building is, which is easy, fast and inexpensive to use, but might on the other hand as well be unfair and superficial in addressing all environmental issues equally. The tools developed to ensure environmentally better practices are welcome, but are mostly rather voluntary than binding.

Until necessary transparent and objective data on building sustainability is available, improvements in environmental profiles are hard to achieve. Therefore, this research was striving to present overall environmental impact using life cycle analysis. The emphasis was on the importance of use phase, which represents a poorly researched area. Unlike in the other, smaller products, it was assumed that the burden of the use phase of the building is significant due to their longer life span and complex structure. Environmental burdens of activities, which occur in the use phase, are usually included neither in the labelling checklists nor energy certificates. This study strived to connect the burden caused by the product including the burden of its use (maintenance) and the energy performance.

A research hypothesis was formed, stating:

A comprehensive environmental assessment of a building element, such as roof, should besides the assembly damage encompass all the maintenance activities that occur during the building life and the influence of the material choice on the energy consumption of the building, since they all represent a significant environmental burden. As such all the aspects (assembly, maintenance and energy) have potential for improving the sustainability.

Hence, the research problem was to present a holistic environmental assessment of the roof, encompassing the environmental load of all the activities taking place from the material extraction all the way to demolition, including the environmental load which occurs in the use phase together with the influence on energy use and by that verifying or rejecting the research hypothesis. Due to growing attractiveness in the building sustainability research it was decided to use the life cycle analysis (LCA), sometimes referred to as the “cradle to grave” approach.

Since it was believed the impact of material choice effects environment more complexly than merely by the direct damage caused by materials, three sustainability profiles were undertaken, each of them at a higher level and subsequently more outright. Initially, the direct material damage was examined at the level, named assembly sustainability. However, an insight provided with the environmental impact of assembly is not a complete one, since the choice of materials used in assembly relates to other building characteristics during the building life. A certain roof type can for example, enable the building to save more energy due to better insulation but at the same time cause more maintenance-related environmental load. Therefore, research incorporated for the assembly-related maintenance damage in the second level assessment. The third, but nevertheless important indirect influence of assembly on the roof sustainability profile is the energy consumption.

This three stage impact assessment provided a thorough analysis of a flat roof system and will thereby, offer answers to the following practical questions: What are best material choices? Does maintenance represent a significant burden on the environment? What about energy efficiency? Are there possibilities for improvement? If yes, what kind? All these issues are discussed observing the results and lead to verification or rejection of the research hypothesis:

In this diploma work, first an overview of the theoretical background is given (chapter 2). In the second part of the chapter, materials examined are described together with their most characteristic features (particularly on environmental issues and production). In the Practical section, chapter 3, the techniques of obtaining the results are described. Based on comparative environmental impact analysis in chapter 3.2, roof scenarios are formed in the following chapter, 3.3. In chapter 4 results are presented and discussed on all three mentioned levels, answering the practical questions set in the introduction. In the Conclusions the findings are linked to the research hypothesis addressed in the introduction.

This diploma work represents a partial analysis of the life cycle assessment of the whole building for maintenance company Bouwteam P&O, which was undertaken by OTB Research Institute for Housing, Urban and Mobility Studies, where I held an internship position. The report of assessment of whole building is expected to be ready in September 2009. The results presented here will also shortly be published (article was already accepted) in Dutch TVVL Magazine, which is a journal issued by the Dutch technical association for building services. The paper is in Dutch with the original title *“Daken met PV-cellen, groen of traditioneel? Een LCA van platte daken.”*, meaning *“Roofs with PV cells, green or traditional? A LCA of flat roofs.”* The authors are (besides me) also dr. Ad Straub and dr. Laure Itard.

The assumptions of materials and maintenance activities in this diploma work were decided upon with a consensus of other researchers at OTB and employees of Bouwteam P&O, but the results, discussions and conclusions presented are, however, my own findings.

2 THEORY

2.1 Building sustainability – state of the art

2.1.1 Building sustainability in European legislation

The residential and tertiary sector, the major part of which is buildings, accounts for more than 40 % of final energy consumption and is currently still rising. Such trend imposes a threat to the quality of environment, depletion of natural resources and the increasing problem of global warming. The EPBD (Energy Performance of Buildings Directive, 2002) of the European Parliament and Council on energy efficiency of buildings is considered a very important legislative component of energy efficiency activities of the European Union designed to meet the Kyoto commitment. Directive suggests member states to take the necessary measures to ensure that new buildings (total useful floor area over 1000 m^2) meet the minimum energy performance requirements thorough systems such as decentralized energy supply systems based on renewable energy, district or block heating or cooling, heat pumps etc. When buildings undergo major renovation, their energy performance is upgraded in order to meet minimum requirements. When buildings are constructed, sold or rented out, an energy performance certificate is made available to the owner or by the owner to the prospective buyer or tenant, as the case might be. The validity of the certificate shall not exceed 10 years. Regular inspections of boilers should also be carried out in all the member states.

The European Commission stated in the publication Towards a European Strategy for Energy Supply that with successful implementation of the EPBD directive EU will save around 100 million tones of carbon dioxide per year, which equates to a reduction of around 22 percent. By now, even thought with a delay, all the 27 member states declare full transposition. For further developments, research on building sustainability and the search of alternative technologies and their overall environmental load is of crucial importance.

However, a research carried out in Denmark and Belgium (Gram-Hanssen et al., 2006) has shown that energy certificates and labelling (as mentioned in the introduction) do not *per se* ensure more rational behaviour of people, even though they are provided with a proof and guidelines of what the energy efficiency of the house is and how to improve automatically when they buy a new dwelling. Research suggests that there should be other inputs to increase people's knowledge besides energy label and this diploma work strives to make a contribution on that by providing scientifically based transparent results on roof sustainability.

2.1.2 Methods used in assessing building sustainability

Apart from legal instruments, there is a broad range of commercial tools available for building assessment. The concepts of sustainable design and high performance buildings, as well as the increasing adoption of these concepts in the marketplace during the 1990s, have been furthered by the development of assessment tools (Todd, 2001). Initially these tools were conceived and still function as voluntary, market place mechanisms to enable home owners who undertook the effort to improve building sustainability to be more competitive (Cole, 2005). The expectation is that the widespread adoption of assessment tools would eventually lead to market transformation by increasing demand for sustainable housing. However, sustainability is being emphasized more and more, and the tools have to evolve in order to become more precise and rigorous.

Some of the tools developed internationally are presented in the Table 7 in Appendix A, where their application, criteria and results characteristics are shown. However, below there are three most common deficiencies of most of the tools, which are at the same time representing the motive for not using these tools in the present diploma work:

- Criteria are limited to certain issues to make an assessment simple and cheap. However, in a scientific context such cut-off is not desirable. All the environmental issues should be taken into account.

- Weighing is present in all the tools. Weighing environmental impact to one single score can be very subjective and dangerous; in scientific context one environmental issue should not be given advantage over another. The problem of reliability of categorization persists in this study as well and will be addressed later on.

- Commercial tools are qualitative - based on comparison with other buildings or design alternatives (for example use of alternative insulation vs. the current insulation).

Since commercial tools proved to be inappropriate for application in this research, Life Cycle Assessment (LCA) was used. This method studies environmental load of product systems (goods and services) from cradle to grave, including extraction of raw materials, production of materials, product parts and products, and discarding them by recycling, reuse, or final disposal (ISO 14040). The product system is the total system of processes needed for the product, which in this case is a flat roof. Inputs and outputs are materials and energy, which enter and leave the product system.

2.1.3 Life cycle assessment

Life cycle assessment (LCA) is a technique, developed in the sector of food industry in the 60s and gaining popularity as environmental assessment tool ever since. The standard for LCA has been issued by the International Organization for Standardization (ISO) with the goal of enhancing environmental protection awareness (ISO 14040). According to the standard, LCA studies environmental impacts throughout a life of a product from raw material acquisition through production, use and disposal. It is an environmental analysis of a product that includes the following four phases, all of them are also present in this diploma work. The more standards followed to elaborate the method more precisely and this overview is a short summary of those standards (ISO 14040, ISO 14041, ISO 14042 and ISO 14043).

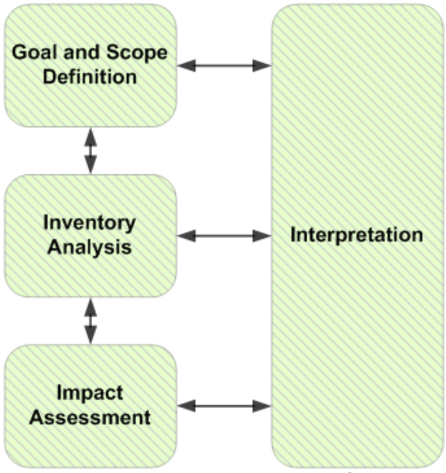


Figure 1: *Phases of LCA*

The purpose of LCA is to evaluate the full range of environmental and social damages assignable to products and services, to be able to choose the least burdensome one. It gives us the chance to compare the environmental performance of a range of products and to improve the design flaws that impact the environmental quality significantly. An LCA defines and quantifies the service provided by a product, quantifies the environmental exchanges caused by the way in which that service is provided, and ascribes the potential impacts of those exchanges to the service. Any recycling or recovery for example, leads to a proportionate reduction in the adverse environmental impact. The scope of an LCA study should clearly specify the functions of a system which is studied. The functional unit is a measure of the performance of the functional outputs of the products system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related, which ensures comparability of LCA results. Furthermore, system boundaries have to be determined according to the intended application of the study, the assumptions made, data and cost constraints and the intended audience. Also data quality requirements are set, specifying precision, consistency, sources of data as well as geographical and time coverage. Next step is inventory analysis in which data is collected and calculated to quantify relevant inputs and outputs of a product system. In the last, impact assessment phase, significance of potential environmental results is evaluated based on results from inventory analysis.

How exactly this is done – which methods are used and which impacts viewed, depends greatly upon the first two stages in LCA – goal and scope definition. This phase might include:

A. classification (assigning inventory data to impact categories[4])
B. characterization (we get the relative contribution to the impact category indicator result)
C. weighing (aggregating results to few impacts, which only happens in very specific cases where it makes sense)

[4] The impact categories (ICs) represent environmental issues of concern to which LCA results may be assigned. The ICs selected in each LCA study have to describe the impacts caused by the products being considered or the product system being analysed. Selected ICs should be the ones where international consensus has been reached and should not be too many (Haes et al., 1999). Characterisation methods must be defined for each category (Table 3).

From the above, given that there is sufficient data available on the various phases of any given product, process or service, it should be possible to define the LCA fairly precisely for a given location (circumstances that are changed with change of location might also influence LCA – climate, resources, relief etc.). However, LCA is primarily intended for comparing the life cycles of alternative processes designed to achieve similar objectives in order to discover which of them is the most environmentally sound. In general, if a comparative system is to have any credibility, the product ideally must use some sort of numerical score, therefore characterization is necessary. This has been the approach adopted by all LCA's, also in this diploma work. The final assessment scores are used to make judgments about the environmental acceptability of competing processes. For energy, water and resource consumption, scoring is a fairly straightforward exercise, but allocating numerical values to pollutant effects is far from straightforward.

2.1.4 Use of LCA in building industry

Application of LCA on whole buildings or element entities (such as roof) is not as straightforward as LCA of smaller appliances (Klunder and Van Nunen, 2003). A characteristic of building is, that is has a large number of unique components unlike, for example, electronics which are mass produced.

The other difficulties are caused by the long life span. The long life span means the necessity for renovation of different components at various frequencies and time components is not a defined dimension in LCA. In this diploma work, however, LCA was adapted through modelling to incorporate the time dimension and to include the impact of use phase throughout the life span.

As difficult as it is to predict the maintenance strategy for the while life span, forecast of the end-of-life stage is also a tough task, stage since it is in the distant future. Through time technology evolves which is also reflected in the practices employed. Based on this, static and dynamic approaches are defined by Klunder and Van Nunen (2003). The dynamic approach takes into account all innovations, changes and trends, whereas the static one extrapolates from current situation. Life Cycle Assessment is a static method that sums up all environmental effects during the life cycle of the product However, the behaviour of buildings is dynamic. As the development of a dynamic LCA method was far beyond the scope of this diploma work, static approach was used and the current practices were extrapolated throughout the life span.

2.1.5 Studies of building sustainability through LCA

In the building research community, LCA is generally accepted as a legitimate basis for comparing building materials, components, elements, services, and entire buildings. Several LCA tools were developed in the past decade to assess buildings, due to the fact that buildings are much more complex than the simple goods for which the LCA method was primarily developed (mentioned in chapter 2.1.4). Each building has its own characteristics and contains a very large number of components. Unlike simple goods such as a cup or even a computer, buildings have a long life span and during this period produce environmental effects that may represent a substantial part of their total environmental burden. Some of the studies, each of them tackling this difficulty differently, are presented below.

LCA is used as a tool in assessment of buildings with various functions. Kofoworola et al. (2008) analysed an office building, whereas Blanchard et al. (1998) made an assessment of a residential home. The first one took into account material assembly and the energy use during operation, but as a one time score at the end of life. Maintenance activities are not taken into account, as in most other studies. A deficiency is also that the results are presented only on three environmental impact categories which are claimed to be 'relevant for Thailand'. Such selection is subjective and interpreting results based on only three categories might be very misleading. Blanchard et al. (1998) on the other hand, presented the results in terms of life cycle energy[5] cost and global warming potential. It is not surprising that the results were almost parallel, since the materials with higher energy cost will intensify global warming. This shows that in construction industry the most greenhouse effect is caused by energy consumption, other greenhouse gasses related to construction are negligible. The study also establishes that by making incremental design changes that reduce the embodied and use-phase energy consumption, the total life cycle energy can be reduced by a factor 2.8, which is extremely high and proves the potential for great sustainability improvement of building sector. However, none of these researches enabled observation of environmental damage throughout the life of the building.

A life cycle energy research was conducted by Treloar et al. (2000), translating the impacts of building elements (walls, roofs, substructures etc.) into energy cost. Nevertheless, a sustainability assessment should encompass other aspects rather than energy, since environmental degradation is also caused by activities, other than energy generation and also depends greatly on the type of the energy used.

Itard and Klunder (2007) used LCA to compare different construction activities. The study proves the transformation of residential buildings to be environmentally better than demolition and new construction. The research emphasises the importance of time dimension in building sustainability assessment and claims that the results have to be disaggregated as the functions of time, which is important since the present diploma work also deals with a similar issue. The research hypothesis in introductory chapter stresses the importance of the use phase of the building and observing the environmental impact throughout the use phase requires the inclusion of time dimension.

Kosareo and Ries (2007) on the on the other hand used LCA to compare three types of roofs, two variations of green roof and conventional ballasted roof, but without incorporating the use phase activities.

2.1.6 Uncertainties in LCA

Strictly, uncertainty arises due to lack of knowledge about the true value of a quantity. The reliability of life cycle assessment (LCA) is affected by dependence on data from different countries, different unit operations, different sources, data that is frequently not collected for LCA purposes, and more or less subjective methodological choices (Bjorklund, 2002). LCA results are usually presented as point estimates, which strongly

[5] Such research method is a variation of life cycle analysis, called life cycle energy analysis (LCEA) and is characterised by assigning energy values to product flows.

overestimate the reliability. This may mislead public perception about the environmental profile of a product or process. The recent ISO standard recommends the use of methods for quantifying the reliability (ISO 14040, 1998), but gives little practical guidance. All the possible sources of uncertainties are gathered in Table 1. Classification and characterization inaccuracies are joined together in this table, because they all originate from method inaccuracy. It is also important to realize that inaccuracies in inventory stage can propagate through classification and characterization.

Table 1: *Different types of uncertainty in LCA and examples of possible sources (Bjorklund, 2002)*

Type	**LCA phase**		
	Goal and scope	**Inventory**	**Classification and characterization**
Data inaccuracy		Inaccurate emission measurements	Inaccuracy of chosen method - inaccurate relative contribution to impacts, uncertainty in life times of substances
Data gaps		Lack of inventory data	Lack of impact data, unknown relations between processes (such as synergistic effects of chemicals)
Unrepresentative data		Lack of representative inventory data	
Model uncertainty		Static instead of dynamic modeling: Linear instead of non-linear modeling	Static instead of dynamic modeling: Linear instead of non-linear modeling
Uncertainty due to choices	Choice of functional unit, system boundaries	Choice of allocation methods, technology level, average data	Choice of classification and later, if used, characterization method
Spatial variability		Regional differences in emission inventories	Regional differences in environment sensitivity
Temporal variability		Differences in yearly emission inventories	Choice of time horizon, changes in environmental characteristics over time
Variability between objects/sources		Differences in performance between equivalent processes	Differences in environmental and human characteristics

Different types of uncertainty appearing in LCA as described by Bjorklund (2002) and Krozer (1998) models can occur:

Data inaccuracy: Data inaccuracy concerns the empirical accuracy of measurements that are used to derive the numerical parameter values. Measurements can be subject to random error, which results from imperfections in the measuring instrument, observational techniques, or systematic error.

Data gaps: Missing parameter values may leave the model with data gaps.

Unrepresentative data: Data gaps may be avoided by using unrepresentative data, typically data from similar processes, but of unrepresentative age, geographical origin, or technical performance.

Model uncertainty: Model uncertainty is due to simplifications of aspects that cannot be modeled within the LCA structure (temporal and spatial characteristics lost by aggregation).

Uncertainty due to choices: There is often not one single correct choice, which results in uncertainty in choice, for instance, of allocation rules, functional unit, system boundaries, characterization method etc.

Spatial variability: There are natural variations between different geographical sites, but environmental interventions are usually summed up in the impact assessment, regardless of the spatial context (for example background concentration).

Temporal variability: Variations over time are relevant in both the inventory and impact assessment, as processes and factors in the receiving environment vary naturally over short and long time scales. Examples are process emissions, wind speed, and temperature. Another aspect is the chosen time horizon to integrate potential effects, which, for instance, applies to global warming potentials, photochemical ozone creation potentials, and emissions from landfills.

Variability between sources and objects: Variability also appears between sources of the inventoried system (e.g. inherent variations in comparable technical processes), objects that determine the impact on the environment (e.g. human characteristics such as body weight or sensitivity to toxic substances), and preferences that determine the weighting of impacts.

In the Table 1 it can be observed in which stages of LCA the mentioned sources of errors propagate.

Classification and characterization are a source of methodology – related errors. In fact, the main problems faced during life cycle impact assessment (LCIA) result from the need to connect the right burdens with the right impacts at the correct time and place. Many difficulties on environmental impact category definition in LCA spring from a lack of current standardization in several impact categories (Reap, 2007). Consequently, different organizations tend to propose different impact category lists. It has been observed that some impact categories such as land use, habitat alteration, impacts on biodiversity, nontoxicological human impacts, and impacts in work environment typically escape consideration, which is a significant problem. The quality of results also depends on selecting midpoint or endpoint (damage) impact categories. Endpoint categories are less comprehensive and have much higher levels of uncertainty than the betterdefined midpoint categories. Midpoint categories, on the other hand, are harder to interpret because they do not deal directly with an endpoint associated with an area of protection that may be more relevant for decision making, especially in policy.

Notwithstanding all these uncertainties, the LCA method is currently the most spread method to produce qualitative assessment results. In the building research community, LCA is generally accepted as a legitimate basis for comparing building materials, components, elements, services, and entire buildings (Cole et al., 2000, Cole et al., 2005 and Howard, 2005)

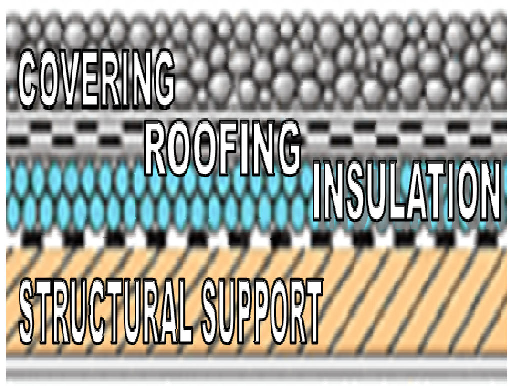
2.2 Overview of properties of the materials assessed – inventory analysis

As mentioned in Chapter 2.1.3, inventory analysis is an essential part of LCA. All the significant material options used in a flat roof will be described in this chapter.

Based on the layered structure, a common flat roof has three components differentiated by their function. Only in the component 'covering layer', the green roof and PV cells do not have an exact function of a covering, but they are physically a part of the covering. They will be for that reason described separately later on. The selection was made after an extensive research on roof types and materials. The choices were presumed for a flat roof, since both reference buildings have a flat roof, but can be extrapolated to any roof which could be using these materials.

Based on the environmental performances and maintenance activities of materials presented in this section and also on the combinations commonly used by roof producers, scenarios were formed in the second part of this section.

Table 2: *Description of components*

Component	Alternatives for each component	Layers in a roof
Covering layer	Reflective coating Gravel Concrete Green roof PV cell	
Roofing type	Bitumen + Bitumen felt EPDM + Adhesive PVC + Adhesive	
Insulation	Polystyrene Polyurethane rigid foam Polyurethane flexible foam Glass wool Wool (sheep)	

The characteristics of the materials will be presented in the same order as in the Table 2, from roof top towards the bottom. All data in this chapter is gathered from three construction handbooks (Kilbert, 2005; Merritt et al., 2000; Miller et al., 2004; and Chudley et al. 2006), unless it is stated otherwise in the text.

2.2.1 Covering layer

An important property of roofs is their reflectivity. Roofing system that has high solar reflectance[6] and high thermal emittance[7] (cool roof) has many advantages comparing to other roofs. Firstly, sun radiation can damage the roofing surface which decreases life span of the roof. Roofs with high solar reflectance reduce both building cooling loads and the urban heat island effect[8]. Achieving high solar reflectance in roofs can also help tackle global warming based on the principle of solar radiation management, provided that the materials used reflect more solar energy instead of absorbing it and causing the temperature of the body to rise. The phenomena is similar than the reflective effect of arctic ice. When the ice will melt, earth will have a lower albedo[9] and will warm up even more as a consequence. The reflectivity of roofs depends on the surfacing material and colour. Reflective coating is one of the solutions for increasing the reflectivity. Only recently, life cycle analysis of green roofs has shown that these roofs also decrease environmental damage due to lower absorption of solar radiation and lower thermal conductance (Saiz, 2006; Kosareo and Ries 2007). Besides green roofs also ballasted roofs were also recently proven to decrease the cooling demand (Desjarlais et al., 2007).

Reflective coating is usually based on polyurethane, it is bright white colour, ensures solar reflectivity of at least 0.7 and thermal emittance 0.75 or higher. It is applied in 2 – 5 layers; each of them has to be dry before the application of the next. For the needs of research, average of 4 layers was assumed. The energy benefit of this white coating was never quantified in climate conditions of The Netherlands, but it would depend a lot on the extent of usage of air conditioning. In the cases where air conditioning is necessary – dark roofs cause increase of global warming by two pathways – firstly, by reflecting less radiation back into space, and secondly – because of energy consumed for air conditioning devices. However, sources claim it also depends on the age and cleanliness of coating (Saiz, 2006; Kosareo and Ries, 2007). If used together with PV cells, reflective coating decreases the surrounding temperature, thus enabling the PV cells to perform more efficiently. Therefore reflective coating was later on combined with PV cells.

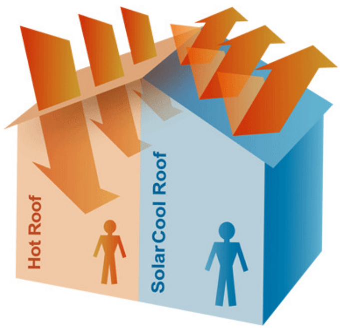


***Figure 2**: Impact of roof solar reflectivity on the indoor temperature*

[6] Solar reflectance - The ability to reflect the visible, infrared and ultraviolet wavelengths of the sun, reducing heat transfer to the building.
[7] Thermal emittance - The ability to release a large percentage of absorbed solar energy.
[8] Heat island effect is a phenomena, where built areas are hotter than the sourroundings. The annual mean air temperature of a city with 1 million people or more can be 1–3°C warmer than nearby rural areas, In the evening, the difference can be as high as 12°C. Heat islands can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water quality (US EPA definition).
[9] Albedo is defined as the ratio of diffusely reflected to incident electromagnetic radiation. It is a unitless measure ranging from 0 (dark) to 1 (bright).


Figure 3: *Applying reflective coating on the roof*

Roofing ballast can be used to protect against radiation from the sun to prolong the life of the roof. Many roofs are ballasted or anchored by a layer of concrete paving blocks. Others are mechanically attached to a substrate or deck using screws and reinforcement plates. A third option is the "fully adhered" roof which is completely glued to the roof substrate.

Ballast stones (gravel) come in different sizes, usually between 1.9 and 3.81 cm in diameter. Other configuration of ballast, also commonly used is concrete pavers. Ballast is applied in loadings from the minimum of 45 kg/m^2 to over 115 kg/m^2. Only recent research has shown that ballasted roofs have a cooling effect very similar to reflective coated or green roof described in previous chapter (Desjarlais et al., 2007), but no specific data about energy benefit which would occur in the Dutch oceanic climate could be found. Consequently, energy benefit was not calculated for gravel ballast, but it would most likely be negligible.


Figure 4: *Gravel ballasted flat roof*

Green roofs are vegetated layers on top of the conventional roof surfaces of a building. Usually a distinction is made between extensive and intensive. These terms refer to the degree of maintenance the roofs require. Intensive green roofs are composed of relatively deep substrates and can therefore support a wide range of plant types: trees and shrubs as well as perennials, grasses and annuals. As a result they are generally heavy and require specific support from the building and cannot be installed in any building. For this reason in this research environmental profile of extensive green roofs is assessed. They are composed of lightweight layers of free-draining material that support low-growing, tough drought-resistant vegetation. Generally the depth of growing medium is from a few centimetres up to a maximum of around 10 cm (The Green Roof Centre…, 2009). According to International Green Roof Association Global Networking for Green Roofs most widely used plant in climatic regions similar to Netherlands (north Germany, UK) is Sedum. Sedum plants were proved most resistant to drought, cold and heat also in research conducted in Michigan State University (Green Roof Research Program…, 2009). Besides energy benefits (better thermal insulation, heat shield and decreased urban heat island effect) green roofs have other benefits, though it might be hard to quantify them. Green roofs represent a habitat for many species, so they increase biodiversity. They help reduce water run-off, because the water if drained off with a temporal delay, thus they prevent local flooding. Plant growing on the roof reduce air pollution, especially pollutants present in smog. One square meter of green roof can filter approximately 0.2 kg aerosol dust and smog particles per year. Green roofs reduce noise levels by decreasing sound reflection for 3 dB.

Figure 5: *Extensive green roof*

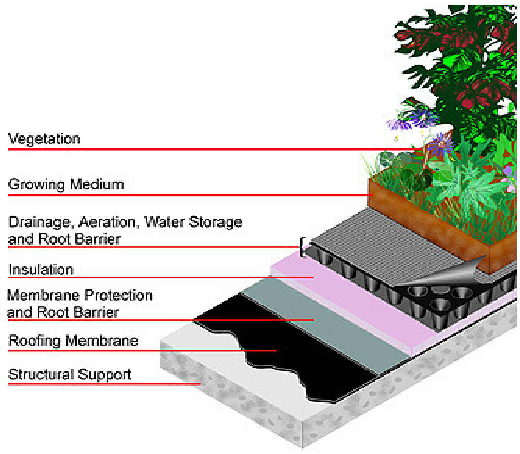


Figure 6: *Components of a green roof*

Gaining popularity, *PV cells* are devices that convert solar energy into electricity by the photovoltaic effect. Photovoltaics (PV) is the field of technology and research related to the application of solar cells. These generate power by converting sunlight directly into electricity due to a difference in the electrical properties in the layers of silicon (Grey, 2003). LCA of photovoltaics has already a long history, but results vary a lot (Bankier et al., 2006). Processes included in Ecoinvent Database data for PV cells include quartz reduction, silicon purification, wafer, panel and laminate production, manufacturing of converter and mounting infrastructure, transports, wastes and 30 years of operation.

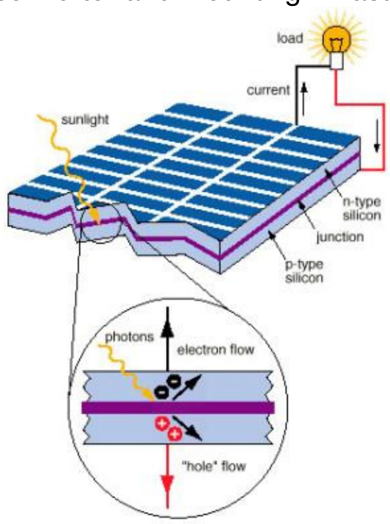


Figure 7:** A scheme of layers of a typical PV ce**ll

2.2.2 Roofing type

Roofing is an important part of roof, since it is the part of the roof which prevents water from leaking into the roof. This is even more difficult to achieve on the flat roofs, which is also why they are more likely to leak than pitched roofs. Materials, used for roofing have different properties (life span, emissions, waste treatment) and they affect the environment differently. The service life of a flat roof is dependent on many factors: geographical location and weather conditions, foot traffic, materials used, conditions under which the roof was installed, slope of roof, type of surfacing material, etc., but is with the modern technology never under 25 years.

The most common type of flat roof is the *bitumen built-up roof (BUR)*. It is made up of multiple layers of reinforcing plies and asphalt. Problem is that UV-rays oxidize the surface of the asphalt and produces a chalk-like residue, which can be solved with a surface coating. As plasticizers leach out of the asphalt, asphalt built up roofs become fragile. Cracking follows, allowing water to penetrate the system causing blisters, cracks and leaks. Compared to other systems, installation of asphalt roofs is energy-intensive (hot processes typically use natural gas as the heat source), and contributes to atmospheric air pollution (toxic, and green-house gases are lost from the asphalt during installation). However, due to a lack of quantitative data on this activity, we did not take this into account. Modified Bitumen roof systems consist of one, two, or three ply systems, among which those with more plies are more resistant and will last longer. For the purpose of the research a 4-ply bituminous roof was chosen.

To produce *Ethylene Propylene Diene Monomer roofing (EPDM)* Ethylene and propylene are copolymerized in an organic solvent or in the liquid phase of the monomer mixture itself, to produce EPM. If a small amount of a third monomer, ethylidene norbornene (ENB), is incorporated into the polymer chain during the polymerization reaction, EPDM, also known as "rubber" roofing results. EPDM is a widely used material besides roofing also in automotive industry, for cables and wires, as oil additive, for sealants, for footwear and rugs etc. The producers claim that the material is able to resist the mechanical and thermal forces of exposure on flat roofs very well. EPDM rubber roofing repels moisture and does not suffer with age from cracking or crazing, but it also allows vapours to escape, thus preventing blisters. Another benefit is that it does pollutes the runoff water less (Clark et al., 2008), which is of crucial if the house owner wishes to use this water for personal sanitation or hygiene.

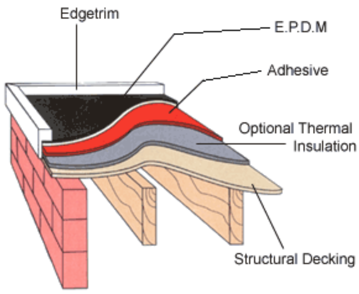


Figure 8: *EPDM roofing*

Polyvinyl chloride, commonly abbreviated PVC, is the third most widely used thermoplastic polymer after polyethylene and polypropylene. In terms of revenue generated, it is one of the most valuable products of the chemical industry. Around the world, over 50% of PVC manufactured is used in construction. It is produced by polymerization of the monomer vinyl chloride. Carcinogenity of vinyl chloride monomer to humans was proven as early as in the 70s and has been a cause of several controversies. It was established by Environmental Protection Agency (EPA) U.S. (Fact Sheet: Proposed Air Toxic Standards, 2000) that it does indeed cause liver cancer. On the other hand, it is true that given mass of PVC requires less petroleum than many other polymers, which decreases carbon footprint. There are, however, other concerns related to this material. First are the chemicals, mainly phthalates, added to change the chemical consistency of the product and can leach out of the product. There are also concerns about the creation of highly toxic polychlorinated dibenzo-dioxins when organic coatings are burned in an electric arc furnace during recycling. However, opinions of producers and dealers are exact opposite, such as of Vinyl Institute U.S. (Factsheets: The Energy and Environmental…, 2009). They claim that PVC roofing is environmentally friendly roofing choice and is claimed to have outstanding leak-free performance record and environmental safety. PVC membranes are also stated 99.5% recyclable, meaning there is only 1/2 of a percent waste in the recycling process, and the rest supposedly goes into production of new products.

2.2.3 Insulation

In cool climates like the Netherlands, one of the most important aspects of roofing is providing insulation to prevent heat loss in winter. Clearly this will reduce energy use and contribute to a building’s sustainability. Thermal insulation of buildings (external walls, roof and floor, double pane window) reduces annual energy consumption for space heating, by lowering heat losses through the building's envelope. Energy consumption in insulated buildings may be 20–40% less than in non-insulated buildings (Dzioubinski, 1999). Households consume about 20 per cent of the total energy used in the Netherlands; majority of it comes from natural gas. Considering that almost 80% of the natural gas in households is for space heating (Dzioubinski, 1999), investing in good insulation is a very reasonable choice.

Polystyrene is an aromatic polymer made from the aromatic monomer styrene, a liquid hydrocarbon that is commercially manufactured from petroleum by the chemical industry. Extruded polystyrene foam (XPS) has air inclusions which gives it moderate flexibility, a low density, and a low thermal conductivity. Polystyrene insulation comes in panels which do not require much energy to manufacture and they do not use formaldehyde, CFCs, or HCFCs in manufacturing. Because of its light weight (especially if foamed) and its low scrap value, polystyrene is not easily recycled. It is also not biodegradable, and since it floats on water and is blown around by the wind it became the main component of the sea debris found on shores. On the other hand, it causes no toxic emissions when incinerated (if the temperature is carefully managed).

Polyurethane is a polymer consisting of a chain of organic units joined by urethane links. Depending on the different diisocyanates and diol or polyol constituents, the resulting polyurethane might take a liquid, foam, or solid form. Depending on its density, it also has different functions. Low density rigid foam panels for example, are used for thermal insulation. They are often flammable and produce toxic fumes when they burn. Polyurethane foam (including foam rubber) is often made by adding small amounts of volatile materials, so-called blowing agents, to the reaction mixture. Since the Montreal Protocol banned the CFC's, they are no longer in use as blowing agents, but some manufacturers still use HCFCs.

Glass wool is a form of fibreglass. It consists of thin strands of glass that are arranged into a spongy texture. It is made of recycled glass, which is an advantage, but there was also research carried out to determine whether the material is carcinogenic. However, International Agency for Research on Cancer has stated that glass wool cannot be classified as carcinogenic to humans (IARC Monographs on the Evaluation…, 2002).

Performance of *stone wool* was not assessed separately because their environmental impacts are quite similar and so are the densities. Therefore, we can assume that stone wool insulation would perform similarly.

Wool, particularly *wool of sheep*, can be used as insulation as well. Since the development of synthetic materials natural wool has become and unwanted side product. Wool fibres are hygroscopic by nature and will have a moisture weight content of up to 35%, dependent on the relative humidity of the surroundings. While absorbing this moisture, wool releases energy in the form of heat, thus raising the temperature of its surrounding areas. Naturally releasing this moisture in the warmer seasons, wool creates a cooling effect on the same surroundings. The problems which might arise due to the constant moisture of the material were not researched, but might impose a threat. Wool is not irritating to the respiratory system or the skin like glass wool might be, because its fibres are more than 30 micrometers thick which is too big to be a health risk. When used in insulation wool is often treated with Borax to enhance its fire retardant and pest repellent qualities. They claim that Borax mining employs one of the cleanest mining techniques available and has low toxicity indicators as well (Sheep Wool Insulation Website, 2009).

3 PRACTICAL WORK

The LCA approach, described in the previous chapter, was the basis of this study. As a tool for the research, SimaPro 7.1 software, developed by a Dutch company PRé Consultants was used. With this software it is possible to collect, analyze and monitor the environmental performance of products and services. Complex life cycles can be monitored in a systematic and transparent way, following the ISO 14040 series recommendations.

3.1 Use of SimaPro software

SimaPro was first released in 1990, now it is used worldwide and considered a good tool for LCA. It is used for the assessment of products, processes and services. Since the program is designed according to ISO standard described in previous chapter, the steps of environmental assessment are the same: goal and scope definition, inventory analysis, impact analysis, interpretation (SimaPro 7 Tutorial, 2006).

3.1.1 Goal and scope

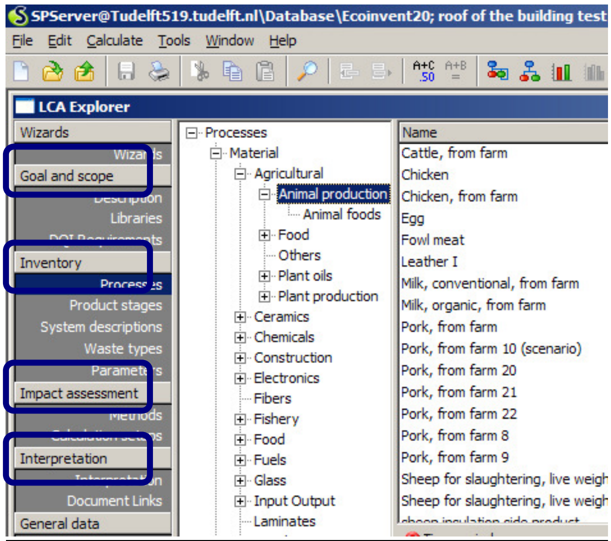


Figure 9: *SimaPro user interface organization following the ISO 14040 guidelines*

In the fist section "goal and scope" project goal, functional unit, and other details are described. Data Quality Indicators (DQIs) are set, specifying data time period, geography, representativeness and system boundaries. The ideal LCI data are the most current possible and are obtained from the same geographic area as the study, in this diploma work was mostly data for European average. In the section all inventory processes and product stages are defined. The system boundaries were defined as indicated on the left side of the Figure 2.

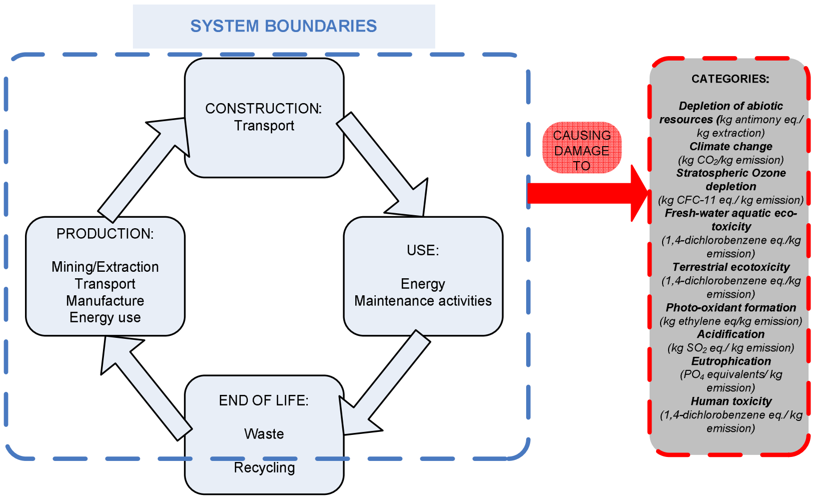


Figure 10: *System boundaries and impact categories*

Impact of recycling is intentionally left out, since recycling involves processing used materials into new products. It was assumed that the environmental damage which occurs due to the recycling processes damage should be affiliated to that product. Therefore, only incineration and landfilling were taken into account as waste treatments.

3.1.2 Inventory analysis

Data for many materials comes already with Ecoinvent Data v2.0 database, which was used in this study. It was developed by the Ecoinvent Centre, also known as the Swiss Centre for Life Cycle Inventorie (a joint initiative of several Swiss research institutes). Ecoinvent data v2.0 contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services (Ecoinvent Centre, 2009). The software also allows creating a new or modifying an existing material. For this diploma work, we usually needed processes from materials in folders “construction” and “chemicals”. Some of the processes for different insulations can be seen in Figure 11. All the materials described in the chapter 2.2 had to be defined. If available, unmodified Ecoinvent data was used and if not, the data was customized so all the process and production characteristics match the ones used in practice. A defined material comprises for all the processes needed for its manufacturing and all the substances that are either released (output) or used (input) through production. These substances are ultimately responsible for environmental degradation.

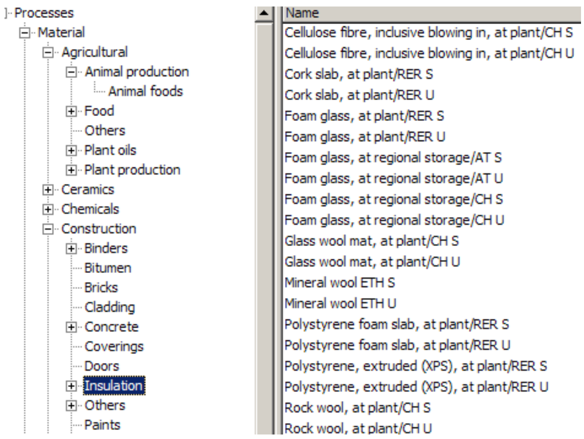


Figure 11: *Some processes for insulation available in EcoInvent database*

In the product stage assemblies are composed, of previously defined materials, also adding the waste treatment. The connections among the inputs from nature (resources), the end product and its life cycle can be observed in the Figure 12. In this study the product was flat roof, composed of three components with optional PV cells. Besides processes included in production of these roofing components, transport of the final product to the site was also included in the assembly sustainability separately. Transports included in the stages prior to manufacturing are already included in processes available in the database. Relationship among resource inputs and outputs to nature can be observed in the figure below. From material, whose processes were mainly already joint together in the Ecoinvent database we formed assemblies. Included in the processes are all inputs (resource extraction, indicated with grey arrows on the Figure 12) and outputs (emissions into the environment, indicated with black interrupted arrows).

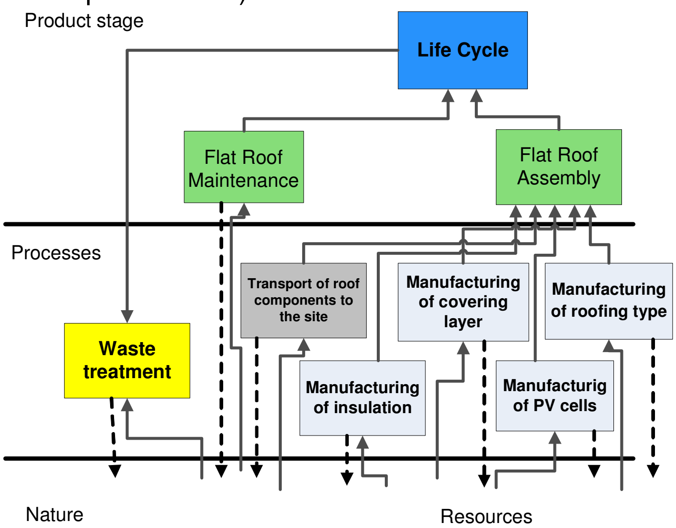


Figure 12: *Relationship among building blocks*

3.1.3 Interpretation and its reliability

The results SimaPro offers after analysing the inventory and composing the assembly can be presented in for of a network (also called “flow chart”), as the one presented in Figure 33, Appendix B. In that figure, the cut-off is limited to 2.5%, meaning that only the processes which contribute more than 2.5% total assembly are shown. If we would set cut-off criterion to 0, there would be more than 1900 processes visible. These processes are responsible for an output or input of some 600 substances, which effect different environmental categories differently. These 600 substances are the ones responsible for the environmental impact and have to be understood more easily. SimaPro contains a number of impact assessment methods, which are used to calculate impact assessment results. In 2001 a group of scientists at CML (Centre of Environmental Science of Leiden University) proposed a set of impact categories and characterization methods for the impact assessment. As said before, all the processes which occur during the life cycle of a flat roof are responsible for output or input of more than 600 substances. The impact of those substances is in the CML 2001 characterised into 9 impact categories using proper factor for each of those substances (Table 3). Hence, all of the approximately 600 substances related to the roof type in Figure 33 are multiplied with a characterisation factor that expresses the relative contribution of the substance to a specific category. For example, the characterisation factor for CO_2 in the impact category Climate change can be equal to 1, while the characterisation factor of methane can be 21. This means the release of 1 kg methane causes the same amount of climate change as 21 kg CO_2. The total result is expressed as impact category indicators. Impact categories, characteristics and characterisation factors used in this method are shown in Table 3 (SimaPro 7 Database Manual, 2008).

These are problems in selection of impact category method, their reliability and comparability, as pointed out in 2.1.6. Therefore a pre-defined method, CML 2001 was chosen in the present study, which was fast and simple faster and less costly. However, it must be noted and cautioned that depending on the methodology chosen and the impact categories of interest, the user may obtain qualitatively different results (Reap, 2007). Unfortunately, there is no existent research on accuracy of CML methodology.

The classification of environmental damage to categories with CML method varies from more precise to vague. On the top of this scale are the categories like global warming potential, ozone layer depletion and photochemical oxidation. For these categories, exact error intervals based on calculations with different parameters are defined. Category acidification is less precise. The acidification potential is based on number of protons, impact of which on ecosystems is not well known and is dependant on the actual ecosystem. In all the toxicity categories, classification is even more complex and these categories do not meet the ISO standards yet (Haes et al., 1999). The development of more complete databases may solve some of these data gaps, but toxicity impact categories are not expected to be greatly improved due to the large numbers of chemicals used by society and the potential synergistic effects between these chemicals (Finnveden 2000). Due to this reason and bad experience regarding the 10^{th} category (as defined by CML in Leiden), marine aquatic toxicity, was left out, due to incoherent results.

Table 3: *Impact categories in CML 2001 (SimaPro 7 Database Manual, 2008)*

Impact categories	Characteristics	Characterisation factor *(unit)*	Time *(Infinite if not stated other)* & Geographic Scope
Depletion of abiotic resources	Concerned with protection of human welfare, human health and ecosystem health. This impact category indicator is related to extraction of minerals and fossil fuels due to inputs in the system.	Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels *(kg antimony eq./kg extraction)* based on concentration reserves and rate of deaccumulation.	Global
Climate change	Adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air.	Developed by the Intergovernmental Panel on Climate Change (IPCC), factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in *kg CO_2/kg emission.*	Global
Stratospheric Ozone depletion	Ozone depletion causes a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related.	The characterization model is developed by the World Meteorological Organisation (WMO) and defines ozone depletion potential of different gasses *(kg CFC-11 eq./ kg emission).*	Global
Fresh-water aquatic eco-toxicity	This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.	Eco-toxicity potential (FAETP) is calculated with USES-LCA, describing fate, exposure and effects of toxic substances. Characterisation factors are expressed as *1,4-dichlorobenzene eq./kg emission.*	Global
Terrestrial ecotoxicity	This category refers to impacts of toxic substances on terrestrial ecosystems (see description fresh water toxicity).		
Photo-oxidant formation	Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with "summer smog". Winter smog is outside the scope of this category.	Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in *kg ethylene eq/kg emission.*	local and continental scale, time span is 5 days
Acidification	Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings).	Acidification Potentials (AP) for emissions to air are calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as *kg SO_2 eq./ kg emission.*	local and continental scale
Eutrophication	Includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. Fate and exposure is not included	Eutrophication potential (EP) is based on the stoichiometric procedure and expressed as *kg PO_4 equivalents/ kg emission.*	local and continental scale
Human toxicity	Effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included. The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale.	Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as *1,4-dichlorobenzene eq./ kg emission.*	

3.2 Comparing the environmental impact of different materials

To understand better which materials would be more sustainable, a partial LCA was made in each category of components, firstly of assemblies themselves and later on also the energy benefit and necessary maintenance activities. Energy benefit is important in the long term, since one component (especially insulation part) can be more harmful that alternatives if we only look at the assembly, but the decrease in energy consumption or the reduction of necessary maintenance activities might override these benefits in just a few years.

This part of research does not yet give answers to research problems. nonetheless it was helpful for two reasons:

- To get an insight of the component assembly itself and to help form scenarios logically (for example, to prevent from including the most damageable roofing type in the sustainable scenario).

- To find out which specific materials are the actual culprits for the high damage in some categories, one can never tell that only by observing the environmental damage of assembly, where the environmental burden of components is already summed.

The results are always presented on one graph only for more transparency. They cannot be compared among different impact categories, since they do not share the same unit. The graph is only illustrating how differently various materials influence a certain category. The importance of categories (their weight) is also subjective to assess and should therefore not be misinterpreted.

3.2.1 Covering layer

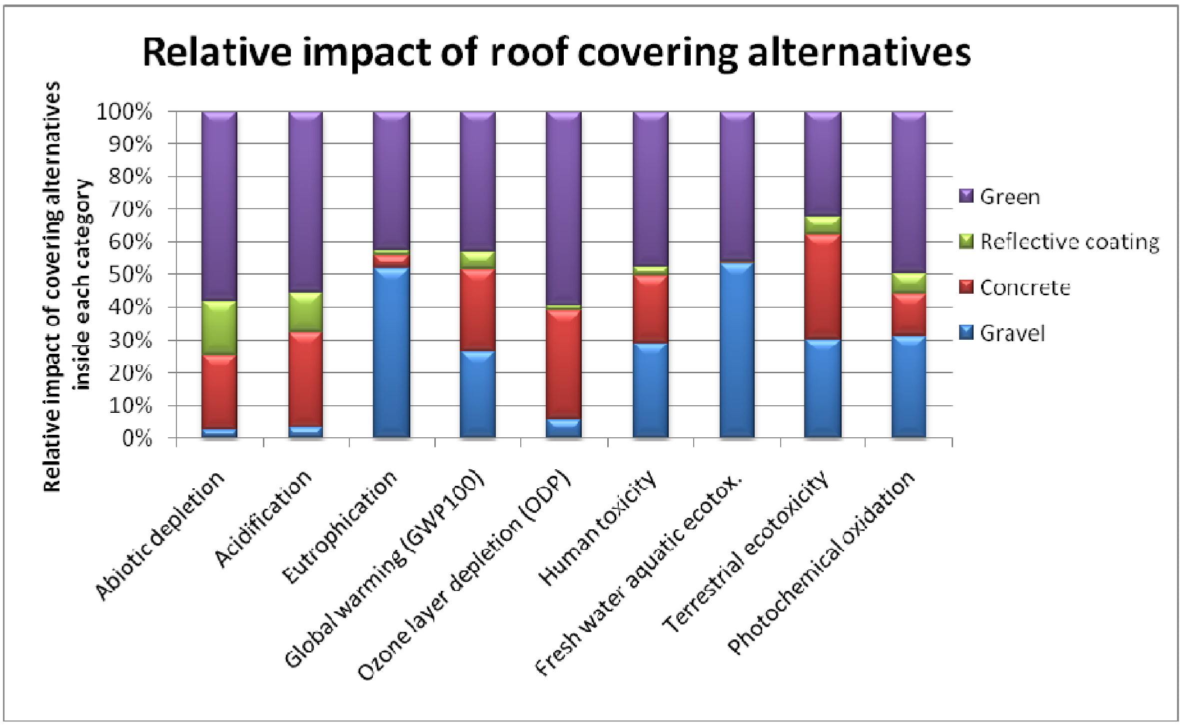


Figure 13: *Environmental impacts of different surfacing materials*

Green roof, as expected, does not perform very well in terms of these 10 impact categories. It has more constituent layers, therefore it weighs more. Its advantages are not in the assembly, but are connected to the service life of green roof and will be evident only on the long term. Some benefits will be obvious later on in the research. It is also evident from the figure that concrete and gravel perform, if we only look at the assembly, worse than reflective coating, which can be explained by the simple fact that reflective coating is applied to the roof in quantities 20 times less than concrete and around 30 times less than gravel (Table 3). It is subjective and very dangerous to say which material is the last preferable, since concrete is damageable in different environmental categories (abiotic depletion, acidification, ozone layer depletion) than gravel (eutrophication, fresh water aquatic ecotoxicity, photochemical oxidation). This is the first indication in this diploma work of the importance and care one should dedicate to the issue of weighing. Usually the environmental impact is never coherently influencing all the categories and the weight of the categories should never be judged, if a scientific analysis is to be carried out.

What is not visible from the graph is that concrete per unit of mass has approximately 10 times higher impact to every environmental category due to a larger number of different processes involved in its production. But since there is 5 times more gravel on the roof per unit surface, the impact of gravel prevails on this graph. An important advantage of concrete, which is not included in the assembly of concrete, is the fact that the concrete ballasted roof is less prone to damages since it can be walked on without fear of injuring the sensitive roofing.

3.2.2 Roofing type

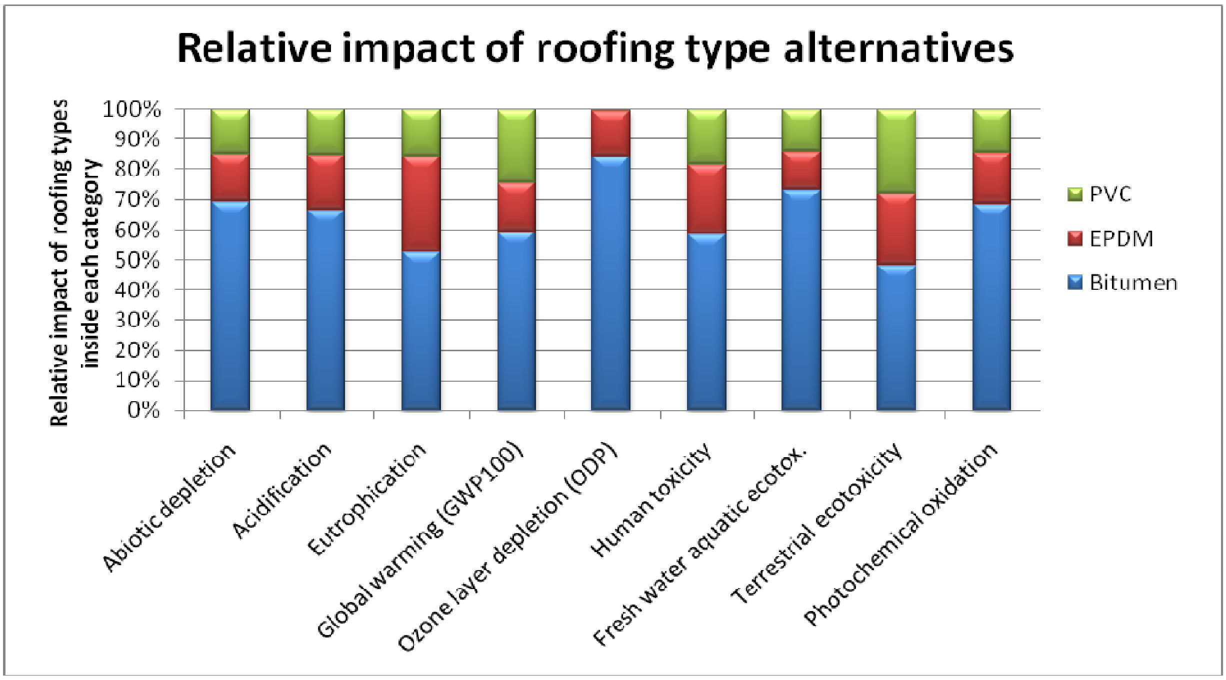


Figure 14: *Environmental impacts of different roofing materials*

As illustrated by the graph above, bitumen performs worse than other single ply roofing materials. Although less chemical processes requiring energy are involved in production, the weight necessary for bituminous roofing to have the desired properties is around 6 times more than in case of other, single ply materials. It is also true that bitumen is produced in process of crude oil fractional distillation as residual (bottom) fraction. This means that it represents a side product. However, it was not included in the inventory as a side product, since it might be a controversial idea (it is not certain if bitumen would still be extracted even if the world would depend on other energy resources and not crude oil). Still, in the land when the bitumen is initially mined large quantities of toxic chemicals which are a threat to acidification, euthrophication, fresh water and terrestrial ecotoxicity and possibly human toxicity are used. Eventually, most oil based products are burned which together with deforestation (also a consequence of mining) contributes to global warming, which is an immense disadvantage to bituminous roofing products over single ply synthetic ones.

3.2.3 Insulation

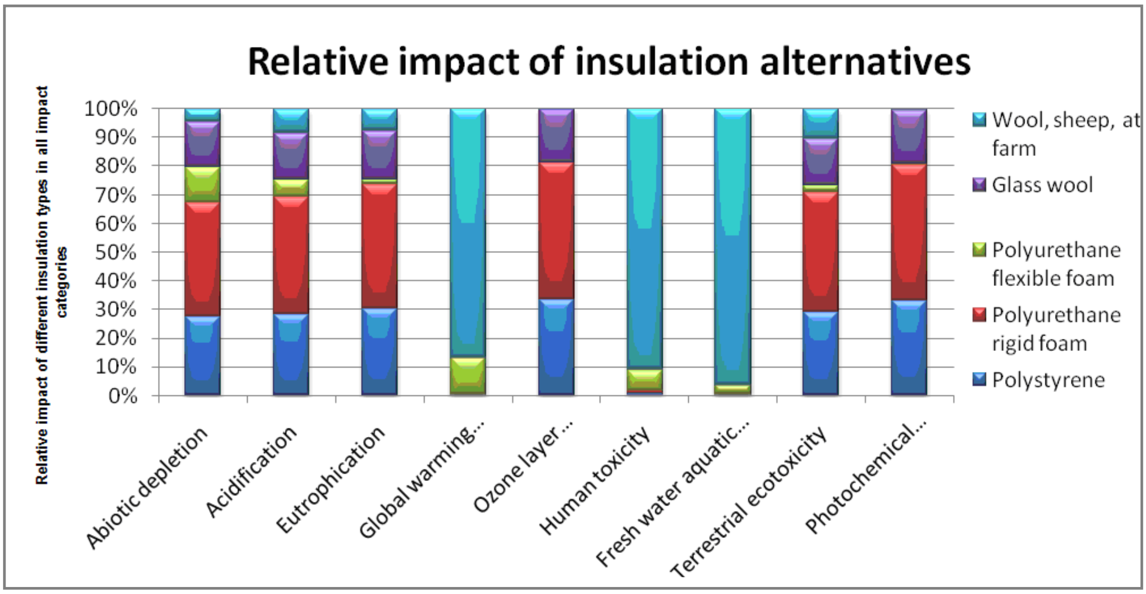


***Figure 15**: Environmental impacts of different insulations*

The impacts of the insulations are the most diverse. Sheep wool is usually a side product, which is incinerated or used as compost. With organized waste wool collecting the wool which is usually discarded would be taken advantage of. In that case only transport to production plant and energy needed for the assembly are processes causing environmental load, others are inevitable and contributed to other products (such as sheep meat for example). The assumption of energy used in this process is based on quantity of embodied energy data of sheep insulation (Sheep Wool Insulation Website, 2009). Assumed distance was 200 km to plant. The impact is especially detrimental in three categories, which are typically the ones which transport influences the most; these are global warming, human toxicity and fresh water toxicity.

In terms of ozone layer depletion polystyrene was expected to perform worse due to refrigerant 134a (tetrafluoroethane) used in its production. This is not observed on the graph, the reason might be that this substance has recently been a subject to restrictions due to its high global warming potential (Climate Change 2007 Synthesis Report…, 2007) and its composition might already be altered in the database.

Glass wool is the most toxic to terrestrial organisms because there is ammonia involved in its production. In case of abiotic depletion and acidification, methylene diphenyl, a component of polyurethane, is the element responsible for the most footprint and in case of photochemical oxidation polyols together with methylene diphenyle cause the impact.

To conclude, choice of environmentally friendliest insulation is difficult in this stage, since it is obvious that the advantage of certain insulation will only be obvious when we take into account energy use (further on in this diploma work).

3.2.4 PV cell

In order to give the reader of this report an idea about impact of PV cells assembly impact was compared with the benefit gained by energy generation in the upcoming years. It is true that efficiency of a PV cell in a residential building depends on the roof to volume ratio, meaning less in apartment blocks than in detached houses. However, it is proved later on, that it still is beneficial in an apartment block. Electricity generated on the roof could be used for appliances that are installed in the building for all the dwellers, for example for lighting in hallways, bike garages, intercoms, laundry etc. and the dwellers avoid one expense.

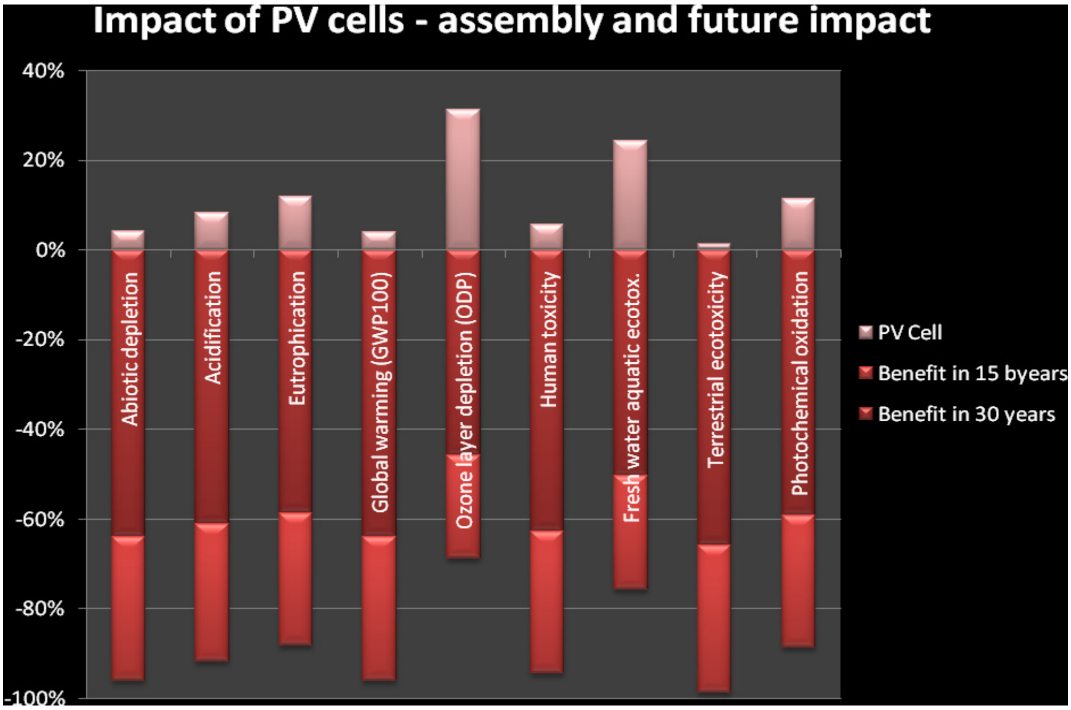


Figure 16: *Beneficial impact of PV cells in time*

3.2.5 Uncertainty on material level

As mentioned before (2.1.6), LCA data are full of uncertain numbers. These uncertainties can have different causes - uncertain measurements, or uncertainty about how representative a figure is can be called uncertainty of data. Data uncertainty calculations can be made in the SimaPro using Monte Carlo method. The statistical principle is simple. A calculation is repeated many times, each time a random value is chosen for each flow, for example an emission or raw material input. The resulting range of all calculation results form a distribution from which uncertainty information can be derived with basic statistical methods. The result of the uncertainty analysis for traditional roof is in the shown in Figure 21 below.

In the results there is always a level of uncertainty. Possible sources of uncertainties apart from data uncertainties were presented in Table 1.

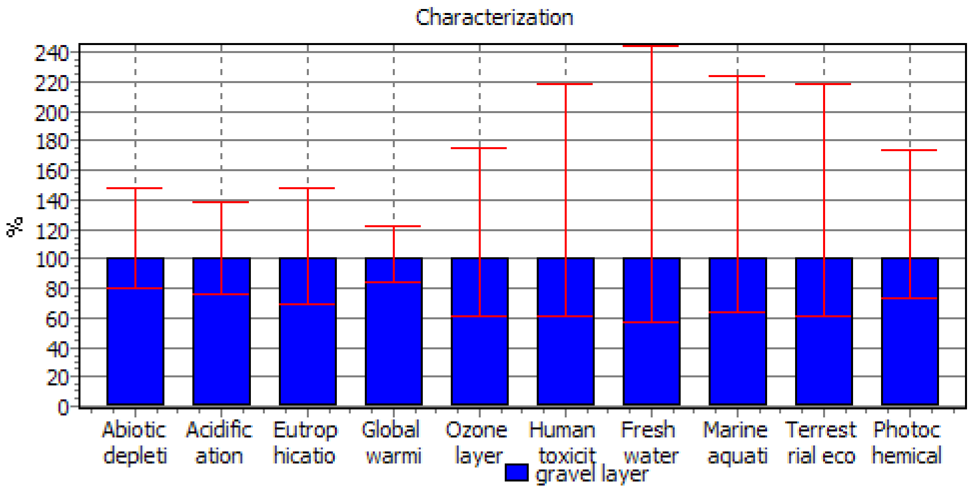


Figure 17: *Uncertainy of a single material – gravel at interval of confidence 95%, method is CML 2001*

Similarly, uncertainties for other materials could be presented. Since the study was a comparative analysis, and since even by incorporating the Monte Carlo analysis there would still be a lot of unquantified uncertainties, these will not be addressed in the figures presenting the results. Nevertheless, comments on reliability will follow.

3.3 Scenarios

Study was preformed through environmental assessments of different roof scenarios. A roof is an entity where materials are interdependent, and can therefore not be viewed separately one by one. Each material choice will depend on material choices of other roof layers. A building's roof scenario describes the material assembly of the whole roof. Assembly consists of material damage done at the location of manufacturing and the transport of the roof component to the site.

Maintenance activities necessary also depend on the assembly and therefore each scenario has its specific maintenance activities. Similarly is true for energy. Each roof scenario has its specific influence on energy use and will therefore influence environment differently.

Summing up, roof scenario provides the following information:

- Materials used (assembly) and their transport distances;
- Frequency and types of maintenance activities;
- Energy use of the building covered by such roof type.

The scenarios used in this study are based on studies of materials (chapter 3.2) and experiences of maintenance companies (Bouwteam P&O, The Netherlands). It is important to keep in mind, that the formulated scenarios were nothing but assumptions based on experience and logic and the assessment results that they provide are not 100% accurate and have a certain degree of uncertainty, which will be addressed later on. The results of the assessment are shown as the accumulated contributions to various environmental effects over time. When comparing environmental impact of scenarios, one scenario may be consistently better than another over the entire time period in question. Alternatively, one maintenance scenario could have a significant impact on the environment during the initial phase (assembly), but a lesser annual environmental impact during the following years (due to maintenance activities and energy use); while another maintenance scenario might perform in the opposite way. In the long term, the former scenario might be preferable to the latter; viewed in the short-term, however, the latter is preferable to the former. The time taken for a measure to be 'earned back' in terms of environmental performance is known as the 'environmental pay-back time', as explained by Itard and Klunder (2007).

3.3.1 Traditional roof

This scenario represents reference conditions. Roofing in this scenario is bituminous, which is very common for flat roofs constructed in the 60s or 70s in the Netherlands. A large number of these buildings are now in need of a major renovation and this research might provide renovation, construction and maintenance companies with valuable information. The scenario assumes gravel ballast, which was also commonly used. The roof insulation is glass wool, although it was also common not no use insulation, especially in apartment blocks (where energy losses are relatively smaller) – but in the 70s they usually did add some insulation to all roofs.

3.3.2 EPDM roof

This is nowadays a very common scenario, based on materials widely used. Roofing is EPDM; concrete is used as ballast, which can be a benefit, because the roof can be in this case used for other purposes, since it can be walked on. Insulation is polystyrene, which performs quite well in the Chapter 3.1, with the exception of Ozone layer depletion category. This combination would in theory cause less environmental impact than traditional scenario and would need, if we compare it with the previous two scenarios, less maintenance.

3.3.3 Green roof

The second scenario is based on a currently very popular green roof technology. How green roof is composed and its advantages were described in previous chapters. Green roof assembly used in this research also contains EPDM waterproof membrane. This would be the case if there is no previous roof installed on the building. If the existing roof of the building still performs satisfactory, green roof could in theory also be installed directly on top of it, according to manufacturers. However, to make scenarios comparable, this was not the case in this research.

3.3.4 PV cell roof

In this alternative scenario, PVC roofing was assumed (its good performance was presented above in environmental impact of materials) together with a very alternative choice of sheep wool insulation. PVC is fastened mechanically, this way the possible negative impact of ballast can be avoided, but reflective coating is used to keep the roof cool in hot summer conditions, since it was proven that the photovoltaic cells are more efficient when operating at low temperatures (Luque, 2003).

3.3.5 Reference building

A reference building was used for interpreting the results. It was an apartment block, located in Leiden, The Netherlands and currently occupied by working youth. Masonry building from the 60s is 5 floors high and has 7 45m^2 apartments per floor. Whole flat roof area is 300 m^2. Roofing is multi layer bitumen with gravel ballast and no insulation. Building is constructed of brick, which is typical for The Netherlands.

Figure 18: *Reference building, situated in Leiden*

3.4 Sustainability profiles

As mentioned previously four roof scenarios have been determined and further on also compared, according to results described in the previous chapters and discussions with a Dutch maintenance company Bouwteam P&O, which provided practical information. The first scenario represents the reference condition. Besides the reference, there is one additional scenario, relying on traditional construction and two state-of-the-art scenarios, using sustainable approaches. The environmental profile of the scenarios was observed on three different levels, or as mentioned in the introduction, these are the three different sustainability profiles:

- Sustainability of material assembly
- Sustainability of maintenance
- Energy sustainability

However, all levels are important and all provide the reader with certain useful information. Furthermore, this diploma work analyses the differences among sustainability profiles based on diverse characteristics are also one of the research questions.

3.4.1 Assembly environmental profile

The results in following figures present the weight of the one – time environmental impact which occurs when we reconstruct flat roof of a building. It gives an insight into the relationship between structural design (material solution) and environmental impact of construction of that material building.

The traditional scenario is our reference, meaning that its environmental impact is set to zero. All other results are presented relatively to the reference.

The material assembly also includes the environmental damage of the 150 km of lorry transport, which was assumed to be the average distance for the any roof scenario to reach the building site.

Table 4: *Data and assumptions regarding the materials used*

Scenario		Traditional roof			Green roof				EPDM roof			PV cell roof			
Material		Gravel	Bitumen (4layer)	Polyurethane flexible foam	Pumice	Growing medium	Waterproof membrane	Fleece	Concrete	EPDM	Polystyrene (XPS)	Reflective coating	PVC	Wool insulation	PV cells
Physical data	Weight per m^2 (kg)	44,8	11,2	4,1	6,5	25,6	1,8	7,4	22,8	1,8	2,72	1,33	1,84	2,5	12,2
	Thermal conductivity (W/(mK)	0,27	0,03	0,03	0,03				0,8	0,25	0,03	0,17	0,19	0,04	/
	Thickness (m)	0,1	0,03	0,05	0,1				0,1	0	0,1	0	0	0,15	/
Waste treatment by % of total	Landfill	100	20	20	100	100	12,5	20	50	12,5	7,5	0	20	0	100
	Burning	0	80	80	0	0	87,5	80	50	87,5	92,5	100	80	100	0

3.4.2 Maintenance environmental profile

As was already presumed in the introduction, materials that influence long term performance of building should be dealt with great care since they might require heavy maintenance, and the constituent materials might deteriorate fast in time. Therefore, the most important distinction among the results on assembly level and the results on maintenance level is the component of time, which is introduced only now.

In the databases which were the source for the research, all the environmental impacts of different components are aggregated to one value over the life span. In case of a building, its service life exceeds most of the components service lives and therefore it is necessary to have a model which enables one to observe the impacts throughout the building life cycle. Since the maintenance activities occur every year, the environmental impact will grow throughout the service life of the building. Some scenarios might need fewer repairs and will perform better than others, but the impact might increase dramatically if that component needs to be replaced often.

To asses sustainability of maintenance we had to assess how much and which maintenance activities were needed for the different scenarios. Maintenance comprises for the entire repair, replacement activities, as well as inspections and cleaning. For all these activities we have to establish the proper frequency. More often maintenance might extend the service life of a component, but it can at the same time be damageable to the environment. Therefore, there might be a conflict of interest among roof producers and maintenance companies in terms of maintenance frequencies. Producers advice planned maintenance, replacements and inspections whereas in reality not all those activities actually take place. For this reason, the assumptions were made on basis of data collected from both - maintenance companies (already mentioned Bouwteam P&O) and roof producers and also databases, such as EcoInvent or EcoQuantum software. All the maintenance activities comprise also of transport of materials and workers to (and from) the site. The distances of transport vary, depending on the level of specialization of inspectors, for example green roof inspector will probably come a longer way that bituminous roof inspector.

Table 5: *Maintenance activities and frequencies*

Scenario		Traditional roof			Green roof			EPDM roof			PV cell roof			
Component		Covering layer	Roofing type	Insulation	No such division			Covering layer	Roofing type	Insulation	Covering layer	Roofing type	Insulation	Extra
Annual Maintenance	Cleaning	2 a year, 2 workers, 200km			2 a year, 2 workers, 200km			2 a year, 2 workers, 200km			4 a year, 5 workers, 200km			
	Inspecting	2 a year, 2 inspectors, 200km			4 a year, 2 inspectors, 300km			1 a year, 2 inspectors, 200km			3 a year, 2 inspectors, 300km			
	Watering	None			2 a year, 2 workers, 200km			None			None			
Repair (% of material replaced)		Every 10 years 10%		None	Every 10 years 10%			Every 10 years 10%		None	Every 10 years 10%		None	
Replacements (Lifespan)		75	40	75	30	30	30	75	25	75	25	25	75	25

For assessment of environmental influences of maintenance, assumptions concerning the lifespans, replacement guidelines and necessary annual activities had to be made. The assumptions were gathered from various sources, all can be found in the references, and are presented in Table 5. In Appendix D, there is description of the model, how it was constructed and what its functions are.

Traditional roof

Gravel, which is used as ballast might be partially removed throughout the years due to climate conditions (heavy rain, wind) therefore a replacement of 10% of material every 10 years will be necessary (EcoQuantum software). Gravel has a lifespan longer than building itself, and is therefore never completely replaced (if roofing needs to be replaced, ballast can be simply reused).

To avoid the neglect and misuse of bituminous roofs, they should be inspected on a regular basis. All the debris, including debris that has gathered behind HVAC units, pipes and pitch pans, and any other roof penetrations should be cleaned from the surface of the roof as often as necessary. If the roof is under trees, this has to be done quite often. Debris holds the water which causes the material to deteriorate. Based on the local climate conditions the occurrence of inspections and maintenance activities were determined: two inspections per year with the material replacement of 10% every 10 years will suffice. Life span of a 4 layer bituminous roof was estimated at 40 years (EcoQuantum software). In case there are bare spots on the roof (ballast removed by the wind for example), they should be cleaned thoroughly and a thin layer of asphalt has to be applied over the bare area about 30 mm thick. This was estimated at the rate of 10% of material with a frequency of 10 years.

The polyurethane flexible foam insulation does have a life span for which the producers guarantee its good performance, but its in practice never replaced, only after the buildings service life is over (in approximately 80 years) and major renovation is needed. Service life of gravel is as long as the building service life, whereas the life span of bitumen is much shorter. Because resistant, 4 layer bitumen was assumed, it will perform satisfactory for 40 years. Gravel can be, after the bitumen is replaced, simply reused through the building life cycle.

All the components will be transported from a 150 km distance to the site. Same goes for all component repairs and replacements. For cleaning, 3 workers are needed (one could have done it, but this is environmental – wise a better choice) twice a year, usually in the autumn. They will make 200 km to the site and back. The distance is the same for inspectors, only that only two of them are needed.

Green roof
Maintenance includes inspection of the roof membrane, the most crucial element of a green roof, and a routine inspection and maintenance (as needed) of the drainage layer flow paths. According to Environment Agency of England, extensive green roofs need an annual inspection to ensure all drainage outlets and shingle perimeters are vegetation free. An assumption was made, that every 10 years there is a 10% of material replacement needed (plants, growing medium, and membrane). Even though sedum plants are very undemanding, they have to be partially reseeded and some fresh growing medium should be added. Also pumice, which acts as a drainage medium deteriorates and also waterproof layer of EPDM might need repairs.

There is supplemental irrigation and fertilization needed in the first few months. Green roofs are generally more effective than conventional roofing systems in protecting the roof membrane. This reduces regular maintenance costs and extends the life of the membrane itself. An assumption was made, that green roof extends the life spam of the roofing below for 10 years. More might be possible, but 10 seem more realistic since no scientific evidence was found. If for example EPDM is used as roofing its life span extends from 25 to 35 years.

Besides that, more frequent inspections are necessary, to ensure that the plants are healthy and have met all the conditions necessary for growth (such as drought prevention and maintaining the soil fertile). The inspectors should be more specialized; therefore an assumption was made that they will be in average coming from a greater distance, 300 km with the frequency of four times per year. Cleaning is still necessary to remove debris, mainly from the gutters. Average watering frequency depends largely on climate conditions. In the Netherlands, watering shouldn't be necessary to often, but since there are more and more cases of longer periods with no rain and weather patterns are changing due to global warming, watering 2 times a year was assumed.

PV cell roof
The assembly of PV cell roof requires quite a lot of maintenance activities. Going from the top – Albedo of reflective coating decreases as the dirt is collected on its surface. Washing it with soap is efficient in restoring the initial albedo. One person-hour of work is required for 50m^2 of roof surface (Bretz, 1997). Since the warranties of the coating products found on the internet do not extend over 10 years, 10 years was the estimated life span. PVC roofing should be repaired every 10 years, with 10% of material. After 25 it has to be replaced. The reflective coating covering the PVC could in theory stay longer, but has to be reapplied when the roofing is replaced. It should also be reapplied every 10 years on the spots where necessary (for example where roofing needed to be repaired). Sheep wool insulation has, like other types of insulation no service life limitation, because it can outlive the building.

The PV cells wear out significantly in 25 years. The module must be cleaned periodically, since the dirt accumulated on the transparent cover of the module reduces its performance and can produce reverse effects similar to those produced by shading. The problem can become serious in the case of industrial waste or waste caused by birds. The layers of dust that reduce the intensity of the sun are not dangerous and the reduction in power is not usually very significant.

Preventative maintenance should occur every six months, including examination of the fastening and state of the module's terminals of the connection cables, inspecting the water-tightness of the terminal box. Should waterproof failures be observed, the affected components should be replaced and the terminals should be cleaned. It is important to take care of the terminal box seal, using new clamps or a silicon seal. Visual inspections mentioned above can be carried out at the same time.

Until they are replaced, they require regular inspections (3 times a year from 300 km distance) and cleaning. Also reflective coating requires cleaning as indicated; therefore we assumed five workers could take care of that 4 times annually.

EPDM roof

In general, concrete has a very long life span, but we assumed a replacement of 10 % of it every 10 years, only to replace the possibly cracked and weathered tiles. That should suffice to keep the concrete ballast going through the whole service life of the building (even if it has to be removed for reconstruction it can be put back on, similar to gravel).

Every 10 years, EPDM should be replaced with 10% of the material as all other roofings, and after 25 years it has to be replaced. The insulation layer outlives the building service life.

Since the roofing material is well protected by the concrete later on top, it does not need so many inspections, one every two years performed by two inspectors is enough. The material itself is also known to have better resistance to weathering than bituminous materials. Cleaning twice a year is still recommended.

3.4.3 Energy environmental profile

For a complete sustainability assessment, the energy use of the building also has to be assessed, since it is also determined by the type of roof. Therefore, a house with a roof with better energy performance saves some energy (in the case of Netherlands this usually means natural gas) which influences the environmental impact of roof positively.

R and U values are the means of indicating the design thermal performance of a building material or assembly. R values represent the resistance of heat flow through a building material. The higher the R value, the greater the resistance and the insulating value. It is defined as thermal conductivity (λ) in unit of material thickness (l) with the unit of m^2K/W (Meritt et al., 2000).

$$R\ value = \lambda / l \qquad (1)$$

U values on the other hand are the direct opposite. U values represent the amount of heat flow that transmits through a building assembly, which is built-up of various materials and the surface air film resistances. The lower the U value is, the slower the rate of heat flow and the better the insulating quality. It is defined as:

$$U = 1 / R\ value_{(total)} \qquad (2)$$

Where R value $_{(total)}$ is the total thermal resistance and is given by:

$$R\ value_{(total)} = R\text{-}value_{(surfacing)} + R\text{-}value_{(roofing)} + R\text{-}value_{(insulation)} \qquad (3)$$

A reference roof was needed in order to determine, how much better (if better at all) our scenarios perform. Traditional scenario, which represented the current state of the building (marked as blue curves in graphs of subchapters), was composed of bituminous roof with gravel ballast and basic insulation. Its R-value was 3.2 m^2K/W. Total R-values for different scenarios were calculated based on material conductivity data and thickness assumptions using equations above. R values for our scenarios were as follows in the Table 6.

***Table 6**: Energy data for different scenarios*

Scenario	Traditional roof			Green roof				EPDM roof			PV cell roof			
Material	Gravel	Bitumen (4layer)	Polyurethane flexible foam	Pumice	Growing medium	Waterproof membrane	Fleece	Concrete	EPDM	Polystyrene (XPS)	Reflective coating	PVC	Wool insulation	PV cells
R-value (m^2K/W)	0,37	1,07	1,79	3,3				0,12	1,64	4	0,01	0,0008	4,05	/
Total R-value (m2K/W)	3,25							5,76			4,15			
Energy benefit per year in kWh	/			328,9				1090,1			867,1			

Theoretical benefit of one roof assembly over the other can be estimated by using:

$$Q= (1/R_{reference} - 1/R_{alternative})\ A\ (T_{outdoor}-T_{indoor}) \qquad (4)$$

We calculated the energy benefit using this equation first, but due to uncertainties considering standard conditions, we later on used A Dutch software Vabi EPA-W for this purpose. It already includes all the characteristic values for the Dutch climate, so that the energy use for the building is calculated under standard conditions. The actual energy use can differ by actual user behaviour (desired internal temperature, presence, established equipment, etc.) and real climate data (outside temperature, solar radiation, wind speed, etc.). With that software, we managed to get the results for a specific flat in the apartment building. One of the characteristics of roofs of apartment blocks is that they directly influence the energy use of the apartment below them. Apartments have different energy usages according to where in the building they are situated. If we compare the apartment below the top floor (in our case, 4^{th} floor) and the apartment on the top floor, their energy uses will be different for as much as there is lost through the roof on the top floor. The difference was calculated for the reference scenario. From this difference we deduced the difference of energy use in flats of our scenario and we got the total energy benefit (in m^3 of natural gas).

$$E_{benefit} = \underbrace{(E_{use\ top}-E_{use\ below})}_{\text{Reference}} - \underbrace{(E_{use\ top}-E_{use\ below})}_{\text{Our scenario}} \qquad (5)$$

The results are shown in Table 6 and it is obvious that the scenarios with EPDM and PV cell result in the best energy benefit. It is interesting to notice that, since their R values are different and EPDM should theoretically perform better, but here the law of diminishing returns applies: Each additional unit of R-value contributes less energy savings than the previous one. The U-value curve (amount of heat that moves through the material for each unit of temperature difference) quickly flattens as R-value continues to climb. An example is shown in Figure 19. When upgrading a typical insulated roof 1 to roof 2 there is some difference in the U value, but from 2 to 3 this difference is already almost negligible. Economically, the highest R value to be implemented would be determined by cost of energy. Currently, the highest R values of insulation on the market are between 3 and 4 m^2K/W.

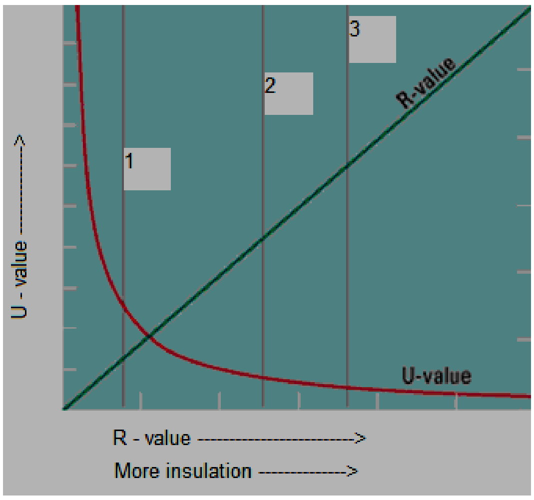


Figure 19: *Relationship between R and U - value*

Besides the influence of insulation on energy use which, the electricity generation was also taken into account in the PV cell scenario. One square meter of PV cells produces in average 85 kWh of electricity (Zonnepanelen, 2009) which means 25500 kWh for a 300 m^2 roof. In case of the apartment building, this does not represent a major part of electricity use, since this roof area is covering a bigger volume of electricity consuming space than for example in the case of a detached house. An average apartment uses 3300 kWh electricity a year, thus PV cells can account for a maximum of 4% of the needed electricity (70 apartments in the block). This electricity would be best used for the mechanisms utilized by all the building's dwellers such as lightning in the stairs and halls, doorbells and elevators. The percentage is small (since PV cells can easily account for more than 30% electricity in an individual house), but the environmental benefit was assessed nevertheless.

The energy consumption needed to be somehow added to results of the assembly, so the relative contribution would be visible. Since the absolute amount of energy consumed has an environmental impact far greater than the one of roof assembly and maintenance, it was decided not to add up the absolute impact of energy consumed, only to take into account the energy benefit of the chosen scenario relatively to reference (traditional scenario). The influence of the energy benefit was added to the impact of assembly and maintenance in the green roof, EPDM and PV cell scenario.

The improvement of R value of the roof means less natural gas consumption (most common for heating in the Netherlands), whereas the benefit of PV cell influences electricity consumption. Electricity is generated by a mix of fuels, different from country to country. In this case, Dutch electricity mix was used.

4 RESULTS AND DISCUSSION

Results were obtained for all the scenarios, using course of action as described in the chapter 3.1. They are characterized into nine impact categories as presented in the Table 3. An important emphasis is the time component, which needs to be incorporated for the sustainability assessment of maintenance and energy; therefore the obtained results from SimaPro were modeled in Microsoft Excel, as described in Appendix D.

4.1 Sustainability of material assembly

4.1.1 Results

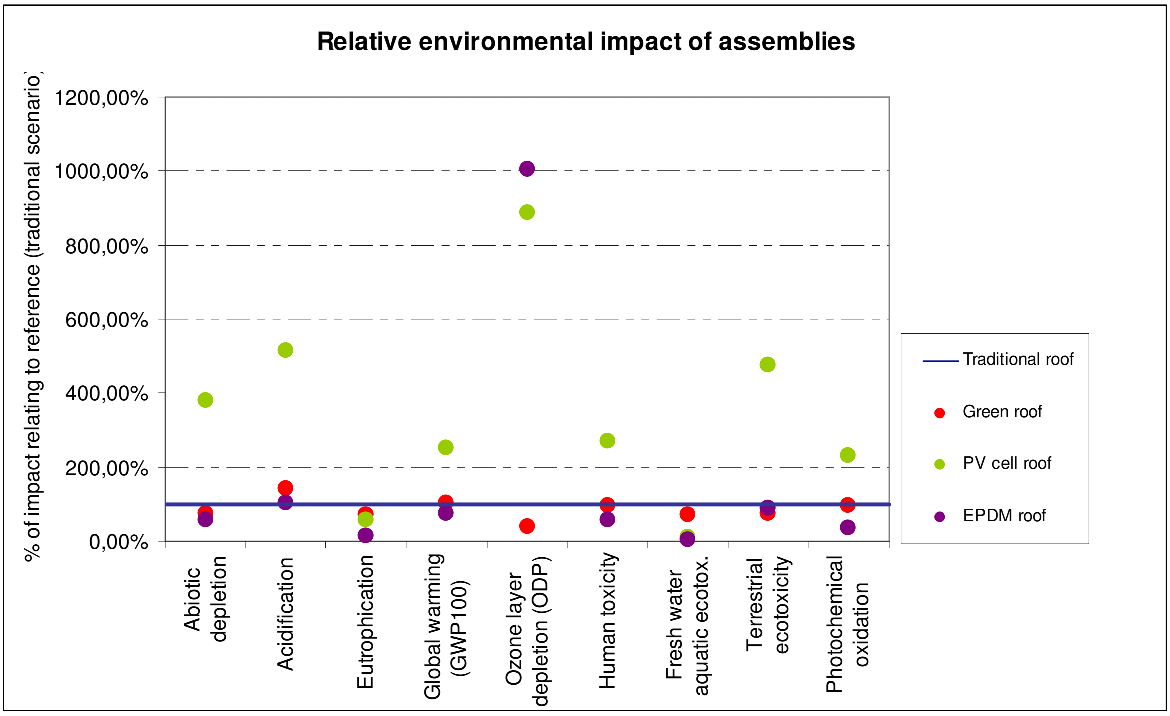


Figure 20: *Environmental impact of different roof scenarios to nine environmental categories*

All the results presented on the figure above are calculated relatively to the traditional scenario. This means that the damage the traditional scenario causes to the environment when it is assembled is set to 100%. The impacts of other scenarios are then presented relatively to the damage of the reference.

4.1.2 Discussion

The graph, where all the results could be presented equally well, was very hard to make, since the variability of results fluctuates from one category to another. We have to be carefull in interpreting the values below the 100% trendline (this is the impact of traditional scenario), since it seems that In category fresh water aquatic ecotoxicity, where traditional roof performs the worse, the best scenario has 250 times smaller impact (only 0,4% of the damage done by traditional scenario – represented by the 100% tredline). However, the reliability of this category was already questioned in chapter 2.1.6 and we will not reason this result, since there is a justified doubt in the certainty of this result. In many cases, two or all of the scenarios perform better than traditional; this is indicated on the graph with all the dots that are located below the x axis. The culprits for a relatively bad sustainability of traditional bituminous roof are bitumen itself and even more the gravel, used as ballast. The extent of the damage caused by implementation of gravel is surprising, but its weight (Table 4) is considered, damage becomes understandable. Green is the only roof type which does not need another component besides surfacing; the other components are omitted for its functions are fulfilled in an alternative way. The waterproof foil is somewhat thinner than other roofing foils due to the protection from climate factors provided by the layers of soil and plants. These are also responsible for insulation, which is also not used in green roof assembly. This type performs significantly better than the reference in four scenarios, almost the same in three and worse only in one impact category; therefore it is preferable (comparing to traditional). Furthermore, the PV cell roof wins as the least environmentally friendly roof in six categories. Assembly of PV cell is very complex and quite damageable if not viewed together with the energy benefits that it brings. Besides PV cells, the assembly consists also of PVC foil and sheep wool, but these two have impacts from 10 to 1000 times lower than the PV cells an do not present a relevant part on the graph.

As mentioned before (3.2.5), results in this study do suffer from uncertainties, even though not depicted in the figures. The result of the uncertainty analysis for an assembly, traditional roof, is in the shown in Figure 21 below.

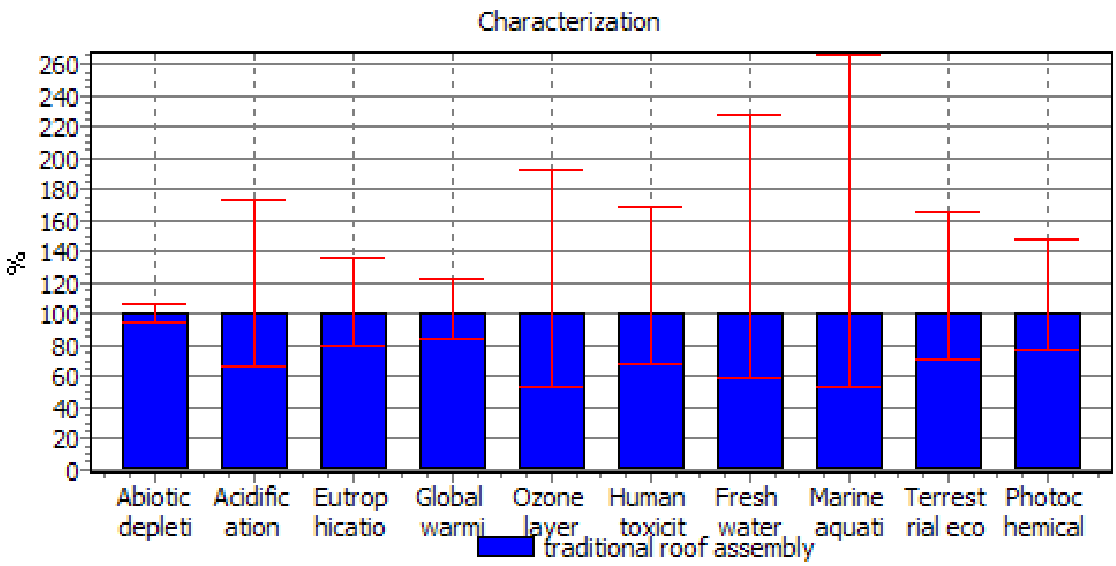


Figure 21: *Uncertainty analysis of traditional roof assembly at interval of confidence 95%, method is CML 2001*

However, the figure above only takes into account the uncertainty caused by the data in the databases and does not reveal anything about uncertainties of assembly or scenario assumptions which can also cause errors in results. These are not depicted, since they were assumptions of researchers and maintenance company and human error is hardly quantifiable.

Additional interesting observation on the graph is how similarly all scenarios perform in some categories, such as acidification or global warming. Does it mean that concerns of global warming are needless while one is deciding on roof type? It will be shown later on that this is not true, since the overall sustainability does not comprise only of assembly but also of maintenance and impacts on energy use.

4.1.3 Guidance for increasing sustainability

Formulation of guidelines is at this point practically impossible, since the results are only a one time impact of assembling a roof and are not complete. Importance of time component was emphasised already in the theory chapter. The guidelines according to the assembly results are only here for the sake of comparing environmental impact of assembly, maintenance and energy sustainability of roof later on.

Examining the environmental impacts results solely on the basis of assembly damage suggests the implementation of EPDM roof as the most sustainable. Green roof follows, traditional being the second worse. According to these results, PV cell roofing is not a reasonable choice, but it is clear that this scenario can only turn out to be reasonable in the long term assessment, which will be presented in following chapters.

4.2 Sustainability of maintenance

The principle of calculating the environmental impacts of a roof is illustrated in Figure 22.

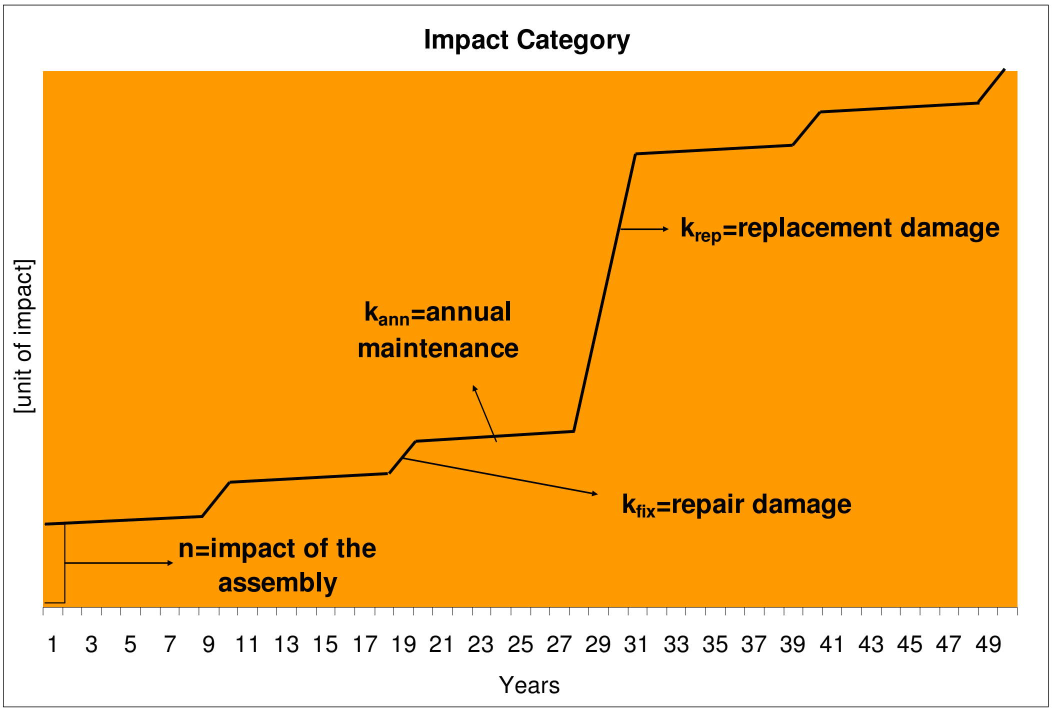


***Figure 22**: Example of a result of LCA including maintenance for one type of roof*

Each roof component has a particular life span, different than the life span of the whole building, but it should nevertheless be observed in the entire building service life, since the performance of component might change significantly. Firstly, if we look at the graph, we can in general observe three different slopes on all the lines, caused by three categories of maintenance activities. The highest slope represents the most damageable activities, the impacts of replacements. It includes the impact of removing the old component (with its embodied energy), assembling a new component and all the activities needed for that (transport of cargo, workers). The middle slope is caused by repairs and it usually occurs every 10 years, just like the repairs themselves. It consists of same activities as the replacement activities, but in a lesser extent (only some components or the damaged part of them is replaced). The last, the most horizontal slope is caused by yearly activities, such as transport for inspections, cleaning and watering. In theory, if there are often replacements, the repairs and other maintenance activities should be rarer. Subsequently their impact is expected to be smaller. In the Appendix C all the slopes of the curves are presented, since sometimes the differences in graphs bellow are too miniature to be seen by the naked eye.

Where the graph intersects the y-axis is the value of impact of the assembly including the transport necessary.

Due to practical reasons, in this section, the reference (traditional scenario) was not set to zero, it was preferred that all the values are kept positive. All the slopes of the curves which appear in the following chapter are gathered in the Table 8 in Appendix C.

4.2.1 Results

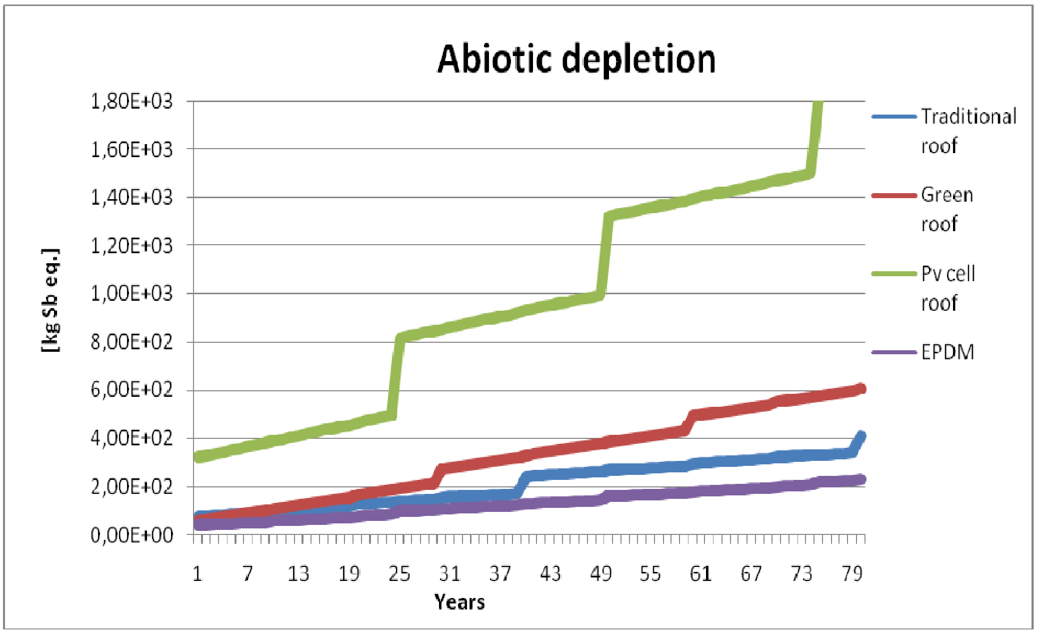


Figure 23: *Maintenance impact on abiotic depletion*

Abiotic depletion

All maintenance activities should have a relevant impact in this category depending on the quantity of the resource used for the production of the component and the amount of reserves of that same resource. It comprises for the use of non-renewable resources, such as oil, natural gas, coal, metals.

For PV cell roof scenario, for example, the yearly maintenance causes almost as much damage per unit time as the repair activities and the last are therefore not visible (no change in slope in ten year intervals). Even though the annual activities are high in the PV cell roof scenario, the main impact is caused by replacements. Already here it is clear that without incorporating the energy benefit, the PV cell roof will not have the cleanest performance. The high impact of PV cells on the abiotic depletion is due to fuels consumed in their production, the amount of ores used (tellurium, silver, molybdenum) turned out to be negligible.

Green roofs, although these are even a bit more damageable in terms of repairs perform similar as the PV cell roof. The impacts are also mainly due to fuel consumption, a part is probably contributed by use of cadmium, needed for EPDM waterproof membrane. However, as will be contemplated in discussion section leter on, these relations are very difficult to understand, since they can be very complex and integrated in the method.

Traditional roof turns out to be environmentally better than the green roof after only few years of operation. In total in terms of abiotic depletion, the PV cell and Green roof have the worse performance, whereas EPDM roof performs the best in terms of maintenance and assembly.

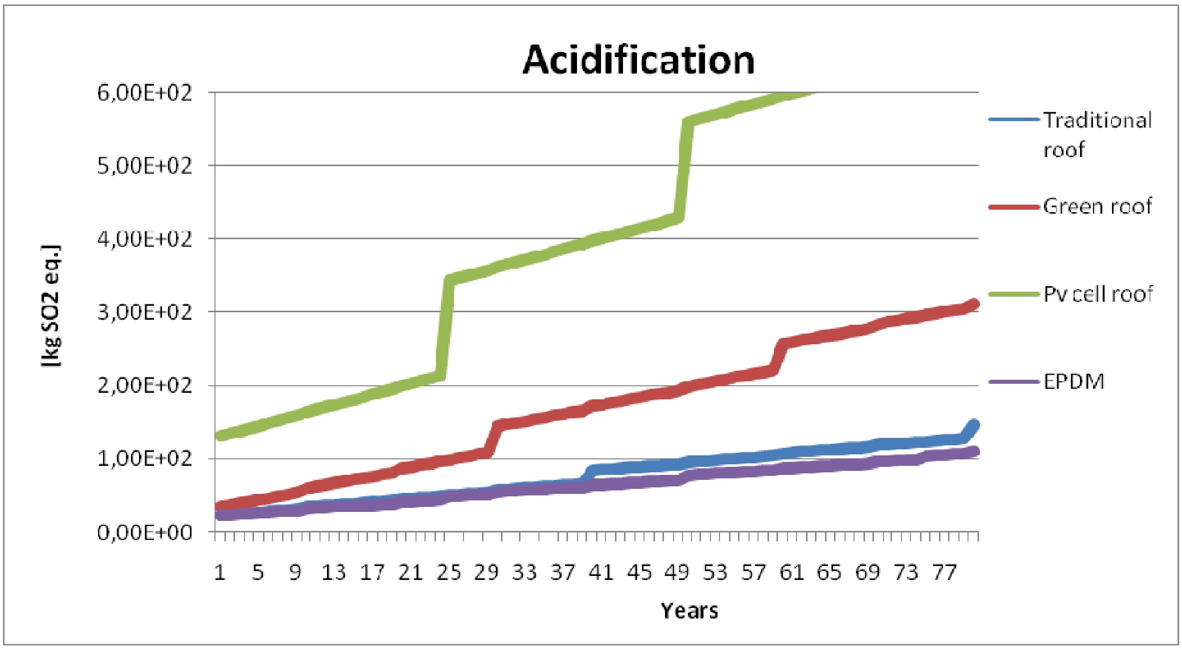


Figure 24: *Maintenance impact on acidification*

<u>*Acidification*</u>

As loss of nutrient bases (calcium, magnesium and potassium) through the process of leaching and their replacement by acidic elements (hydrogen and aluminium), acidification is a natural process. However, it is commonly exceeded by anthropogenically derived sulphur (S) and nitrogen (N) as NO_x or ammonia which disrupts the neutralizing capacity of soil and acidifies waters. Therefore, roof components, which require any of these substances for their production, will perform worse.

Impact of annual activities on acidification is probably mainly due to nitrogen radicals released in fuel combustion (transport of workers), which eventually results in nitrogen oxides. The highest impacts are again caused by green and PV cell roof, since they require more annual maintenance. Also other impacts follow this logic – the more the fuel consumed, the highest the acidification, since it is caused by sulphur and nitrogen oxides. We can observe on this graph that frequency of replacements also has an important role. The most frequent replacements are needed in EPDM scenario, than PV cell scenario, third is green roof scenario and last traditional scenario. If we were to increase the life span of PV cells to twice as it is today (50 years) that would mean that after years, the impact would be similar to green roof impact.

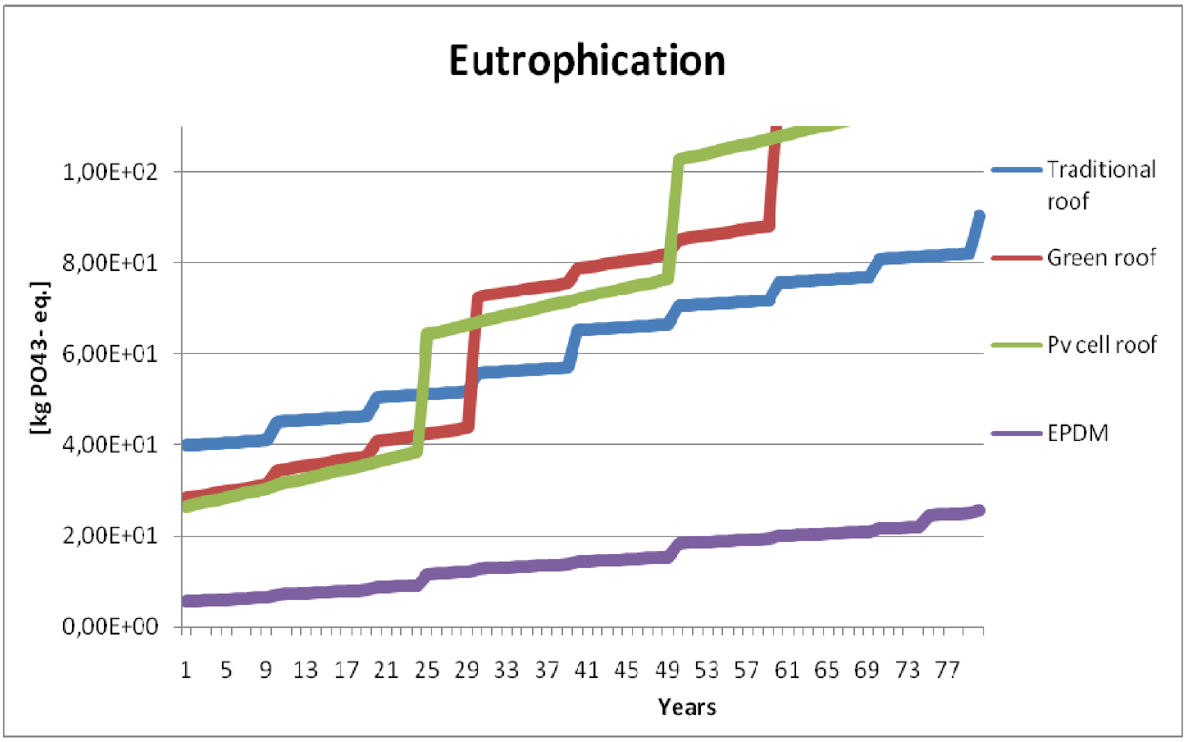


Figure 25: *Maintenance impact on eutrophication*

<u>*Eutrophication*</u>

Eutrophication describes the biological effects of an increase in the concentration of nutrients. Nutrients are the elements that are essential for primary production by plants or other photosynthetic organisms. Eutrophication is most often caused by increases in the availability of nitrogen and phosphorus, commonly present in soil and water in the form of nitrate and phosphate, respectively. Traditional roof for example causes the highest initial impact, which continues to increase steadily each 10 years, when gravel is partly replaced. We suspected this growth was, more than environmental impact of gravel itself, a consequence of transport of the heavy gravel. There is also a further indication of this, which is the high impact of replacements in case of green roof, which is even heavier than gravel and coherently also the impact increases more. Green roof and PV cell roof cause similar damage in terms of material assembly, even though the green roof weighs more. Anyways, when we compare the transport environmental damage, the weight (three times more in case of green roof) plays a crucial role.

After approximately 80 years of building life the three different scenarios end in almost the same environmental impact. Energy performance presented in the following chapter will therefore help in deciding which one is more sustainable.

The best performance in terms of eutrophication is achieved by use of a component which needs less annual maintenance and is also lighter and available from places nearer to the construction site, in this case EPDM.

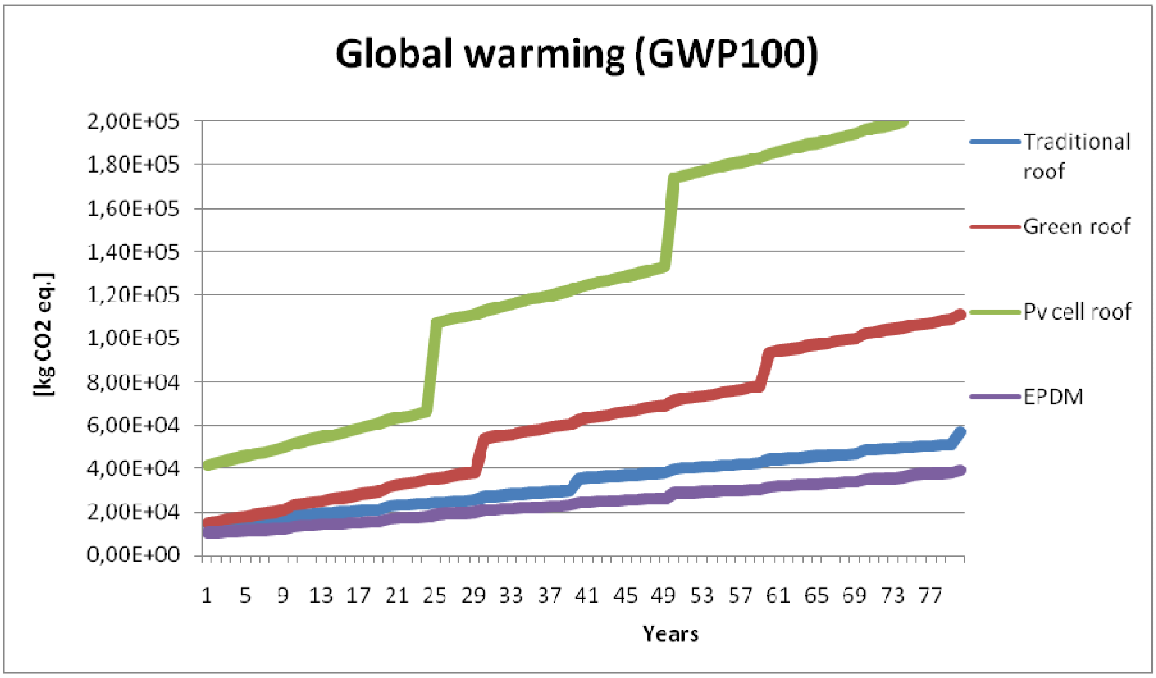


Figure 26: *Maintenance impact on global warming*

<u>Global warming</u>

Global warming is one of the more 'popular' environmental issues nowadays. It means an increase in the average temperature of the air and oceans since the mid-twentieth century and is projected to continue. Politicians and government are struggling to find appropriate actions to tackle the problem, but so far the mitigations have not been especially relevant. By sector, residential was found to be one of the eight major culprits, comprising for 10% of green house gas emissions (Climate Change 2007 Synthesis Report…, 2007).

It is rather unfair to compare the four scenarios with completely different energy performances only in terms of assembly and maintenance, but nonetheless. As expected, green and PV cell roof damage the environment the most due to the complex assemblies. The interesting difference is between repair activities – in case of green roof it is around 400 times greater, but still ten times less than the impact of replacement. Again, it is worse to replace green roof than the PV cell roof, probably due to annual activities (transport). In the graph of the green roof (Appendix C), all the impacts of all maintenance activities can be seen very clearly. In terms of maintenance, EPDM and Bituminous roof perform around 300 times better than PV or green roof. The biggest difference among the cleanest two scenarios in case of global warming is between replacements, which we can ascribe to weight and the fact bitumen (oil derivative) used in the later.

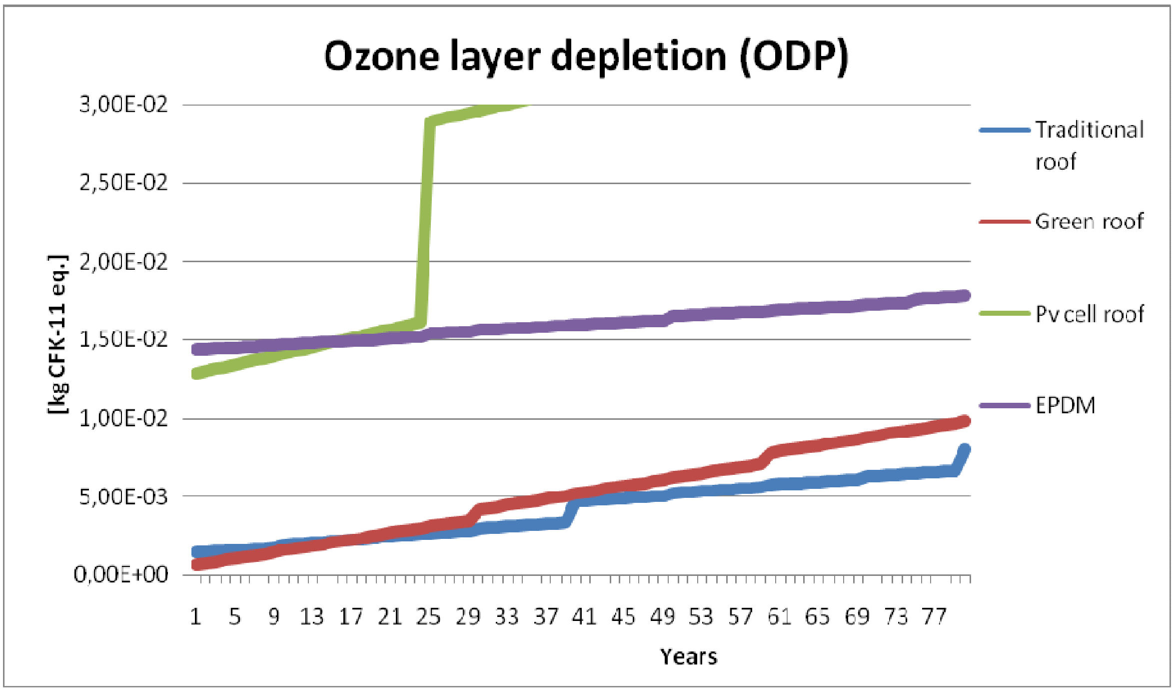


Figure 27: *Maintenance impact on ozone depletion*

Ozone layer depletion

Ozone depletion is a process, where the layer of ozone in stratosphere gradually decreases, due to catalytic destruction of ozone by atomic chlorine and bromine. The main source of these halogen atoms in the stratosphere is photodissociation of chlorofluorocarbon (CFC) compounds, commonly called freons, and of bromofluorocarbon compounds known as halons. The components that are produced of those substances influence the thinning. Success in tackling this issue was achieved by implementation of Motreal Protocol globally, but some substances that deplete ozone are still on the market. The biggest number of (comparing these roof types) these substances is found in PV cell roof scenario, some of them are tetrachloromethane (CFC – 10), chlorodifluoromethane (HCFC – 22), bromochlorodifluoromethane (Halon 1211), dichlorodifluoromethane (CFC – 12), etc. The highest slope is represented by replacement of bituminous roof, probably because of transport.

Interestingly, the second worse scenario in ozone depletion category seems to be EPDM, which is not common in other categories. As mention in chapter 4.1.3 this is due to polystyrene insulation. The graph above represents well the influence that only one component may have on the overall sustainability of the roof. In about 15 years, however, this effect is compensated by the low annual and repair activities needed in EPDM roof scenario and PV cell roof is more damageable from there on. Also in the bottom two scenarios it is obvious that it is very important in which year do we decide to assess sustainability. Namely, the answer to which roof scenario has greater impact at a given moment changes through time.

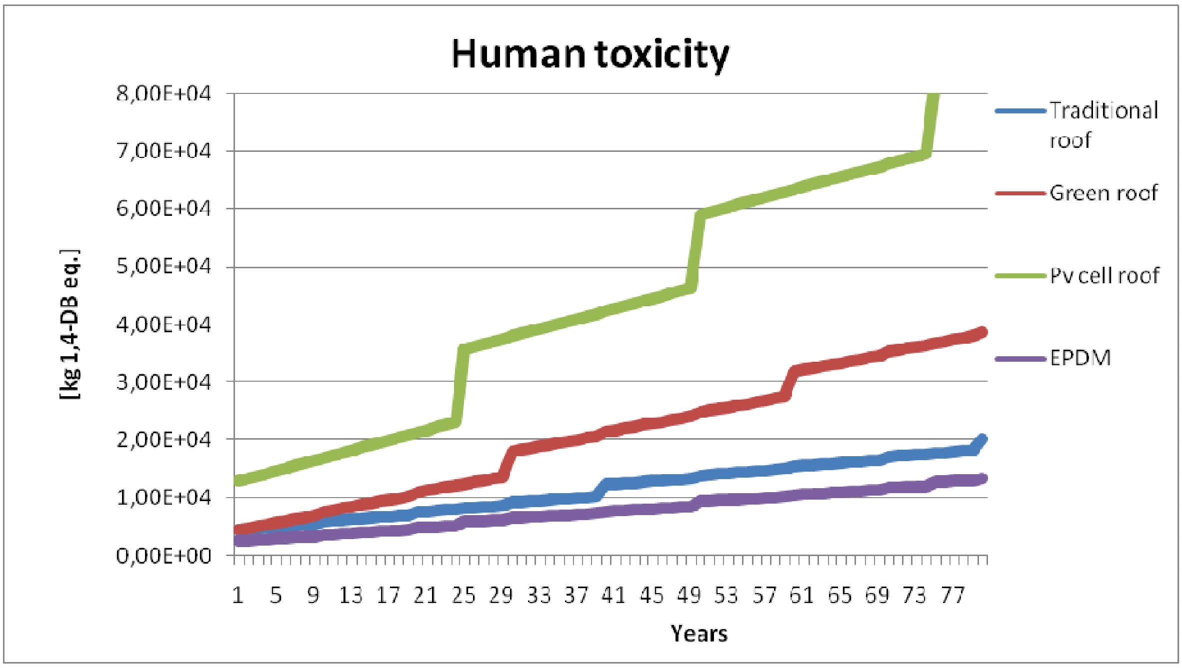


Figure 28: *Maintenance impact on human toxicity*

<u>Human toxicity</u>

Toxicity is the degree to which a substance is able to damage an exposed organism. Toxicity can refer to the effect on a whole organism, such as an animal, bacterium, or plant, as well as the effect on a substructure of the organism. Evaluation of Human toxicity is important, since it determines whether or not a certain material is safe for human beings.

Again we can observe very high values for Green and PV cell roof toxicity (Total values). In PV cell roof we can for example find arsenic, chromium, PAHs, propylene oxide etc. Additionally in green roofs there is also vanadium. Maintenance – wise the most damageable scenario is green roof and the best choice would be EPDM roof. It makes a relatively big difference whether we choose PV cell or Green roof or one of the other two scenarios, that's why the indirect benefits should be considered (in the following chapter).

Graph is in a way similar to the global warming graph. The initial impact is relatively low comparing to the intensive damage due to repairs in replacements of PV cell and green roof and we cannot even observe it at this scale. Since there is a huge difference between impact of green and PV cell scenarios and on the other hand EPDM and traditional roof, energy benefit should be assessed to obtain more relevant sustainability assessment.

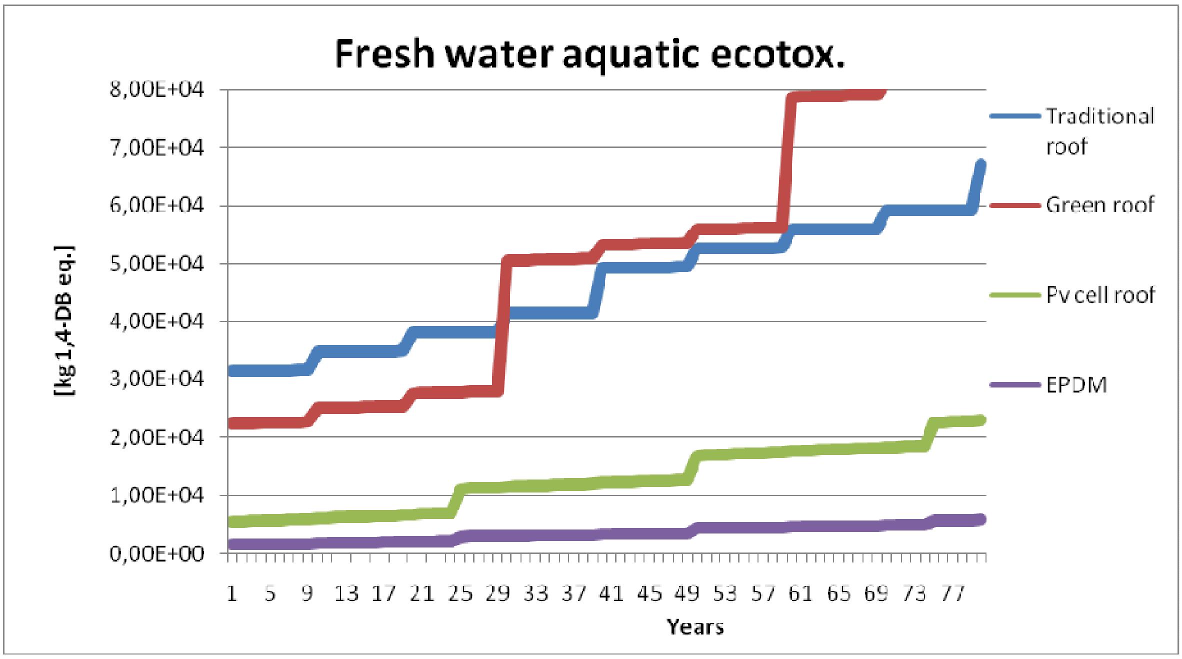


Figure 29: *Maintenance impact on fresh water aquatic ecotoxicity*

<u>*Fresh water aquatic ecotoxicity*</u>

Ecotoxicity of fresh waters refers to the potential for biological, chemical or physical stressors to affect fresh water ecosystems. Such stressors might occur in the natural environment at densities, concentrations or levels high enough to disrupt the natural biochemistry, physiology, behaviour and interactions of the living organisms that comprise the ecosystem.

It is obvious from the figure above that maintenance of green roof influences fresh water aquatic ecotoxicity significantly more than other roof scenarios. It is also intriguing that traditional roof performs better than the PV cell roof, which can be contributed to the fact that gravel, which has the most damageable impact among roof coverings (Chapter 3.2.1), is never wholly replaced and in case of green roof the growing medium is replaced partially every 10 years and every 30 years completely.

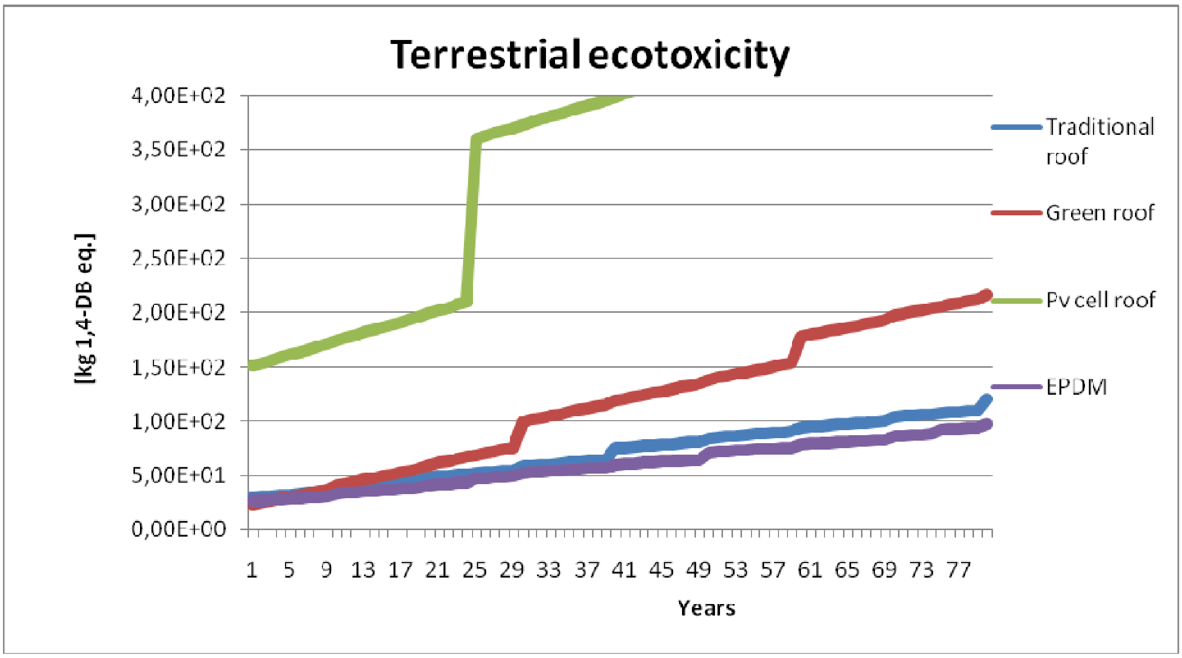


Figure 30: *Maintenance impact on fresh water aquatic ecotoxicity*

Terrestrial ecotoxicity

Similar to fresh waters ecotoxicity, terrestrial ecotoxicity refers to the potential for certain stressors to affect ecosystems, in this case terrestrial.

The largest impact is again by the PV cells; all the others are initially close to one another. After 80 years, however, the replaced green roof has a larger impact than other two scenarios, due to the heavy impact of replacements in green roof scenario.

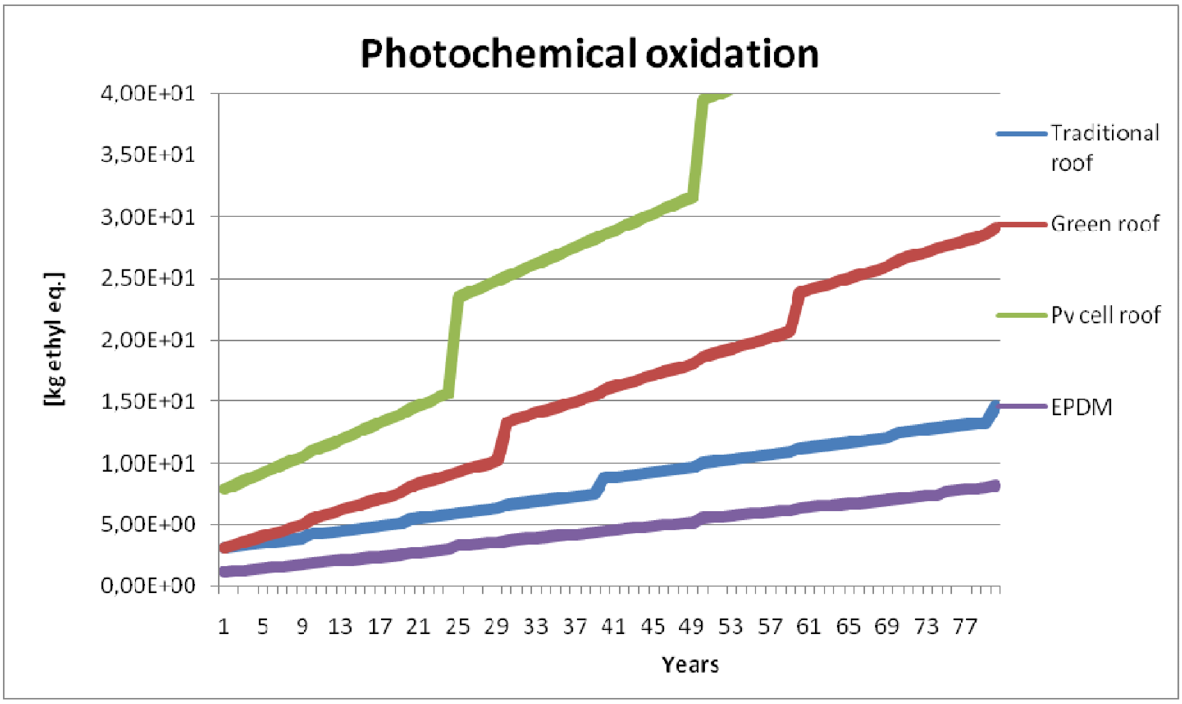


Figure 31: *Maintenance impact on photochemical oxidation*

Photochemical oxidation

Photochemical oxidation occurs when a substance loses an electron and combines with another substance. In some cases this reaction is initiated by having the atoms excited by a UV radiation. A common example is photochemical smog, which is caused by hydrocarbons and NO_x reacting under the influence of UV light.

The slopes of maintenances are here similar; almost all of same order of magnitude. The scenario with the highest maintenance coefficient is traditional roof when replaced. The reason for this is presumably once again the weight of traditional roof, which influences the transport. Comparing activities of other three – they are all very alike, so we can assume that they are all mostly influenced by transport, like eutrophication.

4.2.2 Discussion

It is noticeable that the PV cell roof scenario curves always have a high slope for annual maintenance – the maintenance activities are the most often. Second is green roof, followed by traditional roof and in the end, EPDM roof scenario. PV cell roof have around three times greater impact in annual maintenance than traditional or EPDM scenario, because they require three times more maintenance activities.

In the coefficients of impact it is noticeable that the slope of annual maintenance and the slope of repairs are quite near. Slope of repairs is determined by two variables – the impact of material being replaced and its weight which influences the environmental damage which will be caused by transport. The most damageable altogether is the maintenance of PV cell roof, but since this roof is never repaired (at least not in terms of replacing its constituents); highest repair coefficients are present in green roof scenarios, with the exception of eutrophication and photochemical oxidation, where traditional roof surpasses the impact. Observing the repair factors, it is interesting that in spite the fact that it weighs less, green roof in general performs inferior than traditional. This can be explained by the fact that every 10 years 10 % of the whole roof is replaced in case of green roof, while in case of traditional roof only bitumen and gravel are being replaced. This is very important to notice, since the assembly impact gave us another result – traditional roof performed a lot poorer there. PV cell and EPDM roof are somewhere between traditional and green, observing the repair coefficients. Although lightest than EPDM, PV cell is the second considering repair impact in almost all categories. EPDM roof would perform similar to the traditional, but concrete used as surfacing is approximately ten times more damageable to the environment than gravel (used in traditional scenario), so the impacts of repairs are in general greater, although the average maintenance coefficient is better (lower) for EPDM roof. Another observation is that green roof is, repair-wise, more damageable than PV cell roof, which is not nearly reflected in the replacement or total. As stated before, since the composite materials for green roof are less damageable than the ones for PV cell roof, the only explanation is the transport – green roof components weigh more than 2 times more than PV cell roof. We can conclude, that the repair maintenance impact caused is due to two factors - materials used and not transport to the site. This is supported by the fact that environmental damage which is caused by annual maintenance (meaning transport) is of a similar order of magnitude to repair damage. The damage of transport should be in general of same order of magnitude – in case of annual maintenance it occurs many times and in case of annually maintenance the transport occurs x times and in case of repairs it carries the x weight, meaning that the product of *x*transport impact* would remain approximately the same. The green roof being the second heaviest scenario to transport, it is no wonder that this scenario performs the worse.

Among the replacements, PV cell scenario has the maximum impact in most categories due to the environmentally damageable materials which PV cells are made of. Here the quantities are ten times bigger and also the impacts of PV cells constituent materials are at least 10 times greater than the green roof material impacts, therefore annual activities can sometimes not even be seen on the graph (there seems to be no slope – global warming for example). In few categories such as eutrophication and global warming, the replacement impact of green roof prevails, due to a combination of transport, which is five times more in favour of PV cells because they are lighter, and the specific materials in green roof that influence eutrophication particularly relevantly (growing medium).

As a final remark it should be emphasised, that there was no uncertainty analysis carried out here. Many of the relations between roof production and maintenance and the environmental category are unclear – for example results in category fresh water toxicity and many others. The relations which are argumented in chapter 4.2.1 are based on assumptions, which were educated guesses by researchers and maintenance company, but the issue of accuracy remains nevertheless.

The difficulty of relating the object (its materials, processes it requires etc.) of research with the results obtained through LCA is one of the issues remaining in this type of research. Apart from that, the inaccuracies which might have occurred in previous LCA stages (Table 1) could have an influence on the results obtained here, but the reliability was unfortunately not assessed in this study. Therefore, the accuracy of LCA is an interesting topic for further research.

4.2.3 Guidance for increasing sustainability

Case - specific recommendations
If we start at the roof surfacing, we can say from all the graph presents above that heavy ballast increases maintenance activities, although it is supposed to do the opposite and lengthen the life span of roofing. Mechanical fastening would be better on terms of sustainability, primarily because it does not weigh so much to replace a part of it every few years. Gravel, as well as concrete, is very heavy and could both in theory be replaced by mechanical fastening. They also both cause damage to freshwater ecosystems and all the categories that are impacted by fuel consumption (global warming). These impacts are not very obvious from the graph, since they are overridden by replacements of green and PV cell roofs.

Similar is true for reflective coating as surfacing. It improves the roof performance by decreasing the energy consumption, especially in the summer and it improves performance of PV cells due to more stable temperature. But at the same time, it requires a lot of cleaning – it has to be scrubbed every 10 years to ensure its efficiency does not deteriorate. It should be assessed whether this is rational in terms of real energy use. Maintenance is also very heavy for green and PV cell roof; in average these roof scenarios perform the worse in terms of maintenance. Green roof performs badly despite its relatively low initial because all the components are replaced every ten years. This could be solved by implementing performance based instead of planned maintenance. Nevertheless, other benefits should be researched to reason their implementation as well as the different performances of insulation types.

General recommendations
Generic solutions represent the advice on how to improve the sustainability profile of any building, but it could also be applied in these scenarios:

- Replacement of components should not take place according to a preventive maintenance plan, but rather a failure based plan, meaning repairs and replacements would only occur when the performance ceases to satisfy the needs. Life spans on roofs could be extended, resulting in more often repair activities and maintenances. However, these activities are still environmentally friendlier than replacements and could contribute to lesser environmental degradation in the long run.

- Repair activities could be, like replacements, carried out when necessary (when blisters or cracks are discovered) and not preventively. However, one should be careful to avoid acute problems (such as leakages), since these since they require massive interventions, which also demand a higher toll from the environment).

- Annual maintenances are unavoidable and it is nearly impossible to cut them down and at the same time not decrease the quality of roof components. Better sustainability here could be achieved with better organization of activities. Cleaning, inspections and watering should take place at the same time whenever possible. Annual activities could also be carried out at the same time as repair activities, and the load to environment due to transport would be lessened.

- Heavy components should be reconsidered, since their maintenance is bound to cause more damage to the environment that light components.

4.3 Sustainability of energy

The graphs presented are simplified for easier understanding and focusing on one point in buildings life, the point when it reaches 50 years of age. All results are again presented relatively to the reference.

However, additional figures are presented in the Appendix C for even better understanding. There, environmental impacts can be observed throughout building life, as in chapter 4.2. On those figures there are curves for maintenance scenarios (already observed in chapter 3.4.2) and the energy scenarios (which include maintenance and energy use). This is joined together in graphs to illustrate better; to what extent the energy benefit can influence the impact. There is also an explanation and discussion of the figures.

4.3.1 Results

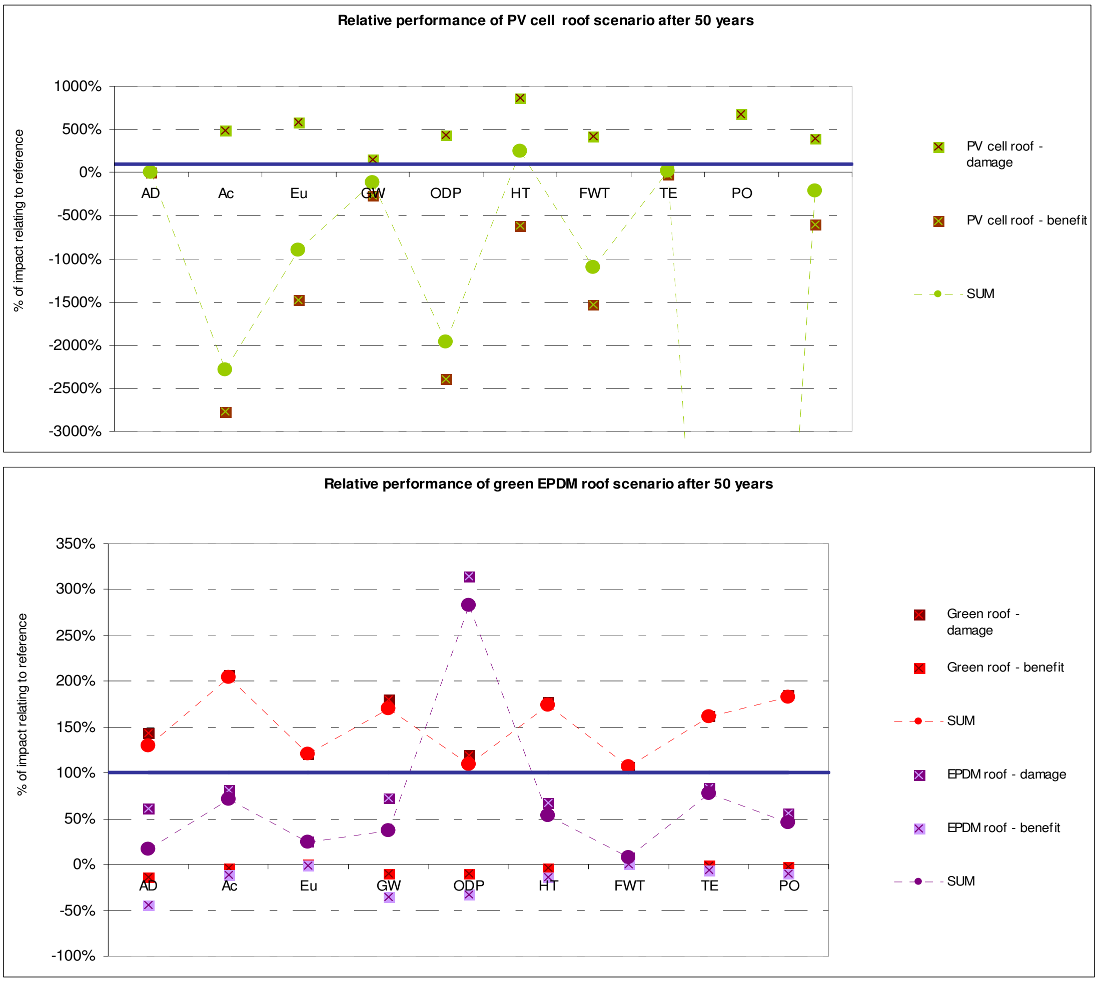


Figure 32: *Energy benefit of scenarios*

4.3.2 Discussion

From the results shown in Figure 32 it is obvious that the PV cell scenario outdoes the others by far, considering the electricity it generates. EPDM, having the best insulation of all also performs well and produces a considerable energy benefit through the years. As already in maintenance and assembly sustainability the green roof again performs the worse also in total sustainability after 50 years, even more, the result is worse than the reference in all the impact categories. Therefore it is already obvious that this scenario is not the most desired one on building roofs. The problem is that the anticipated benefits are hardly quantifiable with current data. No or few research has been conducted, elucidating beneficial impacts of green roof on storm water retention, biodiversity, air pollution. Consequently, if none of these promised advantages are taken into account, the overall activity of green roof cannot be recognized as sustainable, as was demonstrated with the results in this diploma work.

In most cases, at least the annual maintenance activities are nullified by the energy benefit, this is least achieved in case of green roof scenario, due to its heavy maintenance. Therefore it remains desirable, that the guidance for maintenance sustainability is respected. Green roof, as seen from the figure, does not surprise in energy performance. The insulation provided by the soil, drainage and plants is a bit better than the insulation used in the reference building, but the improvement does not even slightly pay back for the damage caused by assembly and maintenance, especially the frequent repairs of all the green roofs components remain problematic and cause a big burden. From the graphs above we can observe, that good insulation might be an possible solution to increase sustainability, since EPDM show quite a good percentage of environmental impact can be rendered null, especially in categories abiotic depletion and global warming.

Another interesting observation is that the positive impacts of good insulation in case of EPDM and electricity generation in PV cell scenario do not influence different impact categories coherently. This can be due to two reasons – the assembly is different and might therefore damage the environment more in certain categories (very obvious in Figure 32, when EPDM scenario impacts ozone layer depletion significantly more than other categories). Secondly, it might be connected to the benefit – the benefit of EPDM is heating related, it improves insulation and so reduces the consumption of natural gas, whereas PV cells influence not only gas usage, but the whole electricity mix of The Netherlands, which is not only gas[10]. From a broader perspective this is logical, since gas is one of the "cleaner" components of the electricity mix. Therefore, we might conclude vaguely, that environmentally friendlier and more influential is definitely an investment into technologies that improve electricity consumption, rather than only heating consumption.

In addition to all so far mention reliability issues in LCA in general and specifically in this study, there was no uncertainty analysis carried out here either. In addition to chapter 3.4.2, here assumptions were calculated (chapter 3.4.3) or gathered from literature (Table 6) regarding energy benefits. Even though the reliability of these data was not quantified it is again believed to be representative enough for this study. However, the uncertainty analysis of this LCA model continues to be a challenge for the future research.

[10] Solid fuels 24%, Oil 3%, Gas 64%, Nuclear 4%, Renewables 7%. (Netherlands – Energy Mix Fact Sheet, 2007)

4.3.3 Guidance for increasing sustainability

In addition to solutions in chapter 4.2.3 there are some more recommendations on how to improve the sustainability through the energy perspective. PV cells turn out to be the best choice an investor can make currently environmental wise even in countries which are not renowned for their year-round sun. Besides that, investment into insulation is generally a good idea, but above a certain R value the effect on energy use will not be so obvious anymore (Figure 19), therefore it should be considered carefully. After a certain point heat losses through ventilation and air leakage become much more significant than those through fabric (at around 500mm insulation), and from here on it is important to ensure building airtightness overall and to use mechanical ventilation with heat recovery in winter. These can be, along with high levels of insulation, essential strategies to minimize heat loss. Usually a straightforward air-to-air heat exchanger is used to pass heat from outgoing stale air into preheating incoming fresh air. This can reclaim up to 75% of the heat from outgoing air, which more than makes up for the energy used to power fans for the system. Good controls and user understanding of the system may be important (A Guide to Sustainable Roofing, 2000). We should consider also the R values of other roof components; sometimes those might have a relatively high R value themselves (like EPDM or PVC). Instead, money should be invested in solar panels, which were in previous chapters proven as of the most sustainable choices possible currently.

5 CONCLUSION

Following the outlined research problem, a holistic environmental assessment of flat roof was presented, observing the sustainability through time and at three different levels. Results proved some interesting practical facts and gave ideas for improvements in sustainability. Brief conclusions regarding the assembly level are as follows:

- Roofing: single ply roof systems (EPDM and PVC) turned out to be a better choice considering environmental impact.
- The insulation: materials performed relatively similarly in terms of material environmental impact, but do make a significant impact in energy sustainability (chapter 3.4.3)
- The ballast: responsible for high environmental load due to the high weight. This damage is both – direct (material) and indirect (maintenance – heavy load on environment due to transport).

Furthermore, maintenance can in some cases be even more significant than the impact of assembly itself. Therefore, more attention should be dedicated to choosing proper maintenance activities, deciding between preventive or curative maintenance tactics and organizing maintenance activities in a way that the environmental load is as low as possible.

Energy savings definitely have the highest sustainability potential, since it can be seen on the Figure 32, that the energy savings in 50 years actually repays for the environmental damage in two of the scenarios. Hence, the first priority is therefore to design buildings which are energy-efficient in use.

As claimed before, it is essential to incorporate all the impacts that a product will have on the environment in the LCA. The problem might be, as it turned out in the case of green roofs, that the anticipated benefits are hardly quantifiable with current data. No or few research has been conducted, elucidating beneficial impacts of green roof on storm water retention, biodiversity. Furthermore, no research could be find to prove, which pollutants does green roof remove from the air or quantify how much does it function as a sound barrier. Consequently, if none of these promised advantages are taken into account, the overall activity of green roof cannot be recognized as sustainable, as was demonstrated with the results in this diploma work. A recommendation concerning green roofs - it should be first thoroughly tested for all the mentioned impacts and only after that implemented massively.

The research presented a holistic approach to assessing environmental damage of a building component – in this case the roof. It proves that incorporating all the life stages of the product (including maintenance) in the LCA of building is of critical importance, since there is no predictable relation between the environmental impact of material assembly and the impact of maintenance and energy of roof types. As illustrated in chapters 4.1.2, 4.2.1 and 4.3.1, environmental performance of roofs was not in any of the categories dependent on the impact in the previous level. Impacts on some environmental categories can stagnate throughout the life of the roof, meaning that maintenance activities do not cause much change in environmental impact (for example impact of maintenance of EPDM roof on fresh water aquatic ecotoxicity), whereas in some categories maintenance was detrimental (more or less all categories in green and PV cell roof scenario). Similar is true for energy benefit, environmental impacts here altered drastically in favour of PV cell roof. Time was found out to be a crucial factor in building sustainability, since the environmental load of maintenance and energy benefit change through time. This at the same time proves the inefficiency of qualitative tools, such as checklists, mentioned in chapter 2.1.2, since environmental impact assessment should always incorporate the dimension of time and thereby all the building characteristics related to it.

As claimed in the research hypothesis it was shown that all the phases do contribute to environmental burden significantly, now there is room for new, innovative sustainability solutions, which are as proved not necessarily only material related. There is proved potential for improvement especially in the use phase, where maintenance burden could be decreased to a minimum with better organisation and cooperation among parties.

In the end, no matter how and what type of roof is set on a building, there will be environmental damage. The planet is affected and so is its quality. The present research, however, has shown that environmental impacts of buildings can be reduced. Construction systems have to be carefully optimized, taking all the relevant influences on sustainability into account, thereby ensuring a brighter and more sustainable future for everyone.

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Appendix A - Overview of specific elements of selected assessment systems

Table 7: *Overview of specific elements of selected assessment systems (Todd, 2001)*

System	Building types	Criteria	Scoring/weighting/reporting results
GBC 2000	• Commercial • Multi-unit residential • Schools	• Resource consumption (energy, land, water, materials) • Loadings (greenhouse gases, ozone depleting substances, acidification, solid waste, liquid effluent, impacts on site and adjacent properties • Indoor environmental quality • Quality of service (flexibility, controllability, maintenance of performance, amenities • Economics* (life cycle, capital, operating/ maintenance) • Pre-operations* (construction management, transportation) * *Optional in GBC 2000*	• Each criterion scored • Scores range from −2 to +5 • Benchmarks for scores based on typical practice, local codes, or national standards • Scores summed to category level • Default weights provided for criteria and subcriteria; can be modified • Results presented as separate bars for each of four major categories
BREEAM UK	• Commercial office (new and existing) • Residential (EcoHomes) • Retail superstores, supermarkets • Industrial units	• Management (policy, procedures) • Energy (operational use, CO_2) • Health and well being (indoor and external issues) • Pollution (air, water) • Transport (CO_2, location factors) • Land use (greenfields, brownfields) • Ecological value of site • Materials • Water consumption and efficiency	• Credits awarded for each criterion • Weightings applied to produce overall score • Score translated into rating of fair/ pass, good, very good, excellent, or a sunflower rating • Certificate awarded • Updated regularly • 25% of new offices have been assessed for certification since inception
HK-BEAM Hong Kong	• Commercial office • Residential	Residential criteria: • Global issues and use of resources (energy efficiency, deforestation and loss of biodiversity, ozone depletion, environmental management, depletion of natural resources) • Local issues (ecological impacts and landscaping, wind and microclimate, noise/air/ water impacts of operation, construction management, waste management, water conservation) • Indoor issues (thermal comfort, air quality, lighting, noise, hazardous materials)	• Criteria linked to local regulations as benchmarks • Scores translated into ratings of satisfactory, good, very good, excellent
LEED United States	• Commercial office • Residential (under development)	• Site • Energy • Water • Materials • Indoor environmental quality	• Credits specified for each criterion • User selects criteria for scoring • Prerequisites must be met • Rating based on total number of points scored • Updated every three years
EcoProfile Norway	• Commercial office • Residential	• External environment (releases to air, water, ground; toxic substances; outside areas; transportation) • Resources (energy, water, land, materials) • Indoor climate (thermal, air quality, acoustics, lighting, radon, EMF, mechanical/ ergonomics	• Each criterion scored • Subcriteria weighted from 1–3 (energy weighted 10) • Results presented as bar charts for three major categories or target plot for detail within three major categories • Certification issued – 60 issued in first two years

Appendix B – Flow chart representing the contribution of products and processes to the environmental impact of roof assembly

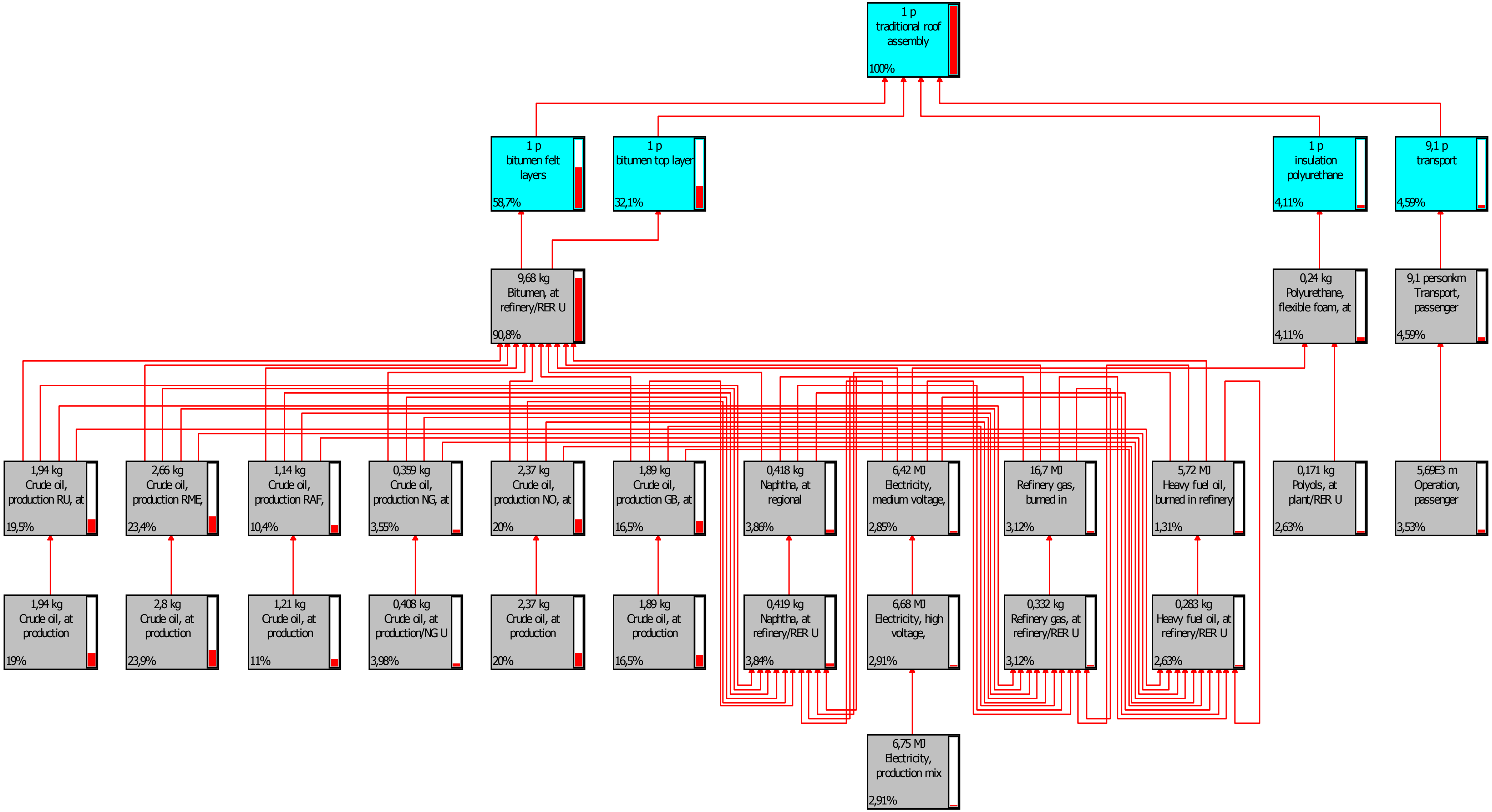

Figure 33: *Contribution of various products and processes to the life cycle environmental impact of traditional roof assembly*

Appendix C - Slope values for all maintenance and energy curves

Table 8: *Slopes of maintenance curves for all categories*

Impact category	Maintenance type	Traditional roof	Green roof	PV cell roof	EPDM roof
Abiotic depletion	Yearly Maintenance	1,96	4,91	7,11	1,47
	Repairs	9,22	10,88	10,18	5,45
	Replacements	69,85	64,62	322,59	15,38
	Total	4,23	6,87	19,4	2,4
Acidification	Yearly Maintenance	0,96	2,39	3,47	0,72
	Repairs	3,05	5,77	4,56	2,96
	Replacements	18,3	36,16	130,57	4,9
	Total	1,56	3,5	8,41	1,1
Eutrophic.	Yearly Maintenance	0,14	0,34	0,5	0,1
	Repairs	4,07	3,19	0,74	0,66
	Replacements	8,17	28,83	25,89	2,52
	Total	0,64	1,28	1,49	0,25
Global warming	Yearly Maintenance	290,19	725,48	1051,94	217,64
	Repairs	1674,97	2210,89	1422,36	1209,6
	Replacements	5787,05	15579,61	40522,98	1345,24
	Total	534,52	1214,35	2588,35	360,91
Ozone layer depletion	Yearly Maintenance	0,00004	0,0001	0,00014	0,00003
	Repairs	0,00018	0,00016	0,00014	0,00009
	Replacements	0,00004	0,0001	0,01283	0,00024
	Total	0,00008	0,00012	0,00062	0,00004
Human toxicity	Yearly Maintenance	119,22	298,05	432,18	89,42
	Repairs	539,87	707,82	506,83	333,39
	Replacements	2060,89	4395,71	12647,39	690,12
	Total	200,33	432,91	903,61	136,93
Fresh water ecotox.	Yearly Maintenance	15,8	39,51	57,29	11,85
	Repairs	3145,41	2285,27	163,16	142,06
	Replacements	7794,09	22497,05	4117,16	810,03
	Total	450,41	778,62	222,19	55,35
Terrestrial ecotoxicity	Yearly Maintenance	0,68	1,7	2,47	0,51
	Repairs	3,57	3,95	3,27	3,09
	Replacements	10,56	24,19	150,61	3,93
	Total	1,15	2,44	8,17	0,9
Photochemical oxidation	Yearly Maintenance	0,09	0,23	0,34	0,07
	Repairs	0,39	0,53	0,39	0,17
	Replacements	1,32	3,19	7,8	0,3
	Total	0,15	0,33	0,62	0,09

Environmental impacts with and without energy benefit

However, additional figures were presented above for better understanding. There, environmental impacts can be observed throughout building life, as in chapter 4.2. On those figures there are curves for maintenance scenarios (already observed in chapter 3.4.2) and the energy scenarios (which include maintenance and energy use). This is joined together in graphs to illustrate better to what extent the energy benefit can influence the impact. The difference between the curve of impact with energy benefit and the curve of impact without energy benefit, tells us how much less damage was done to the environmental category in a period of time. Environmental payback time can be estimated by observing the cross sections of the curves with energy benefit with the x axis (occurs in PV cell scenario).

Slopes with energy benefit (blue, pink, and light blue and grey) have the following characteristics:

If $k < 0$ ------- The energy benefit obtained by the application of this roof scenario dominates over the negative impacts (on a specific category) of the annual maintenance, repairs and replacements of this roof. This is a very desirable quality, but we have to pay attention that a certain scenario will probably not perform in this way in all environmental categories. We should also not interpret the negative values as a 'benefit to the environment', since it only means a benefit to the roof system and does by no means imply that the application of a certain roof type would never lead to an improvement of quality of the environment on a global scale. Therefore, it is good to know that there are negative k values and where they are, but it is not important how big the values are.
If $k = 0$ ------- In this case the impact of the amount of energy which is not used because the application of a certain roof type is exactly the same as the impact of maintenance. The energy represents a benefit and thus has a negative impact on damaging the environment. If an impact of annual maintenance in a certain scenario is equal to the impact of energy generated in that year, than the slope will be zero in this part of the curve. This is, as the previous one, an advantageous property.
If $k > 0$ ------ Here the energy generated, which is not being used (benefit) is not equal or bigger than the impact of maintenance. There are three possibilities in this case:

> $k_{energy} < k_{maintenance}$ ------- The energy benefit has a positive impact on this category, the nearer the k approaches the zero, the better for the environment.
> $k_{energy} = k_{maintenance}$ ------- The energy impact has no influence, energy use has no impact in this category.
> $k_{energy} > k_{maintenance}$ ------- Impossible, since the energy which is not used and represents a benefit, cannot have a negative environmental impact.

The four slopes with added energy benefit are presented on the same figures as the maintenance slopes (these were already presented in chapter 4.2), to enable better visual comparison. All the slopes follow the pattern, described in Figure 22.

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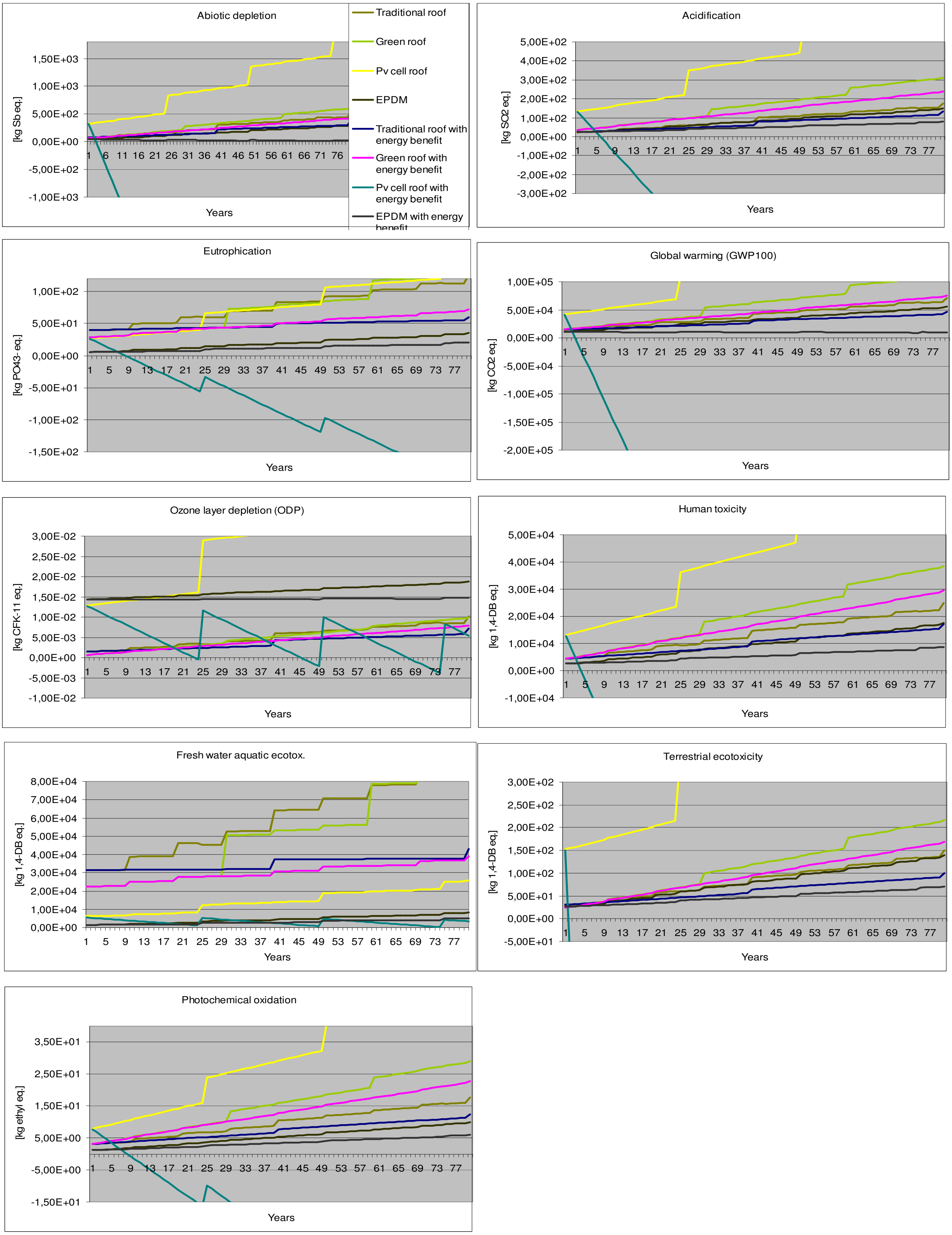

Figure 34: *Environmental impacts in all categories without and with energy benefit*

Abiotic Depletion
We can conclude here, that the energy which is not being used has a lot greater environmental impact than the assembly and maintenance activities, with the exception of green roof. Here, insulation plays a crucial role – the scenario with the best insulation is in this case the best, the second one is second best and so on. Environmentally friendlier scenarios have a shorter environmental pay back time.

Acidification
Again the best performance is given by the PV cell roof. Traditional roof also performs well, while the k values for EPDM is around zero. The largest improvement of sustainability next to the traditional roof scenario arises again in case of PV cell roof. The worse performance in sustainability goes to green roof; energy benefit is low due to low R – value.

Eutrophication
In category of eutrophication, the energy benefit does not have a significant impact. Obviously gas consumption does not influence environment in the category eutrophication enough for the 75 m^3 of gas which is not burned to show an impact. Similar phenomena are obvious if we take a look at EPDM or traditional roof scenario. The only big difference in sustainability is in case of PV cells, due to less electricity consumption. Such a discrepancy is caused by two facts - kWh of electricity 'saves' 7 times more in terms of eutrophication than does the kWh of natural gas and PV cells produce 25500 kWh, which is approximately 5 times the amount saved by improvement in insulations. Therefore, the sustainability of PV cells is again rated highest.

Global Warming
Impact of green and PV cell roof assembly and maintenance is superior to all others. In this graph, they are cut away to make the other impacts more visible. Again, the most sustainable is PV cell roof, followed by EPDM, traditional and green roof. All roof types perform satisfactory (cross x axis somewhere in building life).

Ozone Depletion
Ozone depletion impacts are the most diverse and messy. PV cell scenario, which had by far the highest impact considering maintenance and assembly, here performs a lot better. There is still a very big impact obvious on the occasions of replacements, but the scenario competes very well with green and traditional roof scenario. Also EPDM roof scenario has the worse performance here, although the energy savings cause a significant benefit. In this scenario the high damage produced in assembly is not repaid as well as in PV cell scenario. However, it does still cross the current state curve (red colour) at the age of building around 60 years. After this time, all the 4 scenarios will be performing better than the current state would (all the curves are bellow).

Human toxicity
All the scenarios experience improvement if we view sustainability through the perspective of energy use. PV cell roof has the highest improvement, followed by traditional, EPDM and green roof scenario. The benefit on sustainability depends directly on the amount of energy saved with a specific roof scenario, so according to Table 6 best (in terms of natural gas savings) should be PV and EPDM, followed by traditional and last, Green roof.

Fresh water aquatic toxicity
We can see in the graph above that quite some curves are missing, because they overlap with others. The reason is that (With the exception of PV cells) in this impact category it makes almost no difference in sustainability whether we include energy profile or not, which is understandable if we consider that the impact of assembly and maintenance is at least 3 times the order of magnitude greater than the impact of the natural gas saving. This is the category where energy benefit has the least significant impact on sustainability.

Terrestrial Ecotoxicity
The graph illustrates well, how important it is to take into account the whole life cycle of a product. If we observe the PV cell roof scenario only through its assembly and maintenance impact, it causes by far the greatest impact. By adding the impact of energy savings, which is an important function of PV cell the outcomes change drastically in a very short period of time (less than one year). All the other scenarios are improved according to expectations, similar to those illustrated in Table 8.

Photochemical Oxidation
Results are similar to many previous categories – best performance is attained by PV cells, followed by EPDM, traditional and green roof. If we take a look at the current state – the red line – we can witness in almost all categories all but green roof scenario is bellow. We can conclude briefly, that all scenarios will perform better than the current state would in the long term; the exception is only green roof scenario.

Appendix D - Forming the model

As described in the introduction, the objective was to develop a generic model for simple life cycle analysis. Data gathered from SimaPro software (from EcoInvent database) is very extensive and needs to be processed in order to understand the outcomes better, especially since maintenance is included. Maintenance activities can either improve (if better insulation is employed) or decrease building sustainability performance (if new component needs a lot of cleaning, inspections etc.) meaning that environmental performance of the building must be observed throughout the whole service life of the building. The data was further on managed in Microsoft Office Excel. One sheet, ‘Environmental Effects’ contains the data from Simapro, already normalized to effect of that material per m^2 of roof surface. In this chart there are impacts (all nine impact categories) for production and waste. A template sheet was created with flexible choices of materials, their quantities and most important - maintenance activities. Sheet ‘Maintenance and Lifespan’ contains material properties information, as well as waste treatment for that material. It should be emphasized in this point, that recycling of material was not taken into account, because recycling was considered a process which relates to the life cycle of the product which is produced out of this recycled waste and was not considered a part of life cycle of the roofs. Therefore, waste treatments considered are incineration and landfill, which are the most common ones. In the energy sheet there is data for environmental impact per kWh of Dutch Electricity mix and per kWh of natural oil consumption (for heating). For every relevant component it is also calculated what is the contribution to energy savings. The most important, first ‘Template sheet’ is where roof characteristics are determined (dimensions, materials and the maintenance activities). First, roof properties should be entered, than materials chosen, than the transport distance determined.

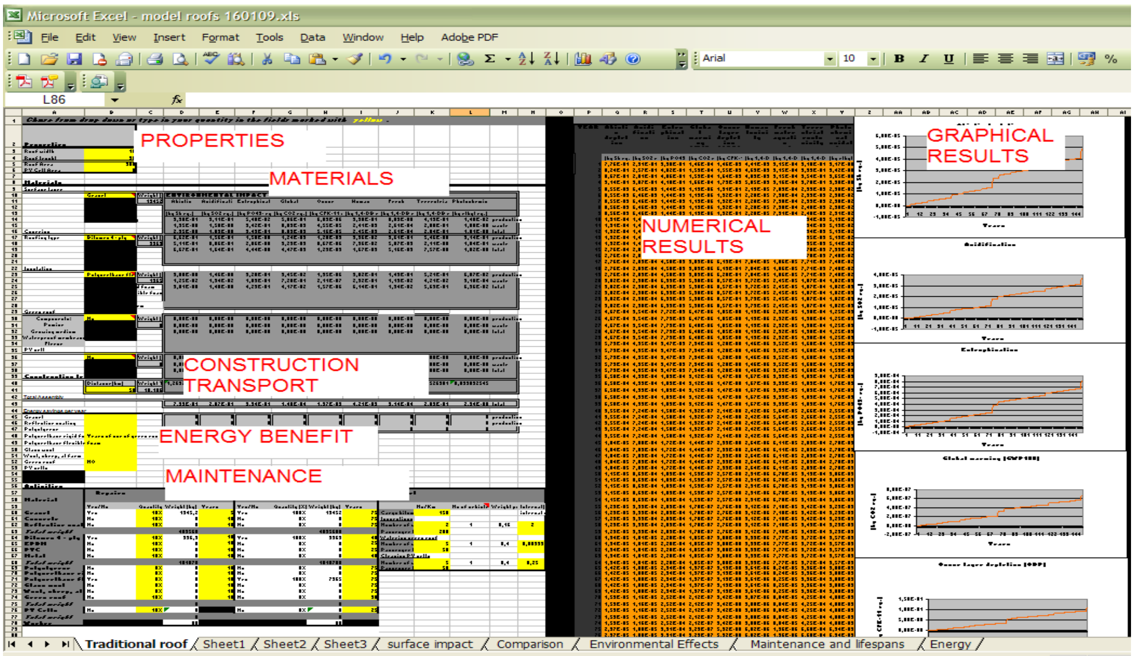

Figure 35: *Template sheet of the model*

Further, there is a tab where energy benefit of the chosen roof components can be either taken into account by choosing YES or omitted by choosing NO from the drop down list. The last are the maintenance activities - quantity and frequency of repairs and replacements has to be determined. Maintenance transports are also set separately from construction transports in this section because maintenance activities are usually carried out by another company that first construction. Due to the same reason, there is also a separate cell for transport of inspections and transport for cleaning.

Activities

Material	Repairs				Replacements			
	Yes/No	Quantity (:	Weight (kg)	Years	Yes/No	Quantity (%)	Weight (kg)	Years
Gravel	Yes	10%	1345,2	5	Yes	100%	13452	75
Concrete	No	10%	0	10	No	0%	0	75
Reflective coating	No	10%	0	10	No	0%	0	75
Total weight			403560				4035600	
Bitumen 4 - ply	Yes	10%	336,9	10	Yes	100%	3369	40
EPDM	No	10%	0	10	No	0%	0	25
PVC	No	10%	0	10	No	0%	0	25
Metal	No	10%	0	10	No	0%	0	40
Total weight			101070				1010700	
Polystyrene	No	0%	0	10	No	0%	0	75
Polyurethane rigid (	No	0%	0	10	No	0%	0	75
Polyurethane flexib	Yes	0%	0	10	Yes	100%	7365	75
Glass wool	No	0%	0	10	No	0%	0	75
Wool, sheep, at farı	No	0%	0	10	No	0%	0	75
Green roof	No	10%	0	10	No	0%	0	30
Total weight			0				0	
PV Cells	No	10%	0		No	0%	0	25
Total weight			0				0	
Worker			80				80	

Transport	No/Km	No of vehicles	Weight per	Interval(yr
Cargo kilome	150			interval ol
Inspections				
Number of w	2	1	0,16	2
Passenger ki	200			
Watering green roof				
Number of w	5	1	0,4	0,08333
Passenger ki	50			
Cleaning PV cells				
Number of w	5	1	0,4	0,25
Passenger ki	50			

Figure 36: *Maintenance section of the template sheet of the model*

On the right side of the sheet, graphs are automatically generated for all nine environmental effects and how they in/decrease through time. This sheet can be copied, which enables a user to compare sheets with different roof assemblies. Graphs can be generated on a separate sheet (in this case, named 'Comparison' to compare the growth of environmental impact of different assemblies (different template sheets copied) through time.