Can the energy transition profit from a circular transition?

A case study measuring the operational and embodied energy and CO2 impacts for the Lunetten Neighborhood.

Name: Marvin Spitsbaard
Adres: Terschelling 110, 3524AZ Utrecht
E-mail: marvin.spitsbaard@gmail.com

Supervisor Utrecht University: Robert Harmsen
Supervisor W/E Adviseurs: Erik Alsema
Second reader Utrecht University: Wen Liu

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Summary:

With large natural gas deposits present within the Netherlands, natural gas historically and currently still plays an important role within the Dutch energy system. However, increasing impacts of earthquakes caused by natural gas extraction, future threads of climate change and potential energy dependency on other countries ahead led to insights among politicians that natural gas should be phased out within the Netherlands. Therefore the Dutch national and local governments recently decided to formulate plans to act on the dependency of the Netherlands on natural gas as one of the main energy suppliers. Various sectors were asked to decrease their natural gas consumption in order to lower mentioned negative effects. One of these sectors is the residential sector in The Netherlands which still relies for the biggest part on natural gas with regard to its heat supply. A large number of houses need to be disconnected from the natural gas grid, while new alternative heat supply options need to be installed which sometimes also asks for intensive renovations with insulation upgrades for the existing building.

In this thesis various heat supply options combined with various renovation / rebuild strategies which together are called transition scenarios were investigated with regard to energy and CO2 impacts of materials use for renovation / rebuild and current and future energy use. Special attention within this research was given to circular renovation and rebuild strategies. To measure these energy and CO2 impacts a Circular Material Flow Analysis-Model (CIMFA-Model) Excel-tool was developed A total of 10 transition scenarios (TS. 1-10) were inserted and analyzed for the specific case study of the Lunetten neighborhood.

The results of this model showed that for the specific case study of Lunetten TS. 5, which is a standard low temperature heat network scenario, a decrease of 113.4 TJ of energy use in comparison to the old situation could be achieved performing best of all transition scenarios in terms of energy. Regarding CO2 emissions, TS. 6, which is a circular low temperature heat network scenario performed best in terms of CO2 emissions with a decrease of 6,860 tonnes of CO2 compared to the old situation. An in depth analysis with regard to embodied impacts further found values for embodied energy ranging 10-13% of the total energy use for standard homes, 15-27% of the total energy use for middle temperature retrofits (TS. 7 & 8), 28-44% of the total energy use for low temperature retrofits (TS. 1, 2, 5 & 6) and 30-53% of the total energy use for demolish & rebuild scenarios (TS. 3 & 4). This correspond with the general observation in literature of the growing importance of embodied energy as share of the total energy. Finally, a special long term scenario for cumulative CO2 emissions showed that over a 10 year period, TS. 6, which is a circular low temperature heat network scenario, with 70,882 tonnes of cumulative CO2 emissions performed best in terms of cumulative CO2 emissions. The savings potential for this scenario is 6,891 tonnes of CO2 / year which is equal to the yearly building energy use related CO2 emissions of approximately 1570 households.

Main conclusions that were formed based on this research is that first of all the energy transition can profit from a circular transition. Embodied CO2 impacts of circular materials were found to be lower than the CO2 impacts for standardly applied materials, therefore a circular transition scenarios allow greater CO2 reductions. Secondly, it was concluded that for the specific Lunetten case study low temperature heat supply solutions always pay themselves back on the long term in terms of CO2 emissions compared to transition scenarios which have middle or high temperature heat supply sources installed.

The CIMFA-Model that was designed for this specific research for Lunetten offers great flexibility in use and also allows itself to be re-used for future comparable research with regard to other neighborhoods. This study however urges that more research is needed in the future to improve the accuracy and data quality of the current model. With these improvements the CIMFA-Model could become a valuable tool for neighborhood analysis with regard to a circular energy transition.

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Table of Contents:

Summary Page 2

Acknowledgements Page 3

1). Introduction Page 6

2). Describing the Lunetten neighborhood Page 10
- 2.1). Building types Page 12
- 2.2). Construction periods Page 13
- 2.3). Building sizes Page 14

3). Model description Page 16
- 3.1). The CIMFA-Model Page 17
  - 3.1.1). Calculating stocks Page 17
  - 3.1.2). Calculating transition scenarios Page 18
  - 3.1.3). Outputs of MFA & results sections Page 20
- 3.2). The CIMFA-Model: assumptions and considerations Page 22
  - 3.2.1). Building envelope Page 22
  - 3.2.2). Heat supply options Page 25
  - 3.2.3). Renovation strategies Page 26
  - 3.2.4). MFA Page 29
  - 3.2.5). Results Page 29
- 3.3). Strengths of the CIMFA-Model and its methodology Page 29

4). Methods Page 31
- 4.1). Choice of (sub-)archetypes and heat supply options Page 32
- 4.2). Settings for a scenario analysis Page 34
- 4.3). Settings for a sensitivity analysis Page 34

5). Results Page 35
- 5.1). Energy and CO2 impacts for various transition scenarios Page 36
  - 5.1.1). Comparing demolish & rebuild strategies for a row house Page 36
  - 5.1.2). Comparing heat & renovation strategies for apartment buildings Page 38
  - 5.1.3). Analyzing the Lunetten neighborhood Page 43
- 5.2). Cumulative emissions for various 10 year transition scenarios Page 45
- 5.3). Sensitivity analysis Page 49
  - 5.3.1). Sensitivity of life-expectansy variables Page 49
  - 5.3.2). Sensitivity of CO2 emissions variables for energy production Page 50

6). Discussion Page 52
- 6.1) Limits of the study Page 53
- 6.2) Contribution to literature Page 54
- 6.3) Recommendations to future research Page 55

7). Conclusion Page 56

8). Reference List Page 59

1). Introduction:

Ranging from the Brundtland report from 1987 (Brundtland, 1987) until the more recent Paris agreements from 2015 (United Nations, 2015), all emphasize the importance of combatting climate change by reducing CO2 emissions. Shifting from fossil energy resources towards renewable energy resources will play an important role in this transition. This is also one of the reasons why the Dutch government recently created plans to phase out natural gas in the built environment. Other drivers to phase out natural gas are the earthquakes in Groningen province (Rijksoverheid, 2016a) and uncertainties about future energy security because of an energy dependency on other countries (TNO & HCSS, 2017). The urge from the national government to act on these three drivers recently led to (local) governments and housing corporations setting themselves targets for a sustainable transition of the existing building stock. Housing corporations for instance targeted themselves to have roadmaps ready by 2018 describing how to make the existing building stock zero carbon by 2050 (Aedes, 2017), while local governments agreed to have a plan ready by 2021 describing how to achieve a natural gas free built environment (IPO et al, 2017; VNG, 2017).

Many targets have thus been set, and achieving this all promises to become a massive task since the Dutch housing stock of approximately 7.7 million homes (CBS, 2017) for the majority still depends on natural gas for its heat supply. From a technical point of view it should however be possible since various heat supply options exist such as district heating and various types of heat pumps. These heat supply options can be combined with a specific renovation strategy for the building (e.g. standard renovation, circular renovation) forming a potential transition scenario.

Having special attention for the last mentioned circular renovation strategy is also in line with recent national and international ambitions regarding circularity from the EU, with recent new laws being passed (EU, 2018) and the Dutch national government, setting targets and striving towards a fully circular economy by 2050 (SER, 2016; Rijksoverheid, 2016b; Rijksoverheid, 2018). Earlier mentioned transition should thus take place in a circular way. But what are the gains of performing an energy transition in a circular way compared to various other alternatives? How do various heat supply options affect this? And does the focus on circularity lead to changes in preferred solutions?

In this study the operational and embodied energy and CO2 impacts will be evaluated for a few transition scenarios. These different transition scenarios are composed of a selection of heat supply options which are combined with various renovation strategies (one of them focusing on a circular renovation strategy). Measuring these energy and CO2 impacts for various transition scenarios is however a challenging task since a lot of data is needed which often is not available.

At this moment a lot of studies are done with relation to the transition of building stocks relying on natural gas towards one using natural gas free alternatives. However specific studies that within this transition specifically aim for a circular transition and measure potential beneficial or detrimental impacts in terms of energy and CO2 are still lacking. This last statement is also underlined by a recent study from Pomponi & Moncaster (2017), which mentioned that literature on circular economy in the built environment is still in its infancy. In this same study three scales for research towards an circular economy in the built environment were mentioned namely: the micro-scale (individual components), the meso-scale (houses) and the macro-scale (neighborhood / city level). This study will focus on the impacts in terms of energy and CO2 on the meso-scale (individual houses) and the macro-scale (neighborhood scale).

General studies towards impacts as embodied energy and embodied CO2 are widespread in literature. Examples are for instance studies towards strategies to reduce embodied emissions (Pomponi & Moncaster, 2016), greenhouse gas emissions of new construction (Säynäjoki, Heinonen & Junnila, 2012), embodied energy of refurbishment vs. new built (Gaspar & Santos, 2015), archetype investigations towards embodied energy in the Netherlands (Koezjakov, Urge-Vorsatz, Crijns-Graus & van den Broek, 2018) and an investigation towards building sector wide embodied energy use and its potentials for savings in the UK (Mandley, Harmsen & Worrel, 2015). However to the knowledge of the author a study that specifically evaluates the energy and building material related energy and CO2 impacts for the building stock that is going through a (circular) transition from natural gas to natural gas free does not yet exist. Therefore this research aims to fill in the following knowledge gap:

''Getting insights into the potential benefits in terms of operational and embodied energy and CO2 impacts for circular transition scenarios in the energy transition from a built environment using natural gas, to one using natural gas free alternatives for the existing residential building stock in The Netherlands''.

For this research two objectives have been set. First of all this research aimed to make a model that could measure the potential benefits in terms of energy and CO2 for various circular transition scenarios for a Dutch neighborhood going to an energy transition, replacing natural gas as main source of heat supply for a natural gas free alternative. When finished the second objective within this research was to measure those impacts for a specific case study (a neighborhood) within the Netherlands and based on these results for the individual neighborhood make statements about how much an energy transition in the Netherlands could profit from a circular transition. Hereby the results will make a contribution to current body of knowledge regarding existing building stocks going through a transition from natural gas to natural gas free neighborhoods. Because of the special attention given to circular renovation strategies this research thereby also makes a specific contribution towards earlier national and international ambitions regarding circularity. The following main research question was formulated for this research:

What are the differences in operational and embodied energy and CO2 impacts when comparing circular transition scenarios with non-circular transition scenarios for a situation of an energy transition where natural gas free heat supply alternatives replace natural gas as main source for heat supply in existing dwellings in the Netherlands?

To answer this main research question the following sub-questions were formulated:
SQ 1). What are the embodied energy & CO2 impacts of the materials within these transition scenarios?
SQ 2). What is the operational energy performance of the buildings within these transition scenarios?

This research project is part of a bigger research project that is currently running between a consortium consisting of, Utrecht University & W/E adviseurs as main partners. This bigger research project named: ''SmartTrans project'' (funded by a Topsector Energie MVI-E research grant) aims to investigate how to make so called smart roadmaps that incorporate factors such as support, a monitorable time-path, flexibility, potentials for synergy and feasibility for the transition from a natural gas to a natural gas free built environment. Pilot-neighborhoods for the SmartTrans project are: Hoge Vucht (Breda), Bottendaal (Nijmegen) and Lunetten (Utrecht) (W/E adviseurs et al, 2017a).

For this specific study the Lunetten neighborhood was chosen. The results from this research for the Lunetten neighborhood can thus form input for the overlapping ''bigger research project SmartTrans'' by giving an example how things work out on the level of an individual neighborhood within the Netherlands.

In order to achieve earlier mentioned objectives and answer the main research question for this research project the report was structured as followed: Starting in chapter two, a short investigation of the neighborhood that will be investigated in this research (Lunetten) is given. Next in chapter three the for this research specially designed model (The CIMFA-Model) will be described (how does it work, which assumptions were made during the creation of the CIMFA-Model and what are the advantages of the CIMFA-Model). Up following in chapter 4 the steps needed to come to results for the specific case study of Lunetten will be described. This asks for a synthesis of data from chapter two with the model as described in chapter three combined with a selection of additional inputs. In chapter 5 then the results of the investigation done with the CIMFA-Model will be described. The portraying of the results will follow a step wise approach going from small scale (starting at a level of one heat supply scenario) to large scale analysis (with examples given on the neighborhood scale for both an immediate renovation and a 10 year scenario). After the results in chapter 6 (discussion) insights will be given into the limits of the current study, its contribution to (scientific) literature and recommendations for future research. Finally this research will conclude with chapter 7 (conclusion) giving an overview of the main results obtained from this research.

2). Describing the Lunetten neighborhood

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The neighborhood of Lunetten is a neighborhood present in the South-East of the city of Utrecht see Figure 1. As of 2018 the neighborhood has 11,552 citizens of which 5,855 male and 5,697 female (Buurtmonitor, n.d.). The neighborhood has primarily been constructed during the period 1975-1985 and mainly consist of row houses and various types of apartment buildings, see Figure 2.

Figure 1: Map of the Lunetten neighborhood (Gemeente Utrecht, 2015).

Figure 2: Overview of typical buildings in Lunetten (images ©: authors own).

Regarding the population in Lunetten data shows that the neighborhood consist of 6442 households (of which more than half is a single person household). Further as can be seen in Figure 3 young adults (approximately 1/3 of the population) are relatively well represented within the neighborhood (Buurtmonitor, n.d.). Both of these details are in line with the fact that Lunetten contains a relatively large student population.

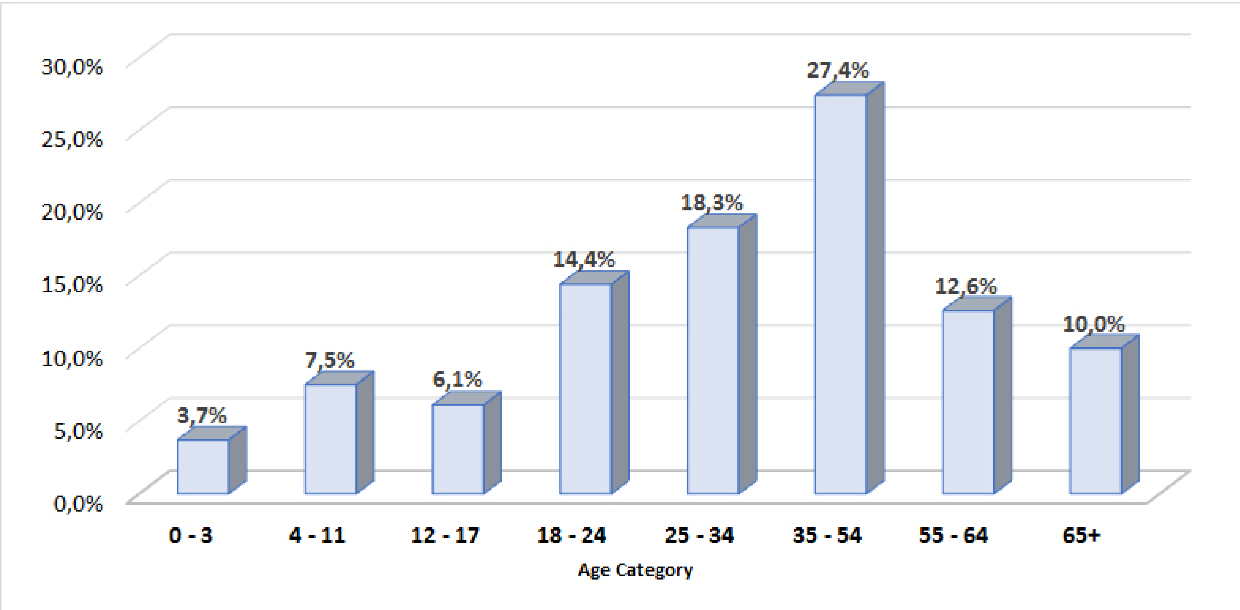

Figure 3: Age distribution for the Lunetten neighborhood (Buurtmonitor, n.d.).

Data about the building stock of Lunetten data shows that Lunetten contains a total of 5685 addresses of which 5476 addresses have a residential function (BAG, n.d.). Of the building stock with a residential function 63.7% falls within the social housing rental sector, 2.2% falls within the private rental sector and 34.1% are privately owned houses (Buurtmonitor, n.d.).

Relevant for this research are the building types and construction periods since they need to be translated into archetypes. Finally these archetypes will then also be further delineated into sub-archetypes based on size, therefore details about building sizes are also relevant for this research.

2.1). Building types

Figure 4 shows when decomposing all addresses in Lunetten (BAG, n.d.) based on house type (archetype) that several archetypes are dominantly present. First of all row houses (corner and middle) account for 1976 dwellings (which is 36% of all addresses that hold a residential function). Secondly one can identify that several types of apartment buildings like apartment, gallery flat, maisonette and tenement house when combined also hold a dominant presence (3279 dwellings or approximately 60% of all addresses that hold a residential function). When thus making an inventory which building types could best represent the existing housing stock in Lunetten, using the building types row house and apartment building would be most beneficial. The categories row houses and apartment building combined capture a large amount (96%) of the existing building stock of Lunetten which holds a residential function with only two building types.

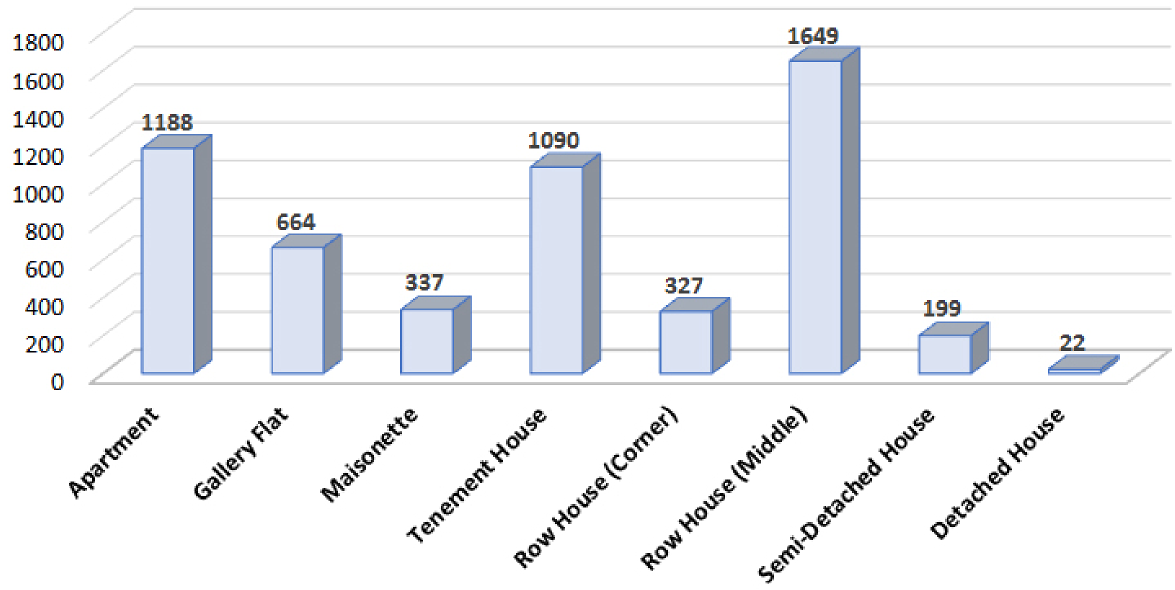

Figure 4: Archetypes and their amounts in Lunetten (BAG, n.d.)

2.2). Construction periods

Having defined the two most common building types within Lunetten, now a further analyse can be made regarding construction years for these most common building types (BAG, n.d.). Figure 5 shows the years that have seen the construction of at least one of these buildings. Analysing Figure 5 learns that major construction in Lunetten started in the year 1977 and lasted untill 1985. Besides this main period for construction one could further distinguish a second smaller and shorter construction period from 1990 - 1993. The amount of row houses and apartments constructed during this period is with 487 dwellings much smaller compared to the 4658 dwellings constructed during the period 1975 - 1985.

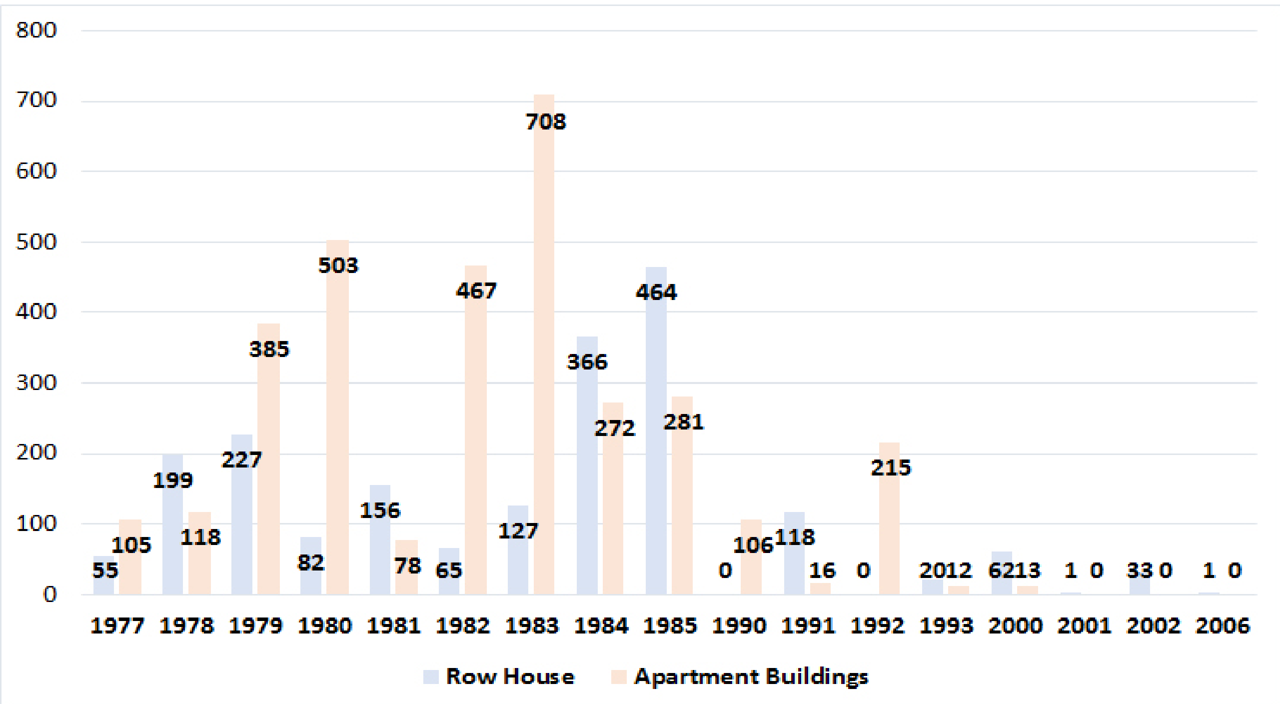

Figure 5: The construction years for building stock of Lunetten (BAG, n.d.).

2.3). Building sizes

Having delineated the building types to only the two most relevant building types row house and apartment buildings, the final part of the building stock that remains relevant to analyze are the sizes of the buildings. In Figures 6 & 7 an overview is given of the various sizes (expressed in useful surface or GBO) of dwellings which is based on the value given in Basisregistratie Adressen en Gebouwen or BAG (BAG, n.d.). This was done by creating classes (with a range of 10m²) for both row houses (Figure 6) and apartment buildings (Figure 7) and shows the prevalence per class. Only classes that hold at least one dwelling have been visualized in the figure.

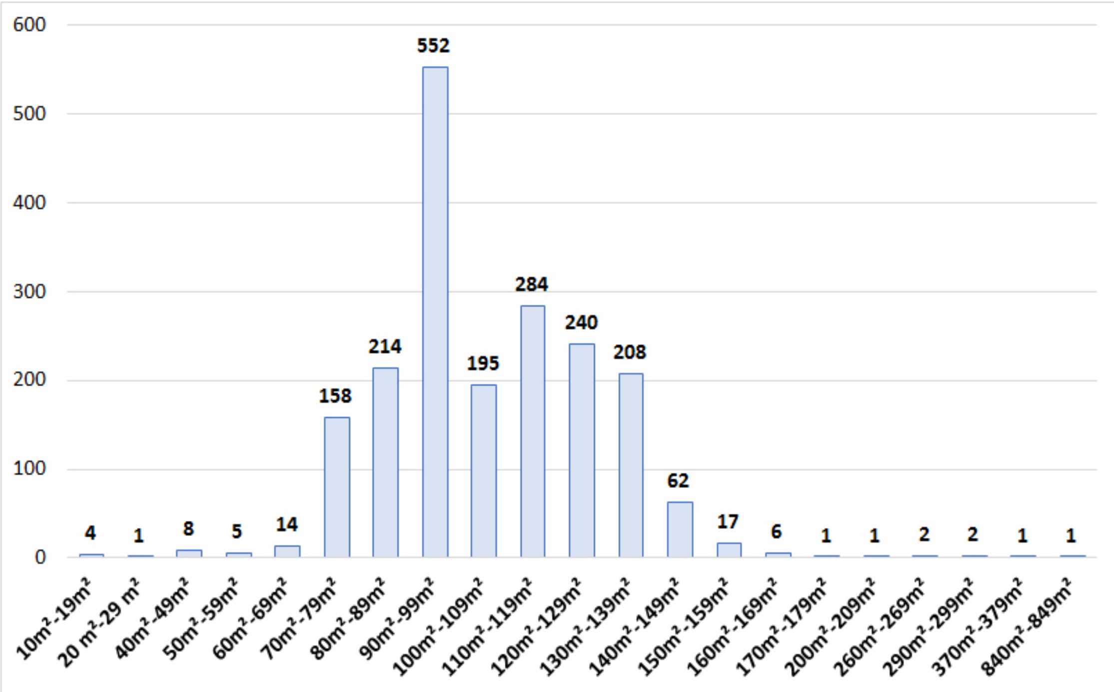

Figure 6: Row houses divided over classes, and their prevalence per class.

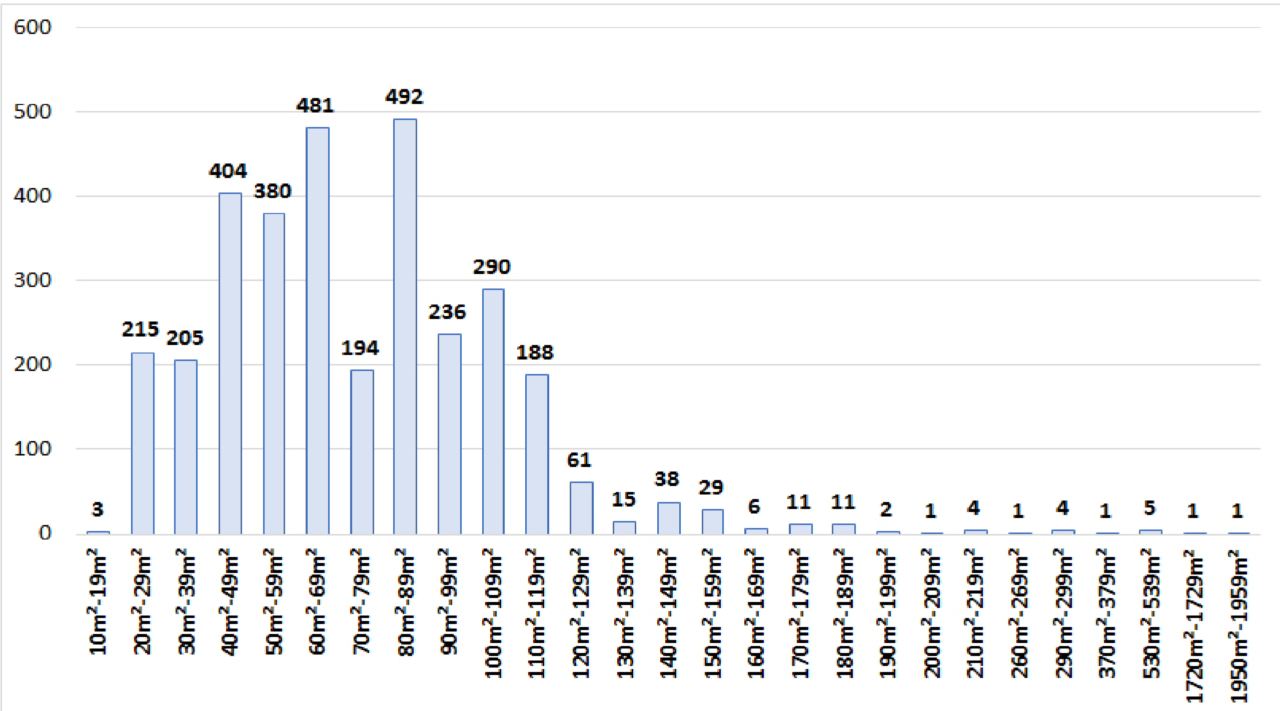

Figure 7: Apartment buildings divided over classes, and their prevalence per class.

Evaluating Figures 6 & 7 one could state most row houses can be seen in the range of 70m² - 139m² while for apartment buildings most dwellings can be found in the range of 20m² - 119m². More classes exist however the prevalence of dwellings is relativity small. Also some of these classes suggest issues regarding the data quality of the BAG-file that was used, for instance the apartment buildings with a size within the range of 1950m² – 1959m² which doesn't seem rather realistic.

Based on the results in Figure 6 & 7 the eventual sub-archetypes that are going to be used for this research can be formulated. In Table 1 below an overview is given.

Archetype number	**House type**	
	Row Houses	**Apartment Buildings**
Archetype 1	70m² - 79m²	20m² - 29m²
Archetype 2	80m² - 89m²	30m² - 39m²
Archetype 3	90m² - 99m²	40m² - 49m²
Archetype 4	100m² - 109m²	50m² - 59m²
Archetype 5	110m² - 119m²	60m² - 69m²
Archetype 6	120m² - 129m²	70m² - 79m²
Archetype 7	130m² - 139m²	80m² - 89m²
Archetype 8		90m² - 99m²
Archetype 9		100m² - 109m²
Archetype 10		110m² - 119m²

Table 1: Sub-archetypes selected for research (split-up per house type).

3). Model description

Section 3.1 explains the working of the Circular Material Flow Analysis-Model (CIMFA-model) that has been developed for this research. Next the considerations and assumptions that have been made for the CIMFA-Model will be described and elaborated up on in section 3.2. Finally in 3.3 the advantages of using the CIMFA-Model methodology are shortly evaluated.

3.1). The CIMFA-Model

When describing the working of the CIMFA-Model in short, three phases could be distinguished. The first phase determines the current situation. The second phase encompasses the determination of material inflows and outflows for various investigated transition scenarios. The third phase will explain how outputs from the various transition scenarios are converted to material flows and associated material related energy and CO2 impacts. The following three sections will further elaborate on these three phases.

3.1.1). Calculating stocks

The first step in the CIMFA-Model encompasses the determination of materials in the existing building stock. This step is visualized in Figure 8. This visualization is further explained below this figure following a step wise approach.

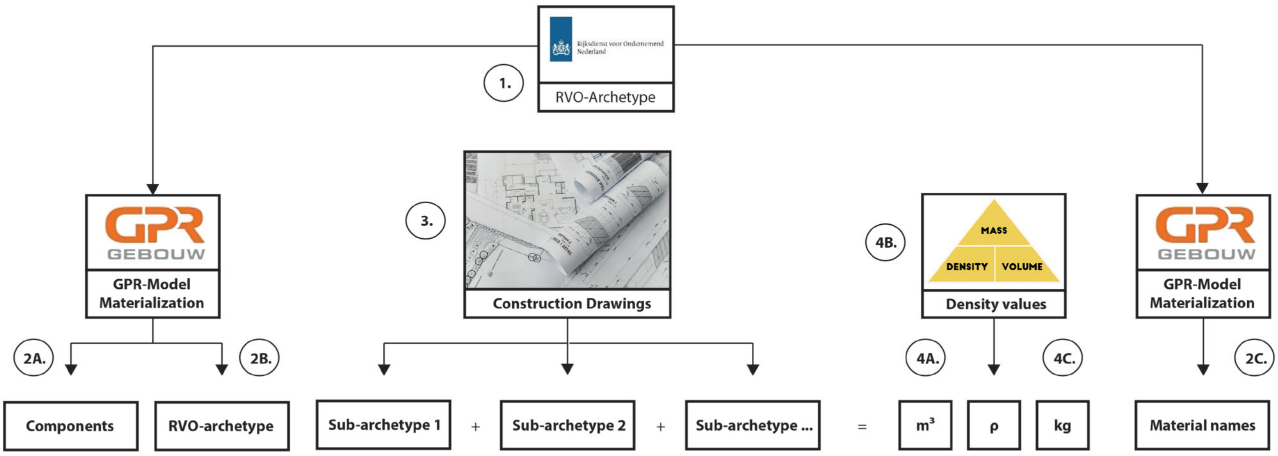

Figure 8: Overview of stock calculation

1). The first step of the CIMFA-Model encompasses the selection of an archetype. Several options existed like for instance the TABULA-webtool, RVO-archetypes or the option of developing own archetypes. For the CIMFA-Model it was eventually decided to use the RVO-archetypes since additional data about material use was available within the GPR-gebouw tool.

2A). Based on the RVO-archetype(s) that are going to be used the built-up of the archetype is defined and divided over 5 components (floor, walls, roof, windows & doors and installations). Each of these components is then further subdivided into several sub-components (e.g. for the (ground)floor: floor, insulation, screed floor, floor finish) in accordance to the values given for the example RVO-archetype in GPR-gebouw.

2B). Data with regard to the building geometry of the RVO-archetype(s) present within the GPR-gebouw tool is inserted into the model. The geometry with regard to material thicknesses will be an input for all up following sub-archetypes (explained at step 3).

2C). Finally a material name has to be allocated to each sub-component defined in step 2A. The material names will be derived the RVO-archetype present within the GPR-gebouw tool.

3). Each archetype within the CIMFA-Model has to be broken up into various classes (sub-archetypes) which are based on sizes of the buildings within the investigated neighborhood. For each of the sub-archetypes the parameters length, width, height (for each separate building level), combined with 4 specific roof parameters: ''front façade to highest point (FFH)'', ''back façade to highest point (BFH)'', ''left side to highest point (LHP)'', ''right side to highest point (RHP)'' have to be inserted into the model. This input will combined with the standard thicknesses for various materials (which are based on the values given for the GPR-Gebouw model of the RVO-archetype) automatically calculate the m³ of materials per sub-component within each sub-archetype.

4A). Based on the data inputs for sub-archetypes all material stocks for each separate sub-archetype were calculated in step 3. In this step for each for each sub-archetype and each sub-components the materials stocks in are multiplied with the amount of dwellings within that category. Finally the totals for each sub-component per sub-archetype are summed together to give for each sub-component the total amounts for all sub-archetypes combined. These outputs can be given (depending on the component type) in m³ (for floors, walls, roofs and windows & doors), as an amount (for installations) or per m² GBO (auxiliary equipment for installations).

4B). Based on the material names given in step 2C this step will for each of the materials (which are given as an amount in m³ of materials) determine the corresponding density value for the material (using a formula that automatically determines this value).

4C). Where values given in the units: ''amount'' or ''per m² GBO'' in step 4A are already the final results regarding the stocks, materials given in step 4A as an amount in m³ will in this step undergo a final conversion. In step 4C these values in m³ of materials will be multiplied with their corresponding density value as determined in step 4B in order to obtain the final stocks in kg of material.

3.1.2). Calculating transition scenarios

The CIMFA-Model contains several tabs that calculate the material impacts for various transition scenarios. Figure 9 is a visualization that distinguishes the main components within such a transition scenario tab. There are several tabs available that differ in heat supply option, with an example: tabs could have in common that for instance they all contain low temperature heat supply solutions. However they could still vary from one another based on how this heat is supplied. Low temperature heat can for instance be supplied with a heat pump but could also be supplied by a heat network). However within these separate tabs three stages for the calculations can be distinguished that are for all these tabs roughly the same namely: sub-components list, sub-archetype list, inputs and outputs and finally scenario outputs. The sections below will further explain these different stages present within the transition tabs of the CIMFA-Model.

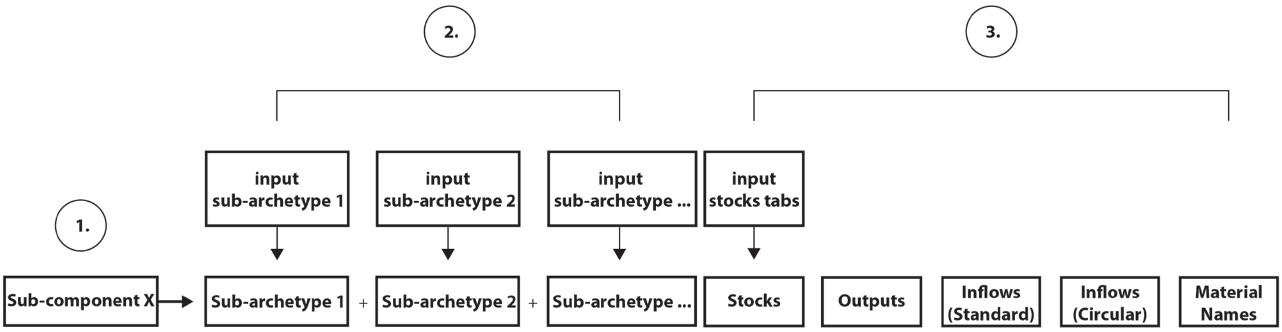

Figure 9: Overview of a transition scenario tab in the CIMFA-Model.

1. (Sub)-component list

At stage 1 in Figure 9 an overview of all the various (sub)-components present within the building is given. These are all similar to the ones used in the stocks tab, however a difference is that a few new sub-components have been added (additional insulation, new outer facing, different heat supply installation etc.). These new sub-components are all related to the changes that take place in each transition scenario.

2. Sub-archetypes, inputs and outputs

In stage 2 the boxes for inputs for the sub-archetypes represent selections that have to be made with drops down selection menus for the specific investigated scenarios. These drop down selection menus allow to steer all transition scenarios within the tab with regard to heat supply strategy and renovation strategy. For heat supply strategy a drop down menu will give the following options:
1). Individual choice
2). High temperature heat
3). Middle temperature heat
4). Low temperature heat

Regarding the renovation strategies a drop down menu will give the following options:
1). Individual choice
2). Standard Scenario
3). Circular Scenario

If for heat supply strategy either option 2, 3 or 4 is selected this will automatically set the corresponding minimal rc-values and maximum u-values given within this tab as the default input value for all renovations that take place within this transition scenario tab. The same counts for renovation strategies when either option 2 or 3 is selected. Choosing for option 1 means for both cases that for every sub-archetype the heat supply strategy and / or renovation strategy has to be manually inserted per sub-archetype . This allows flexibility because for each sub-archetype a different heat supply strategy and renovation strategy can be selected. Based on these settings the formulas in the Excel tab will interact with the data. Depending on what heat supply strategy was chosen rc-values and u-values corresponding with this heat supply strategy will be inserted into the formulas. Secondly based on the renovation strategy that was chosen it is automatically determined which material is going to be used to perform this renovation. The working of these formulas will be explained in more detail in section 3.2.3.

3. Scenario outputs

In stage 3 the stocks, material outflows and material inflows are determined for each separate sub-component. Table 2 gives a detail how this is visualized for stocks and outflows. First three columns give data with regard to the old situation (based on input data from the stock tabs), next four tabs will determine for these stocks which will see outflows and how much these outflows are.

Old Stocks (m^3)	Old Stocks (kg)	Remarks	Total outflows (m^3)	Density	Total outflows (kg)	Remarks
... m^3	... kg	Name ...	... m^3	Density ...	... kg	Name ...
... m^3	... kg	Name ...	... m^3	Density ...	... kg	Name ...
... m^3	... kg	Name ...	... m^3	Density ...	... kg	Name ...

Table 2: Stocks and outputs in the various transition scenarios

Next, the inflows per renovation / rebuild strategy are summed for all sub-archetypes (where the results per sub-archetype are also multiplied with the amount of dwellings that fall within that sub-archetype category). Table 3 gives a detail how the inflows calculation is visualized.

Standard Scenario				Circular Scenario			
Total inflows (m^3)	Density	Total inflows (kg)	Remarks	Total inflows (m^3)	Density	Total inflows (kg)	Remarks
... m^3	Density ...	... kg	Name ...	... m^3	Density ...	... kg	Name ...
... m^3	Density ...	... kg	Name ...	... m^3	Density ...	... kg	Name ...
... m^3	Density ...	... kg	Name ...	... m^3	Density ...	... kg	Name ...

Table 3: Inputs in the various transition scenarios

3.1.3). Outputs of MFA & results sections

In this section the outputs of the CIMFA-Model are shortly described starting with the large tables with individual Material Flow Analysis (MFA) where results of material flows and associated impacts can be found. This section will explain the structure of these large tables by explaining how they allocate materials flows and associated impacts, consisting of 4 categories: m^3 / amount / per m^2 GBO, (for further explanation see next section), kg, embodied energy (MJ) and embodied CO2 emissions (kg). This section concludes with an explanation how these results lead to the eventual results of the CIMFA-Model.

Determining m^3 / amounts / per m^2 GBO, kg

In the first two column sections the material flows are determined for the stocks (current situation) and for every transition scenario. These quantities could be given in either in m^3 (for most construction materials), in amounts (mainly for installations) or per m^2 GBO (mainly for auxiliary equipment of installations). The data inputs for the stocks were obtained from earlier described stock tabs, while up following columns will visualize for each heat supply scenario the inflows of materials (based on inflows given for each transition scenarios given in their specific tab). Table 4 shows this for heat supply scenarios combined with a standard renovation strategy. Table 5 shows the same principle for heat supply scenarios however combined with a circular renovation strategy. Different this time are the final 3 columns which are all related to the demolish & rebuild scenario. In these last 3 columns the first gives the fraction / amount of outflows for each specific material that can be re-used within this scenario (calculated by outflows multiplied by factor re-use), the second columns shows the demand of new materials within this transition scenario and the final column gives the remaining material need for this transition scenario (calculated by: inflows minus re-use). With material stocks and inflows calculated earlier quantities measured in m^3 will be converted to kg of materials in the next two column sections (quantities measured in amounts or per m^2 GBO, are left blank in these column sections of the individual MFA's). The values for kg of materials are obtained by multiplying the amounts in m^3 that were calculated in previous two column section with associated densities for each specific material. The lay-out for these tables is equal to those used for m^3 / amounts / per m^2 GBO in Tables 4 & 5.

Flow ... / per sub-archetype / per material type				
Material Name	Archetype	Stocks	Standard	
			Inflows	
	Name of archetype		Heat Supply Scenario 1	Heat Supply Scenario 2
	Sub-archetype 1	Value ...	Value ...	Value ...
	Sub-archetype 2	Value ...	Value ...	Value ...
	Sub-archetype ...	Value ...	Value ...	Value ...

Table 4: Material stocks and flows for original building and standard renovation scenarios.

Flow ... / per sub-archetype / per material type						
Material Name	Archetypes	Circular				
		Inflows		Outflows (re-use)	Inflows	Balance (Still needed)
	Name of archetypes	Heat Supply Scenario 1	Heat Supply Scenario ...	Demolish & Rebuild	Demolish & Rebuild	Demolish & Rebuild
	Sub-archetype 1	Value ...	Value ...	Value ...	Value ...	Value ...
	Sub-archetype 2	Value ...	Value ...	Value ...	Value ...	Value ...
	Sub-archetype ...	Value ...	Value ...	Value ...	Value ...	Value ...

Table 5: Material flows for circular renovation scenarios.

Determining embodied energy and embodied CO2

In the final four column sections within the individual MFA's the material flows in kg, amounts of installations and m² GBO are multiplied with their associated material impacts (based on values from GPR which uses the nationale milieudatabase or NMD). In this way the energy and CO2 impacts for earlier determined materials flows are obtained for each separate sub-archetype. Lay-outs for the tables are the same for both energy and CO2, Tables 6 & 7 give an overview of the lay-out for these tables.

Flow ... / per sub-archetype / per material type				
Material Name	Archetype	Stocks	Standard	
			Inflows	
	Name of archetype		Heat Supply Scenario 1	Heat Supply Scenario 2
	Sub-archetype 1	Value ...	Value ...	Value ...
	Sub-archetype 2	Value ...	Value ...	Value ...
	Sub-archetype ...	Value ...	Value ...	Value ...

Table 6: Impact category for standard renovation scenarios.

Flow ... / per sub-archetype / per material type				
Material Name	Archetype	Standard		
		Inflows		
	Name of archetype	Heat Supply Scenario 1	Heat Supply Scenario 2	Heat Supply Scenario ...
	Sub-archetype 1	Value ...	Value ...	Value ...
	Sub-archetype 2	Value ...	Value ...	Value ...
	Sub-archetype ...	Value ...	Value ...	Value ...

Table 7: Impacts category for circular renovation scenarios.

From the results as described in Tables 4, 5, 6 & 7 the eventual results within this project are derived. First of all, relevant could be to have an overview of physical material inflows per transition scenario. These will mainly be obtained from the column sections for kg (mainly for construction materials), amounts (mainly for installations) and per m² GBO (mainly for auxiliary equipment of installations). Besides the physical material flows the values for embodied energy and CO2 per sub-archetype also form an important result. At the bottom of the MFA tables totals of all individual material embodied energy and CO2 values are counted up together in order to obtain the indicators total embodied energy and CO2 per sub-archetype/ per transition scenario. From this data two additional indicators are then derived namely: embodied energy or CO2 per m² of GBO and embodied energy or CO2 as share of total energy (calculated by: embodied energy or CO2 divided by (the embodied energy or CO2 + operational energy or CO2)). With these indicators a range of analyzes can be performed with the CIMFA-Model depending on the wishes of the user.

3.2). The CIMFA-Model: assumptions and considerations

Where the previous section visualized and explained the basic working of the CIMFA-Model in this section assumptions and considerations that were made with regard to the CIMFA-Model will be explained. In section 3.2.1 this will be explained on the level of the building envelope, section 3.2.2 will explain this with regard to the heat supply options, in section 3.2.3 it will be explained for the renovation strategies, in section 3.2.4 it will be explained for the MFA outputs and finally in section 3.2.5 insights will be given for the assumption and considerations with regard of the results. More assumptions/references exist, these can be found within the CIMFA-Model

3.2.1). Building envelope

On the level of the building envelope in this research 5 categories have been distinguished that are expected to capture all relevant materials stocks and building components that include materials that will see changes during a process of retrofitting / new construction. These 5 categories are floors, walls, roofs, windows & doors and installations. For each of these 5 categories a further elaboration on assumptions and considerations with regard to the building envelope (measures) was made in the next 5 headings below. In each elaboration an overview of existing options is given and are then followed with an explanation which of the options has eventually been selected and why. This section concludes with a sixth and final heading that explains the methodology regarding compensation for corner houses (row houses) and allocation of (shared) components in apartment buildings (e.g. floors and roofs).

Floors

Regarding insulation measures for the floor two options exist. The easiest option is to add insulation in the crawl space underneath the floor. Secondly in case no crawl space is present or the crawl space is not suitable for insulation, insulation could also be added on top of the existing floor. This last option is however always less desirable because the height between floor and ceiling will decrease. The downsides of this are that decreasing the height by adding insulation can only be done to a certain extend (one could not add insulation unlimitedly) as well as that the doors should be adjusted to the new heights (Milieucentraal, n.d.a). The first options of adding insulation beneath the floor in the crawling space thus has a preference, however can only be applied when crawling spaces are present. Since Lunetten is a mainly 70s-80s neighborhood during which crawling spaces were common, for the purpose of this research it will be assumed that these crawling spaces are present.

Walls

Regarding insulation measures for walls two options can be distinguished. First of all insulation could be added to the walls from the inside of the house. Downsides are however that this options leads to the loss of space inside the house, as well as that when this renovation is not executed properly this could also lead to moisture problems. Another option would be to add insulation to the outside of the house, this options holds none off the earlier mentioned problems above. It will however put a claim on the space outside (Milieucentraal, n.d.b). Comparing the two options mentioned above for the purpose of this research the option of adding insulation to the outside of the building was chosen to be used in the CIMFA-Model since this options holds the least potential problems.

Roofs

Regarding insulation measures for flat roofs three options are available. First of all one could insulate from the inside. This however could lead to mold and moisture problems and is therefore usually not advised. Besides insulating from the inside one could also choose to add insulation to the outside of the roof which in itself can be done at two ways. In the first option the existing roof covering is removed, then insulation is added to the roof and finally a new roof covering layer is added. This option usually means that the eaves need to be adjusted however holds the advantage that it gives better insulation properties then the other option for outside insulation. The other (second) option for outside insulation works by adding insulation on top of the existing roof covering. Downsides of this method are however that this as already mentioned leads to poorer insulation capabilities then the previous option. Secondly this option also demands that the roof covering is in good shape in order to allow this method to be used (Milieucentraal, n.d.c).

Regarding insulation measures for sloped roof four options are available. The first option (spraying insulation under the rooftiles) can immediately be excluded because the gained extra roof insulation is always limited. Therefore this method is not relevant for the large renovations proposed in this research. The second approach is not insulating the roof at all but instead insulating the attic floor. This option can however also immediately be excluded as an option because this only works when the attic floor can be closed off with for instance a hatch. A lot of attics in the housing stock of Lunetten however cannot be closed off at all because they have a so called ''open attics". In case of an open attic, insulating the attic floor doesn't make any sense and therefore the option is excluded.

Excluding two options already, left are two options that cannot be excluded upfront already. First of all there is internal roof insulation, for this option it is important that work is done well so that future moisture problems are prevented. Further this option will also lead to loss of space in the attic. A second option is outside (external) roof renovation, for this option the rooftiles and roof laths are removed. Then insulation is added to the roof (causing the roof to become higher and thus a new gutter is needed) and new roof laths are placed. Finally rooftiles are placed on top, however reusing the old rooftiles is difficult / unpractical since some rooftiles could already be damaged during earlier removal and the furrows of the remaining rooftiles can be worn out during its lifetime causing that they will only fit back on the same rooftile as in the past. Keeping track of this (particularly on neighborhood scale renovations) is very unpractical (Milieucentraal, n.d.c).

Considering the above and taking into account that preservation of as much materials as possible is a key standpoint in the CPG-Strategy which is a guideline for this research, the internal roof insulation is preferred for sloped roof structures. Regarding flat roof structures however insulation from the outside (removing existing roof covering, adding insulation and then placing a new roof covering) is preferred because other options could potentially cause mold and moisture problems, or demand conditions from the existing roof structure which can't be estimated upfront as well as leading to poorer insulation conditions.

Windows & Doors

During the creation of the CIMFA-Model several assumptions had to be made regarding windows and doors in order to be able to determine m^3 of material flows. For both windows and doors the frame thickness have been assumed 114mm while widths are assumed to be 67mm. Thicknesses for window glass are assumed to be 6mm for single glass, 12mm for double glass and 18mm for triple glass (glass in doors although according to archetype present have been ignored for this research). Finally in case glass is replaced in a scenario it will always be replaced by triple glass. Therefore window frames are also always assumed to be replaced because usually existing frames carrying single or double glass are not able to carry the weight of triple glass.

The window surface of the RVO reference archetypes are used to make individual scaling's for all other individual archetypes. These scaling's are done based on the ratio of total wall surface - window surface. Regarding doors no scaling takes place since doors are always assumed to have the same dimension / surface.

Installations

Regarding installations for the various heat supply scenarios, several considerations and assumptions were made during the creation of the CIMFA-Model. These are described in more detail below:

For all installation directly related to gas consumption, which are: the tap water heating installation, space heating installation and gas pipe lines, it was assumed that they are automatically removed in all heat supply scenarios. Where gas pipe lines aren't replaced, the installations responsible for the heat supply of the building (tap water and space heating) needed replacements which can vary depending on the heat supply strategy. For row houses in the all-electric scenarios tap water heating is assumed to be replaced by an electric boiler while space heating will be done by an air-source based heat pump. For apartment buildings in all-electric scenarios tap water heating is assumed to be replaced by an electric boiler while space heating will be done by a ground-source based heat pump. Finally for all remaining scenarios both the hot tap water supply as well as space heating supply will be taken over by a district heating network.

The heat release systems are automatically replaced in all heat supply strategies scenarios except for the high temperature scenarios. For the low temperature heat supply strategies they are assumed to be replaced with low-temperature heat radiators (45°- 55°). For the heat supply strategies in the middle temperature range they are assumed to be replaced by middle-temperature heat radiators (50° - 70°).

The heat distribution systems are assumed to be replaced in all low temperature scenarios. This is because the low heat supply temperatures ask for sections with larger pipe diameters. For the low temperature demolish & rebuild scenarios all stocks are automatically replaced because of the demolishment of the existing buildings stock and up following rebuild (100% outflows and inflows). For low-temperature renovation scenarios an assumption had to be made regarding how much pipework needed to be replaced. For the purpose of this research a replacement of 10% of the existing pipework was assumed.

Finally regarding the power lines, water pipe lines and the internal sewer system, no inflows or outflows are expected except for demolish & rebuild scenarios. In these scenarios all existing buildings will be demolished (all materials are outflows) while for the new built the installation components: power lines, water pipe lines and internal sewer system will be present again. The quantities of materials present in the new built are assumed to be equal to the amounts in the old situation.

Compensation Boxes

When construction drawings / floor plans were selected for archetypes always one was chosen that was somewhere in the middle of the row (row house) or structure (apartment buildings). Since row houses and apartment buildings also include dwellings that are located on a corner and apartment buildings contain parts of a floor and roof where all dwellings in the same column profit from a compensation for this had to be made.

First of all one should look at the type of dwelling. For both row houses and apartment buildings a compensation for corner houses had to be built in. For this, first for each category the amount of dwellings in an average block had to be known. Several assumptions were made for the various archetypes categories which can be seen in the CIMFA-model. Based on the amount of corner houses the compensation in material flows could be calculated (additional window surface, side walls not of concrete but of brick, insulation and limestone). Also the thickness of these side walls were adjusted. For this research it was assumed that the insulation layers of the side wall are 50% thicker than the default value used for front back wall insulation.

Secondly for apartment buildings specifically compensation for the ground floor insulation and (parts of) the concrete roof elements and the roof structure (gravel and bitumen roof covering) should be equally allocated over the various apartments that are within in the column. For this research allocation has been done equally over the amount of dwellings within the column. For this purpose it was thus needed to make a subdivision between a standard apartment building (everything on the same level) and maisonettes (rooms are spread out over two levels). This difference is present in the CIMFA-model.

3.2.2). Heat supply strategies

Regarding alternative heating strategies various options exist like heat pumps, heat network or woodstoves. Differences between these heat supply options can be found in the temperature ranges in which they operate (low, middle or high). Assumptions regarding the temperature ranges can be found in this section, the eventual choice (allocating heating strategies to specific heat supply options) will be done in the methods chapter.

Within the CIMFA-Model renovation or rebuild needs for these heat supply strategies have been distinguished from one another based on rc-values (floor, walls & roof) and U-values (windows & doors). The rc-values and u-values can be divided over 3 classes namely: high temperature heat supply solutions, middle temperature heat supply solutions and low temperature heat supply solutions. An further elaboration per category is given below. An overview of exact rc-values is given in Table 8 while for u-values this is given in Table 9.

Rc-values for high temperature heat supply options

The first category are the rc-values related to high temperature heat supply options (used in the high temperature heat network scenarios). The rc-values for this category have been determined based on information about the archetype (RVO-voorbeeldwoning) that is available in the GPR-gebouw tool. Information about material thickness of a typical house from the studied time period have been combined with lambda values from this model (or derived from literature) to determine R-values. With these R-values the rc-values of the existing buildings have been calculated with the help of the rc-formula (see section 3.2.3). Regarding the U-values the values as named in the report ''Voorbeeldwoningen 2011 bestaande bouw'' (Agentschap NL., 2011) are assumed to be the current situation. For high temperature heat supply options these values are assumed to be sufficient except for some of the values for glass. For this a minimum of 2,9 (u-value of double glass) is assumed which means single glass needs to be replaced in this scenario.

Rc-values for low temperature heat supply options

For the second category, low temperature heat supply options (which are used in the all-electric scenarios, low temperature heat network scenarios and demolish & rebuild scenarios) values for rc-values have been obtained from internal research done at W/E adviseurs. From this research minimum rc-values (for the floor, walls and roof) and u-values (for windows and doors) needed for low temperature heating where obtained from the database of the Routekaart from W/E adviseurs (W/E adviseurs, 2018).

Rc-values for middle temperature heat supply options

In the third and last category middle temperature heat supply options (which are used in the middle temperature heat network scenario) values for rc-values and u-values have been obtained by taking the average of the rc-values and u-values of the low and high temperature heat supply options.

	Floor (Rc-value)	Wall (Rc-value)	Roof (Rc-value)
Low-Temperature (Renovation)	3.50	4.50	6.00
Low-Temperature (Demolish & Rebuild)	3.50	4.50	6.00
Middle-Temperature	2.01	2.90	3.65
High-Temperature	0.52	1.30	1.30

Table 8: Rc-values for floor, wall and roof.

	Doors (U-value)	Windows (U-value)
Low-Temperature (Renovation)	3.50	4.50
Low-Temperature (Demolish & Rebuild)	3.50	4.50
Middle-Temperature	2.01	2.90
High-Temperature	0.52	1.30

Table 9: U-values for doors and windows.

Corresponding with these (new) insulation levels are adjusted values for operational energy use. From internal research at W/E adviseurs (W/E adviseurs, 2018) several values for row houses and apartment buildings were obtained. An overview of these values are given in Table 10 for row houses and Table 11 for apartment buildings.

	Low-Temp. Renovation	Low-Temp. Demolish & Rebuild	Middle-Temp. Renovation	High-Temp. Renovation
Operational Energy Electricity (MJ / m² GBO)	27.8	27.8	29.6	31.4
Operational Energy Heat (MJ / m² GBO)	132.7	74.7	296.6	460.5
Operational Energy - Electric Cooking (MJ / year)	720	720	720	720

Table 10: Operational energy for various heat supply options (row houses).

	Low-Temp. Renovation	Low-Temp. Demolish & Rebuild	Middle-Temp. Renovation	High-Temp. Renovation
Operational Energy Electricity (MJ / m² GBO)	38.6	38.6	36.2	33.8
Operational Energy Heat (MJ / m² GBO)	102.5	72.6	243.2	383.9
Operational Energy - Electric Cooking (MJ / year)	720	720	720	720

Table 11: Operational energy for various heat supply options (apartment buildings).

3.2.3). Renovation strategies

Regarding renovation strategies within the CIMFA-Model assumptions have to be made what kind of renovation strategies are going to be used. Since the basic goal of the CIMFA-Model is to measure the impacts of circular construction strategies eventually two strategies were defined. First of all there was off course a ''circular renovation strategy'', in order measure whether this scenario leads to beneficial or detrimental results a comparison had to be made with a renovation scenario that uses common practices for renovation (business as usual). This became the ''standard renovation strategy''. For both strategies counts that the first step of the CPG methodology preserve (W/E adviseurs, 2017b) is a starting point (and therefore sometimes the argument to choose for a specific type of physical renovation) in every scenario in order to minimize environmental impacts upfront. Differences are found in the destiny of the outflow materials and choices for inflow materials. The ''Standard Scenario'' assumes that all outflow materials will be landfilled while for the material needs for retrofitting materials which according to John Mak of W/E adviseurs (2018) are currently commonly applied will be used (See Table 12 for overview). In the ''Circular Scenario'' the focus is first on reuse of local outflow materials (only applied for demolish and rebuild scenarios because this is the only scenario with considerable outflows). Remaining material needs will be filled in with materials of either recycled or biobased origin (See Table 12). For these recycled and biobased materials an optimization sheet has been constructed in the CIMFA-model (named: ''Circular Scenario Optimization''), were in case multiple options of recycled / biobased origin exist for a specific part of the building, an optimization is made regarding the material CO2 impacts. The goal of this is to always end up with the material that has the lowest CO2 impact. This Circular Scenario with a strategy of preserve, (local) reuse, recycling / biobased alternatives (optimized on lowest CO2 impact) was focused to be in line with some of the main elements of the CPG methodology (W/E adviseurs, 2017b).

	Row Houses		**Apartment Buildings**	
	Standard	**Circular**	**Standard**	**Circular**
Floor insulation	XPS	Flax Wool	XPS	Flax Wool
Cladding	Stone Strips	Plywood (Softwood)	Stone Strips	Plywood (Softwood)
Wall insulation	EPS	Woodfiber	EPS	Woodfiber
Roof insulation	EPS	Cellulose	EPS	Cellulose

Table 12: Material inflows for renovation / rebuild transition scenarios.

Regarding installations assumptions will depend on the heat supply options that are chosen for the scenarios, these are however determined in the methods section.

In section 3.1 it was already shortly mentioned that material amounts needed for additional insulation are determined with the help of the rc-formula. Although the results of material needs will differ for each heat supply scenario, the way it is calculated is everywhere the same. The method to calculate material needs uses a combination of the rc-formula, r-values of the individual sub-components and algebra in order to calculate material needs. In Formula 1 (the rc-formula) and Tables 8 and 9, it can be observed that a lot of values are already pre-defined per situation. In a situation that additional insulation is applied to a certain building component the only part of the formula that will see a change is the r-value part. In case of for instance a wall, two sub-components are added namely a new layer of cladding for the wall (which is already pre-defined and has a standard thickness and thus r-value) and an insulation layer (in which the thickness forms the variable). The Tables 8 & 9 in section 3.2.2 already gave an overview of minimal rc-values needed to achieve certain temperature scenarios. This all allows to rearrange the rc-value formula in such a way that all fixed values, all known r-values and the minimal rc-value needed for the specific temperature scenario are filled in so that a ''shortage in r-value'' is calculated for the insulation layer in case a certain desired rc-value is strived to be obtained. When this shortage in r-value for the insulation layer is known Formula 2 can be used in which this r-value and the λ-value for the specific material (see Table 12 which material is used in each renovation strategy) used to calculate the thickness of the insulation. Combining this thickness with the m^2 of surface will then give the opportunity to calculate the m^3 of material inflow. These functions are all present within the CIMFA-Model and work automated based on the settings selected in previously described drop-down menus, or manual individual settings in case the individual choice was selected.

$$R_C = \frac{\sum R + Rsi + Rse}{1 + \alpha} - Rsi - Rse$$

R_c = Thermal resistance of component (m^2 K/W)
R = Thermal resistance of sub-component (m^2 K/W)
Rsi = Heat transmission resistance (inside)
Rse = Heat transmission resistance (outside)
α = Correction factor for convection and inaccuracies

Formula 1: The rc-value is calculated with the following formula (EKBouwadvies, n.d.d):

$$R = \frac{d}{\lambda}$$

d = Thickness of material in meters
λ = Thermal conductivity of the material (W / m K)

Formula 2: The R-value is calculated with the following formula (EKBouwadvies, n.d.d)

	Rsi	**Rse**
Walls bordering open air	0.13	0.04
Walls bordering water / soil (e.g. basement)	0.13	0
Inner walls (not garage)	0.13	0.13
Floors above outside air, heat flow downwards	0.17	0.04
Floors above unheated rooms, heat flow downwards	0.17	0.17
Floors above unheated rooms, heat flow upwards	0.10	0.10
Intermediate floors between heated building levels	0.13	0.13
Roofs with an elevation of more than 75°	0.13	0.04
Roof with an elevation bigger or equal to 0°and smaller or equal to 75°	0.10	0.04
Floor bordering water / soil	0.17	0

Table 13: Values for Rsi and Rse (EKBouwadvies, n.d.d).

	Factor alpha
1). In case the section contains an insulation layer that on both sides is bordered by an air layer of more than 5 mm thickness, unless special measures have been made to prevent convection.	1
2). In case that was mentioned in (1) isn't applicable and if for insulation purposes exclusively foam glass was applied	0
3). In case that was mentioned in (1) and (2) isn't applicable, but the section apart from finishing layers (including outer skin) is produced under well controlled conditions	0.02
4). All other situations	0.05

Table 14: Values for alpha (EKBouwadvies, n.d.d).

3.2.4). MFA
As described in section 3.1.3 in the tabs MFA of the CIMFA-Model the total amounts of material stocks, inflows and outflows (suited for re-use) becomes clear. Then up following quantities are converted to values for embodied energy and embodied CO2. Regarding this several assumptions where needed. First of all assumptions are needed with regard to recycling rate (which materials can be recycled and what percentage of the outflows can be recycled). Within the CIMFA-Model options to insert this data were created, however they can vary for each research. The eventual assumptions for this data can be found in the methods chapter of this research. The same story also partly counts for the other part in the MFA sections that needed assumptions. As stated quantities of materials and installations are multiplied with factors for embodied energy and embodied CO2. These factors also depend on the specific materials that were chosen for the research (for stocks this means it depends on the chosen archetypes, for renovation / rebuild it depends on assumptions which materials were going to be used in these cases). These assumptions can thus also be found in chapter methods of this research.

3.2.5). Results
Finally upfront the eventual presentation of the results had to be thought-out. A lot of results could be created within this research. But which are most important? And what are the most convenient units for these results? Eventually the following results (with associated units) have been chosen to be the key indicators for this research:

- Kg / Tonnes of materials (stocks, inflows & outflows)
- Total embodied energy MJ / GJ or TJ per year
- MJ of embodied energy per m²
- MJ of embodied energy as share of total energy
- Total embodied CO2 emissions kg or tonnes per year
- Kg embodied CO2 emissions per m²
- Kg of embodied CO2 emissions as share of total CO2 emissions
- Kg / Tonnes of cumulative CO2 emissions

Looking at the units above one type will demand an additional explanation. These are the units that give totals per year (total embodied energy (MJ per year and total embodied CO2 emissions (kg per year). On first sight they may seem strange units, however this was done in order to make the results usable for scenarios with every time scale (accounting for various lifetimes and replacement times). Therefore for each material the total embodied energy / CO2 (full life cycle of material) was calculated an then divided by its life-expectancy. The amounts obtained were then allocated as impacts factors to the materials thereby giving embodied energy / CO2 per year (and not an amount of full life-time total embodied energy or CO2). The exact materials and associated lifetimes depend on the chosen archetype, an overview of these specific data will be given in the methods section.

3.3). Strengths of the CIMFA-Model and its methodology
In this section the strengths / advantages of the CIMFA-Model are named, explained and shortly discussed. Besides advantages and strengths also disadvantages and drawbacks were identified. These will be discussed in the discussion section of this research project.

Officially the CIMFA-Model was specifically designed for the analysis of the material flows for various renovation scenarios applied up on the neighborhood of Lunetten (in which the existing building stock mainly originates from the 70s-80s period). However the design of the model was done in such a way that the model is easily reusable and / or adjustable for other researches on the neighborhood scale. This allows the model to adjust to another level of desired accuracy and / or can represent the building stock of a different construction period and / or building stock of another country. Combine this with the fact that required data inputs for the CIMFA-Model were minimal and one could conclude the model is characterized by the factors: minimal data requirements and flexibility. This is further explained with the following four points:

→ Minimal inputs into the model of relatively easy to obtain data
→ Changing the values of the RVO archetype and associated materials to: adjust to buildings of a different building type and / or period.
→ The possibility to adjust the amount of archetypes (for which construction drawings have to be filled) in order to stir on the factors: time required, budget required and the accuracy of the model.
→ Option to adjust the default values for all material names and thicknesses per sub-component for each separate archetype towards archetype specific (from construction drawings obtained) real values for material names and / or thicknesses (allowing to stir on the factors time required, budget required and accuracy of the model).

The low data needs of relatively easy to obtain data, the flexibility that this model offers regarding it's adaptability towards other buildings stocks of a different construction period and / or different country, and the options to further stir the model on the factors: time required, budget required and accuracy of the model combined form the advantages that this neighborhood analysis model has.

4). Methods

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In this chapter the steps needed to run the CIMFA-Model and obtain the desired results for this research are described. This process exist out of three steps namely: 1). choice of (sub-)archetypes and heat supply options, 2). Settings for a scenario analysis and 3). Settings for a sensitivity analysis.

4.1). Choice of (sub-)archetypes and heat supply options

The first step was to select the (sub-)archetypes for running the CIMFA-Model. In Table 1 of chapter 2 an overview was provided of the sub-archetypes selected within this chapter to represent the building stock of Lunetten. These sub-archetypes had to be implemented in to the model. This was done with the help of construction drawings.

The second step was to define which heat supply options are going to be used for this research. Section 3.2.2 already made a distinction between heat supply strategies (low, middle and high temperature heat) and defined associated building characteristics (rc-values and u-values) in Table 8 and Table 9. Each of these heat supply strategies can only be achieved by using heat supply options which are able to supply that type of heat. In section 3.2.2 options like woodstoves, heat pumps and heat networks were already shortly named. For this research it was decided that at least two heat supply strategies were going to be investigated that combined should give the full range of heat supply strategies (and thereby also the material effects of renovation / rebuild strategies). For this research it was decided to use heat networks because it can operate in all temperature ranges named, and heat pumps because it is one of the best known alternatives. The heat pumps were used in two low temperature all-electric scenarios: renovation and demolish & rebuild. The heat networks were used within the model for all possible temperatures ranges. The following transition scenarios were therefore defined:

TS. 1: All-Electric Renovation (standard renovation strategy)
TS. 2: All-Electric Renovation (circular renovation strategy)
TS. 3: All-Electric Demolish & Rebuild (standard rebuild strategy)
TS. 4: All-Electric Demolish & Rebuild (circular rebuild strategy)
TS. 5: Low-Temperature Heat Network (standard renovation strategy)
TS. 6: Low-Temperature Heat Network (circular renovation strategy)
TS. 7: Middle-Temperature Heat Network (standard renovation strategy)
TS. 8: Middle-Temperature Heat Network (circular renovation strategy)
TS. 9: High-Temperature Heat Network (standard renovation strategy)
TS. 10: High-Temperature Heat Network (circular renovation strategy)

The following installations were implemented as an input (Table 15):

	Present in transition scenarios:
Air-source based heat pump	1, 2, 3 & 4 (only for row houses)
Ground-source based heat pump	1, 2, 3 & 4 (only for apartment buildings)
Electric boiler	1, 2, 3 & 4
Heat network (space heating)	4, 5, 6, 7, 8, 9 & 10
Heat network (hot tap water)	4, 5, 6, 7, 8, 9 & 10
Mechanical ventilation	1, 2, 3, 4, 5, 6, 7 & 8
Pipework	1, 2, 3, 4, 5 & 6
Radiator (middle temp.)	7 & 8
Radiator (low temp.)	1, 2, 3, 4, 5 & 6

Table 15: Inputs of installations.

Remaining values that have to be inserted before the model can be used are factors for alpha (see section 3.2.3 Table 14), factors for Rse, factors for Rsi (See section 3.2.3, Table 13), number of row houses in a row, number of apartment buildings in a row and amount of floors in an apartment building. In chapter three an overview of possible values for alpha, Rsi and Rse were given. In this research for factor alpha the value zero will be assumed (most common value used). Regarding values for Rsi and Rse Table 16 shows assumed values that have to be inserted into the model, these are assumed to be the same for row houses and apartment buildings.

	Rsi	**Rse**
Floor	0.13	0
Wall	0.13	0.04
Roof	0.13	0.04

Table 16: Values for Rsi and Rse

Regarding the number of row houses in a row an average of 6 per row was assumed. For apartment buildings no averages were used for number of apartments in a row and amount of floors. Instead these values were visually derived (on site and / or construction drawings) for the buildings that were earlier inserted into the model. An overview of values is given in Table 17.

	Number of apartments in a row	**Amount of floors**
20 m2 - 29 m2	10	3
30 m2 - 39 m2	9	3
40 m2 - 49 m2	9	4
50 m2 - 59 m2	2	3
60 m2 - 69 m2	6	5
70 m2 - 79 m2	9	5
80 m2 - 89 m2	10	6
90 m2 - 99 m2	6	5
100 m2 - 109 m2	6	5
110 m2 - 119 m2	6	4

Table 17: Overview of amount of dwellings in a row and amount of floors for apartment buildings.

Having inserted everything explained before the first indicators, which are: total embodied energy/CO2, energy/CO2 per m2 per year and embodied energy/CO2 as % share of total energy/CO2 are then automatically calculated. Next step is to combine the results of various indicators in order to calculate saving potentials for the various transition scenarios. This is done with Formula 3 and 4.

$$operational\ energy\ old - (operational\ energy\ new + embodied\ energy)$$

Formula 3: Energy savings potential.

$$operational\ CO_2\ old - (operational\ CO_2\ new + embodied\ CO_2)$$

Formula 4: CO2 savings potential.

4.2). Settings for a scenario analysis

The next step was to obtain results for longer term scenarios. Therefore the model needed some additional adjustments. First of all values Formula 5 that determines the retrofit speed have to be set. This formula needs values for the following variables:

$$f(x) = \frac{N}{1+ e^{-K(X-X^0)}}$$

Formula 5: Retrofit speed.

N (total housing stock)
K (steepness of curve)
X (year)
Xo (midpoint)

The total housing stock (N) that is analyzed for Lunetten consist of 4998 buildings. This analysis is performed over a 10 year time period (so values for X range from 0 - 10) because 10 years was assumed to be a realistic time-period to achieve an energy transition on neighborhood level. The value for midpoint (X0) has to be the middle value of the highest and lowest X value and was therefore set at 5. Finally the steepness of the curve (K) had to be determined. The goal was to create a transition pathway which followed a clear s-curve. Therefore various values for k were inserted into the model (0.5 / 1 and 1.5) and eventually k=1 was determined to give to most realistic pathway (other options gave a rather abrupt transition, while with k=1 a smooth and realistic pathway was obtained).

Secondly, a retrofit approach has to be set. One could for instance start with renovations of the biggest dwellings first and end with the smallest dwellings in the final years. Also an opposite approach can for instance be used. For this research the approach of starting with renovating the small dwellings first and end renovating with the biggest dwellings last was chosen. These setting have to be implemented in the tab: retrofit speed.

4.3). Settings for a sensitivity analysis

In the CIMFA-Model more than a 100+ variables were identified. For the sensitivity analysis it was decided to keep the analysis limited to only the most important variables (which were the variables assumed to have possibly major consequences on the final results when changed). Two categories of variables, CO_2 emissions for energy use per heat supply option and the lifetimes of the materials / installations) were eventually selected for the sensitivity analysis.

- For CO_2 emissions the upper value needs to be set at the current value (since emissions are not expected to increase) while the lower value needs to be set at zero (which is the future aspired value).
- Regarding lifetime upper values needs to be set at 20% higher than the default value while the lower value needs to be set 20% lower than the default value.

5). Results

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5.1). Energy and CO2 impacts for various transition scenarios

In this chapter the first section will give a selection of all results that were obtained in the CIMFA-Model with regard to material flows and embodied & operational energy and CO2 impacts for the various transition scenarios that were investigated. The second section will illustrate the results for cumulative CO2 emissions for all transition scenarios investigated for the 10 year scenario that was earlier described in the methods section. Finally the third and last section will perform a sensitivity analysis on a selection of parameters, thereby illustrating the potential effects inaccuracies in these parameters can have on the final results. More results than described in this chapter are available for the first two sections, these results can be found in the CIMFA-Model.

5.1.1). Comparing demolish & rebuild strategies for a row house

For this first section it was chosen to compare the impacts of the two all-electric demolish & rebuild transition scenarios that were distinguished within the CIMFA-Model. These are the following transition scenarios: all-electric demolish & rebuild - standard approach (TS. 3) and all-electric demolish & rebuild - circular approach (TS. 4). These transition scenarios will be evaluated for the row house sub-archetype in the range of 100m² - 109m² (which uses a dwelling of 103m² as reference).

The heat supply strategies within this comparison are thus similar, difference are only found in the strategy that is used for demolish & rebuild (standard vs. circular). Exact definitions of a standard vs. circular approach were given in chapter 3.2.3. In each approach the existing will be demolished and then reconstructed with for many components the same materials as were present in the existing construction. Some differences could be found though, which were defined earlier in Chapter 3, Table 12. Additionally in the circular approach also some materials were re-used. Which of the existing materials were re-used and how much could be re-used was discussed in Chapter 4. How much materials could be re-used for the specific situation of a row house of 103m² is given in Table 18.

	Name of re-used material	Amount (kg)
Row House (103m²)	Brick	10,126 kg
	Limestone	7,404 kg
	EPS	15 kg
	Glass Wool	40 kg
	Name of re-used material	**Amount (m²)**
	Power Lines	93
	Water Pipe Line	93

Table 18: Re-use of materials for a 103m² row house using an all-electric demolish & rebuild - circular transition scenario.

Having insights into material choices for rebuild and material (amounts) available for re-use, next a comparison between the two scenarios with regard to the energy and CO2 impacts will be given. For this reason several indicators that measure energy impacts where created within the CIMFA-Model. An overview of these values for the various indicators is given for the for the current situation, a situation of all-electric demolish & rebuild - standard approach and a situation of all-electric demolish & rebuild - circular approach in Table 19.

	Current	Standard	Circular
Total embodied energy (MJ / year)	6,204	10,779	10,181
MJ of embodied energy per m² / year	60.23	104.65	98.84
Embodied energy (MJ / year) as (%) share of total energy use (MJ / year)	10.77%	48.89%	47.46%
Total embodied CO2 (kg CO2 / year)	365	487	398
Kg of embodied CO2 per m² / year	3.54	4.73	3.87
Embodied CO2 (kg CO2 / year) as (%) share of total CO2 emissions (kg CO2 / year)	10.74%	31.39%	27.23%

Table 19: Indicators for energy and CO2 impacts.

Comparing the current situation with the results for the rebuild approaches one could clearly distinguish an increasing importance of the embodied energy and CO2 impacts as share of the total energy and CO2 impacts. Comparing the values obtained from the energy and CO2 indicators with one another it can be concluded that for a row house with a size of 103m² a circular transformation performs better both in terms of energy and CO2 than a standard transformation. The values for total embodied energy per year and total embodied CO2 per year were found to be 598 MJ / year (equivalent to 89 kg of CO2) lower for a circular approach compared to a standard approach. Secondly the embodied impacts per m² / year were found to be 5.8 MJ per m² / year lower for embodied energy, while being 0.86 kg CO2 per m² / year lower for embodied CO2 when a circular approach is compared with a standard approach. Finally comparing the embodied impacts as share of total impacts with regard to energy the circular approach is with a value of 47.46% lower than the standard approach. Comparing the same indicator for CO2 again the circular approach is lower than the standard approach (27.23% vs. 31.39%).

Putting these indicators in more perspective: the yearly impacts for energy use for the old situation (non-renovated row house) were 51,380 MJ / year (equivalent to 3,029 kg CO2 / year). After demolishment of the old row house the same row house is rebuild, however this time with a better energy performance (because the improved insulation). This new build row house has an estimated energy use 11,270 MJ / year (equivalent to 1,064 kg CO2 / year). This transformation however came at a cost of 10,779 MJ of embodied energy per year (equivalent to 487 kg CO2 / year) for a standard rebuild strategy and 10,181 MJ of embodied energy per year (equivalent to 398 kg CO2 / year) for a circular rebuild strategy. With this data the energy & CO2 saving potentials for each scenario can be calculated with the help of the Formula 3 (energy) & Formula 4 (CO2) that were introduced earlier in chapter 4. Results derived from these calculations are given in Table 20.

	Savings (amount)	Savings (%)
Standard approach (MJ / year)	29,331 MJ / year	57%
Circular approach (MJ / year)	29,929 MJ / year	58%
Standard approach (kg CO2 / year)	1,478 kg CO2 / year	49%
Circular approach (kg CO2 / year)	1,567 kg CO2 / year	52%

Table 20: Energy and CO2 savings for standard and circular rebuild approaches.

Comparing results for a standard and a circular approach it can be concluded that both with regard to energy and CO2 a circular rebuild approach saves the most MJ of energy and kilograms of CO2 when savings for each of these transition scenarios are calculated compared to the current situation of the building stock. In terms of energy a circular approach saves 598 MJ / year more compared to following a standard approach. Over a 75 year time-span this difference would be equal to 44,850 MJ (which is the same as almost 4 years of operational energy consumption of the new built row house), while in terms of CO2 a circular approach saves 89 kg CO2 / year more compared to following a standard approach. Over a 75 year time-span this difference would be equal to 6,675 kg CO2 (which is equal to more than 6 years of operational energy consumption of the new built row house).

Concluding for this section: all previous indicators and figures for both energy and CO2 emissions taking into account both the embodied & operational impacts show that for a 103m^2 row house, TS. 4 saves with more energy and CO2 then TS. 3 (TS. 4 saves 29,929 MJ / year and 1,567 kg CO2 / year while TS. 3 saves 29,331 MJ / year and 1,478 kg CO2 / year). The differences that were found were however relatively small. This can be explained by the fact that both scenario for the largest part use still use the same materials. The difference in energy and CO2 impacts between those two scenarios transition scenarios are mainly caused by re-use of materials saving additional energy and CO2 in the circular scenario TS. 4, and the more favorable impacts of the bio-based materials that were used in TS. 4 creating savings in CO2 emissions. Finally the results show the increasing importance of embodied energy and CO2 as share of total energy and CO2 impacts (see Table 19) when an existing building is demolished and replaced by an better insulated row house.

5.1.2). Comparing heat supply & renovation strategies for apartments buildings

Previous section focused on specifically addressing the differences in energy and CO2 impacts for two transition scenarios which use the same heat supply strategy but differ with regard to rebuild strategy (standard vs. circular rebuild strategy. This section will take it one step up by focusing on the full range of transition scenarios covering all heat supply strategies that were investigated within this research both for a standard and a circular renovation strategy. This is done only for the sub-archetype category with the range of 70m^2 - 79m^2 (which uses a 79m^2 dwelling as reference).

In this section the full range of transition scenarios investigated within the CIMFA-Model is thus investigated. An overview of all these transition is given in chapter 4, these transition differ from another with regard to heat supply strategy (all-electric & heat network) and renovation / rebuild strategy (standard vs. circular). Exact definitions of a standard vs. circular approach were given in chapter 3.2.3. Differences with regard to renovation / rebuild strategy can mainly be found in material choices which were defined earlier in Chapter 3, Table 12. Additionally in the all-electric demolish & rebuild approach also some materials were re-used. Which of the existing materials were re-used and how much could be re-used was discussed in Chapter 4. How much materials could be re-used for the specific situation of an apartment building of 79m^2 is given in Table 21.

<table>
<tr><td rowspan="10">Apartment building (79m²)</td><td>Name of re-used material</td><td>Amount (kg)</td></tr>
<tr><td>Brick</td><td>7,080 kg</td></tr>
<tr><td>Limestone Elements</td><td>5,065 kg</td></tr>
<tr><td>EPS</td><td>15 kg</td></tr>
<tr><td>Glass Wool</td><td>28 kg</td></tr>
<tr><td>Gravel</td><td>1163 kg</td></tr>
<tr><td>Name of re-used material</td><td>Amount (m² GBO)</td></tr>
<tr><td>Power Lines</td><td>71</td></tr>
<tr><td>Water Pipe Line</td><td>71</td></tr>
</table>

Table 21: Re-use in TS. 4 of materials for a 79m^2 apartment building.

Having insights into material choices for rebuild and material (amounts) available for re-use, next a comparison between all transition scenarios with regard to the energy and CO2 impacts will be given. For this reason several indicators that measure energy and CO2 impacts where created within the CIMFA-Model (see chapter 4). The results for a selection of these indicators is given in Table 22.

	Embodied impacts renovation / rebuild	**Embodied impacts (stocks + renovation)**	**Embodied impacts as share (%) of the total impacts**
Current situation	n.a.	3545 MJ / year	9,51%
	n.a.	224 kg CO2 / year	10,00%
TS. 1	1,415 MJ / year	4,712 MJ / year	28.42%
	107 kg CO2 / year	319 kg CO2 / year	22.15%
TS. 2	1,566 MJ / year	4,863 MJ / year	29.07%
	70 kg CO2 / year	282 kg CO2 / year	20.12%
TS. 3	4,597 MJ / year	4,597 MJ / year	32.60%
	312 kg CO2 / year	312 kg CO2 / year	25.82%
TS. 4	4,131 MJ / year	4,131 MJ / year	30.30%
	247 kg CO2 / year	247 kg CO2 / year	21.59%
TS. 5	1,088 MJ / year	4,385 MJ / year	26.98%
	88 kg CO2 / year	300 kg CO2 / year	29.43%
TS. 6	1,317 MJ / year	4,614 MJ / year	28.00%
	51 kg CO2 / year	263 kg CO2 / year	26.82%
TS. 7	781 MJ / year	4,079 MJ / year	15.18%
	61 kg CO2 / year	273 kg CO2 / year	18.54%
TS. 8	1,005 MJ / year	4,303 MJ / year	15.88%
	42 kg CO2 / year	254 kg CO2 / year	17.50%
TS. 9	360 MJ / year	3,828 MJ / year	10.20%
	27 kg CO2 / year	247 kg CO2 / year	12.82%
TS. 10	361 MJ / year	3,830 MJ / year	10.20%
	23 kg CO2 / year	243 kg CO2 / year	12.63%

Table 22: An overview of results for energy and CO2 indicators for every investigated transition scenarios in the CIMFA-Model for an apartment building with a size of 79m².

From the results for the various indicators in Table 22 several things can be observed. Comparing the values of the current situation with those of all the transition scenarios, it can be concluded that with all transition scenarios that encompass a renovation / rebuild the embodied impacts (both energy and CO2) increase. Renovation and rebuilding thus lead to an increased share of the embodied impacts as share of the total impacts.

Regarding energy TS. 9 performs best while TS. 2 performs worst in terms of total embodied energy. The difference between those two extremes amount 1,035 MJ / year which equals to around 1 month of energy use of a renovated all-electric dwelling of this same type and size.

With the same comparison for CO2 emissions, TS. 10 performs best while TS. 1 performs worst in terms of total embodied energy. The difference between those two extremes amount 76 kg CO2 / year which equals to les then 1 month of energy related CO2 emissions of a renovated all-electric dwelling of this same type and size.

Taking a more detailed look into the data it can be noted that for all transition scenarios that encompass a renovation, the transition scenario for each heat supply source that is combined with a standard renovation strategy will always outperform the transition scenario with the same heat supply source but combined with a circular renovation strategy in terms of embodied energy. Regarding embodied CO2 the opposite seems to be the case since for all transition scenarios the circular scenario always holds the lower emissions then the same heat supply scenario with a standard renovation / rebuild approach. In the basis circular is always the best scenario (both for energy and CO2). The difference in energy use which was described above is however caused by the embodied energy use, and specifically caused of the use of biobased materials. For embodied energy three values where obtained from the GPR-Model for embodied energy namely: renewable embodied energy use, non-renewable embodied energy use and total embodied energy use. For this research total embodied energy use (named in Table 22 as: embodied impacts (stocks + renovation)) was used. However this leads to results in which circular renovation strategies lead to poorer results then when a standard renovation strategy is used. The biobased materials that are used in the circular renovation strategy are mostly composed of wood like materials, these materials have very high numbers for total embodied energy. When looking at the split in the CIMFA-Model between non-renewable and renewable embodied energy one could see that this is caused by the high share of renewable embodied energy (in case of wood: the energy of sunlight absorbed by the tree to grow). To gain a better view of the true impacts for energy, one could better compare the amount of non-renewable embodied energy with one another. For this research however it was chosen to avoid this because the data quality of the data source of the GPR-gebouw model (which is: de nationale milieudatabase or NMD) seemed to be more reliable for total embodied energy then for non-renewable embodied energy. In the discussion chapter there will be further elaborated on this data quality issue present within this research, and how to handle with it in the future.

Combining some of the earlier indicators of embodied energy & embodied CO2 with additional indicators of operational energy & operational CO2 gives an overview of the ratio between embodied and operational energy and CO2 impacts. An overview of these results per transition scenario is given in Figure 10 (energy) and Figure 11 (CO2). An overview of the savings for each transition scenarios is given in Table 23. Comparing transition scenarios with one another in terms of energy savings TS. 5 hold the most favorable results for Lunetten. Savings for this scenario compared to the old situation equal 20.7 GJ / year. To put this into perspective: this is equal to almost 2 years of operational energy use of a renovated dwelling of the TS 5. Comparing transition scenarios with one another in terms of CO2 savings TS. 6 hold the most favorable results for Lunetten. Savings for this scenario compared to the old situation equal 1248 kg CO2 / year. To put this into perspective: this is equal to more then 6 months of energy related CO2 emission of a renovated dwelling according to TS. 6 standards with a size of 79m².

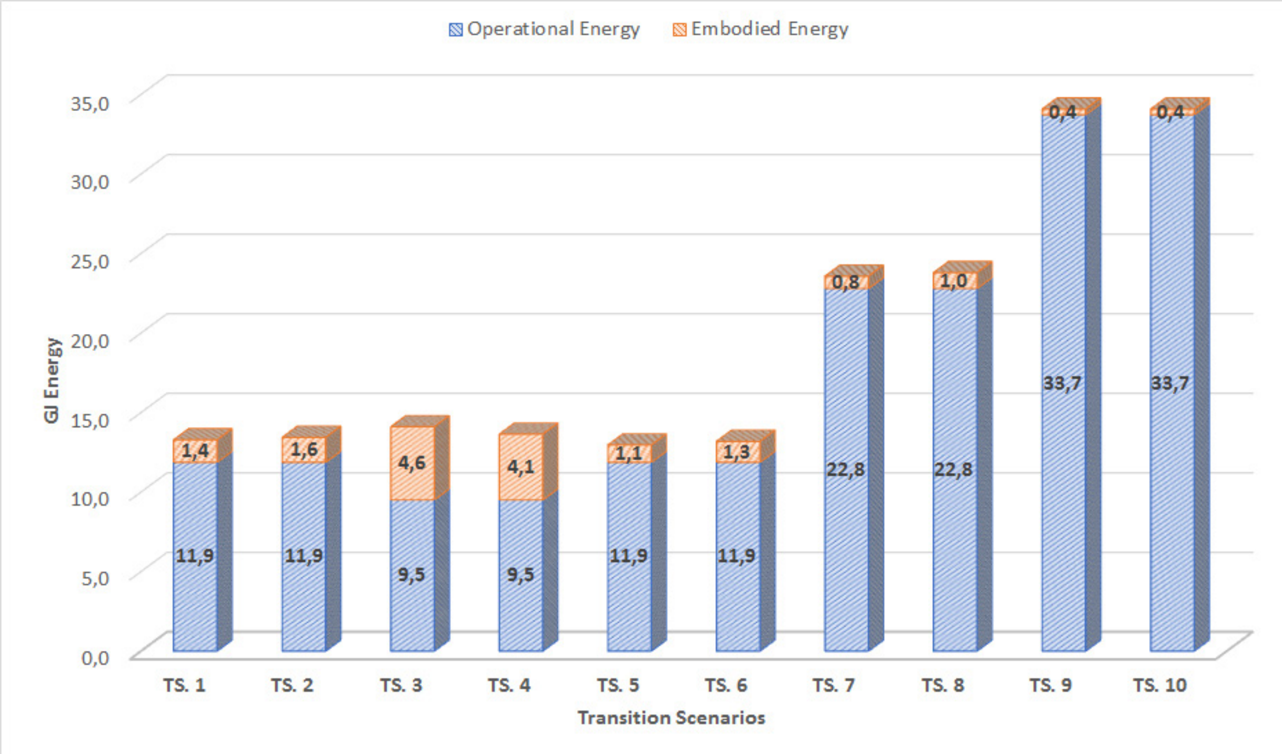

Figure 10: Operational energy vs. embodied energy (renovation)

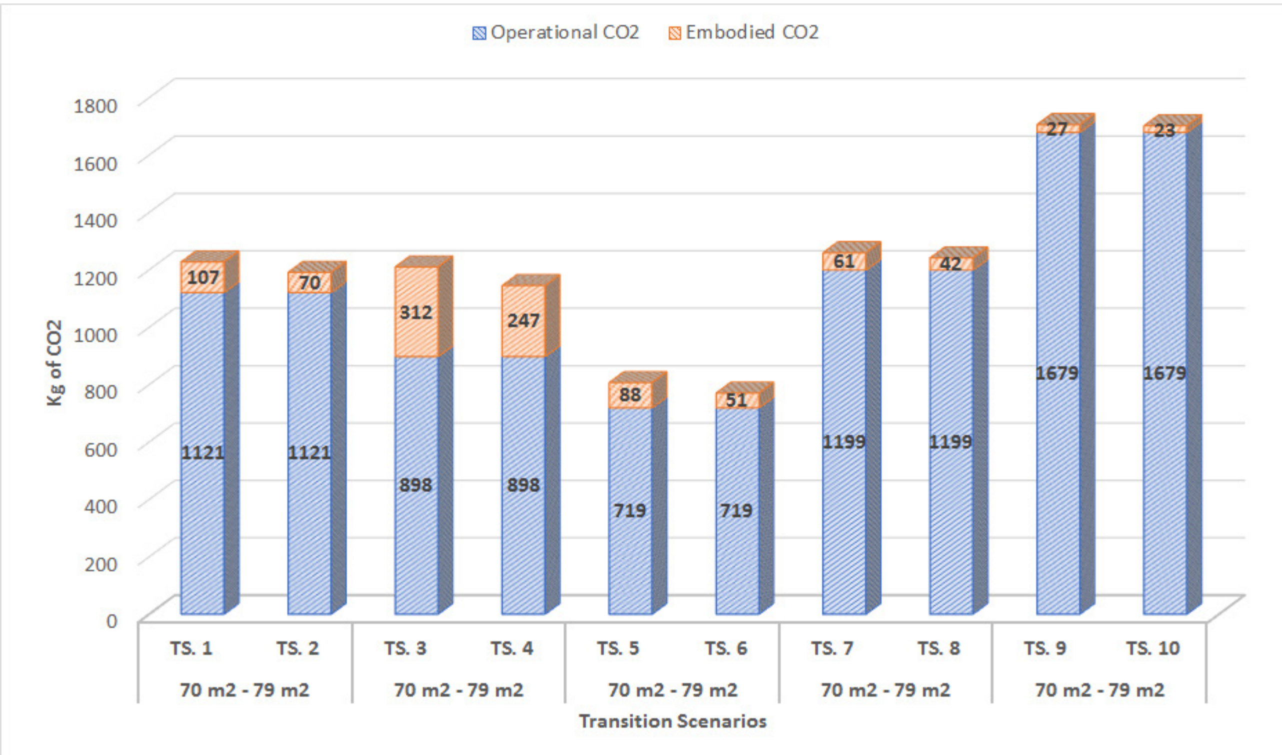

Figure 11: Operational CO2 vs. embodied CO2 (renovation)

TS. 1	-20,436 MJ	TS. 2	-20,286MJ
	-790 kg / CO2		-827 kg / CO2
TS. 3	-19,617 MJ	TS. 4	-20,083 MJ
	-808 kg / CO2		-873 kg / CO2
TS. 5	-20,763 MJ	TS. 6	-20,534 MJ
	-1211 kg / CO2		-1248 kg / CO2
TS. 7	-10,208 MJ	TS. 8	-9,921 MJ
	-758 kg / CO2		-777 kg / CO2
TS. 9	+360 MJ	TS. 10	+361 MJ
	-312 kg / CO2		-316 kg / CO2

Table 23: Annual savings obtained for each transition scenario (negative means savings).

Reasons that this scenario holds the most favorable results can partly be attributed to the CO2 emissions factors for the various heat supply alternatives. While operational energy values (in terms of MJ) are equal for both all-electric renovation and low-temperature heat network, while even be slightly lower for all-electric demolish & rebuild, the emissions factors for their heat supply source vary causing the large difference in savings between these scenarios. For the specific case study of Lunetten the emissions factors of the local heat network where substantially lower than the national average emissions factors for electricity. However they weren't not that low that high temperature heat networks would perform the best (which would be possible because of their low embodied CO2 value combined with a situation where the emissions of the heat network would be almost zero). This shows that although for Lunetten the circular low temperature heat network performs best this could for other neighborhoods vary and depends on local circumstances.

Concluding on this second section: taking all previous indicators and figures for energy use into account for both the embodied & operational impacts results show that for a 79m² apartment building TS. 5, with 13 GJ/year (of which 1.1 GJ/year embodied & 11.9 GJ/year operational) saves more energy than all other investigated transition scenarios. The same comparison done for CO2 emissions taking into account for both the embodied & operational impacts results show that for a 79m² apartment building TS. 6, with 770 kg CO2/year (of which 719 kg CO2/year embodied & 51 kg CO2/year operational) saves more CO2 than all other investigated transition scenarios.

Other notable results were that transition scenarios using standard renovation approaches perform better in terms of energy use than transition scenarios using circular renovation approaches (with the exception of TS. 3 & TS. 4). The difference between these standard and circular renovation approaches was allocated to the use of circular mainly biobased materials in the transition scenario that have a circular renovation strategy. These biobased materials hold high shares of renewable embodied energy while having very low values for non-renewable embodied energy values. The renewable embodied energy (for instance caused by the sunlight absorbed a by a tree to grow) is thus responsible for the high values for total embodied energy. Regarding CO2 emissions the opposite was noticed, transition scenarios using circular renovation / rebuild approaches perform better in terms of CO2 emission reduction then transition scenarios using a standard renovation / rebuild approach. This differences in CO2 emissions is caused by the use of circular building materials which led to larger savings in CO2 emissions.

5.1.3). Analyzing the Lunetten neighborhood

In this section the results of all transition scenarios for all sub-archetypes combined within the Lunetten neighborhood will be presented for both energy and CO2 impacts.

Measuring energy and CO2 impacts on the neighborhood scale

Regarding energy and CO2 the impacts in terms of embodied and operational energy where evaluated. In the situation of no renovations the operational energy would account for 184.8 TJ of energy (equivalent to 10.65 million kg of CO2) yearly. Total building specific energy use (in 2015) in the Netherlands amounts for 335.6 PJ (RVO, n.d.) while total CO2 emission for the built environment (in 2017) for the Netherlands equals around 24.1 billion kg of CO2 per year (CBS, 2018). This means that the operational energy consumption of Lunetten would be equal to approximately 0.06% of the total national energy consumption for building specific energy use, while the operational CO2 emissions of Lunetten would be equal to approximately 0.044% of the total national CO2 emissions for the build environment. However within the CIMFA-Model several transition scenarios were modelled which aimed to to substantially decrease the values for operational energy and CO2. An overview of these results is given for energy in Figure 12 and for CO2 in Figure 13.

In Figure 12 drops in operational energy to as far as 46.4 TJ (saving of 138.4 TJ or 75% of the original energy use) can be seen, while for CO2 in Figure 13 drops in operational CO2 emissions to as far as 3,392 tonnes of CO2 (saving of 7,259 tonnes of CO2 or 68% of the original CO2 emissions) can be seen. This however comes at the cost of additional material use (embodied energy & CO2). Taking account for both operational & embodied energy and CO2 impacts the biggest drop with regard to energy consumption can be made with TS. 5. Total energy savings in this case will total 113.4 TJ (equal to approximately 61% of the original energy use). For CO2 the biggest drop in CO2 emissions can be made with TS. 6. Total CO2 savings in this case will total 6,860 tonnes of CO2 (equal to approximately 64,4% of the original amount of CO2 emissions).

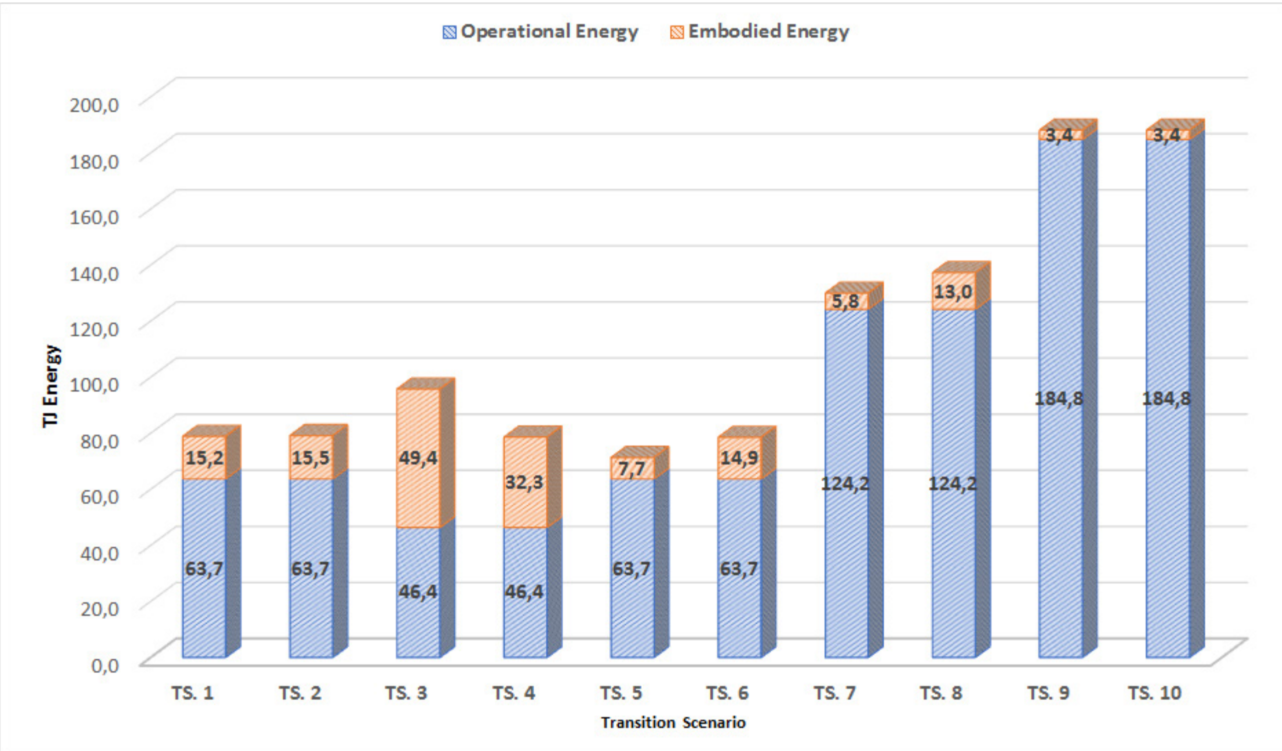

Figure 12: Operational vs. embodied energy (renovation) impacts for transition scenarios for the Lunetten neighborhood.

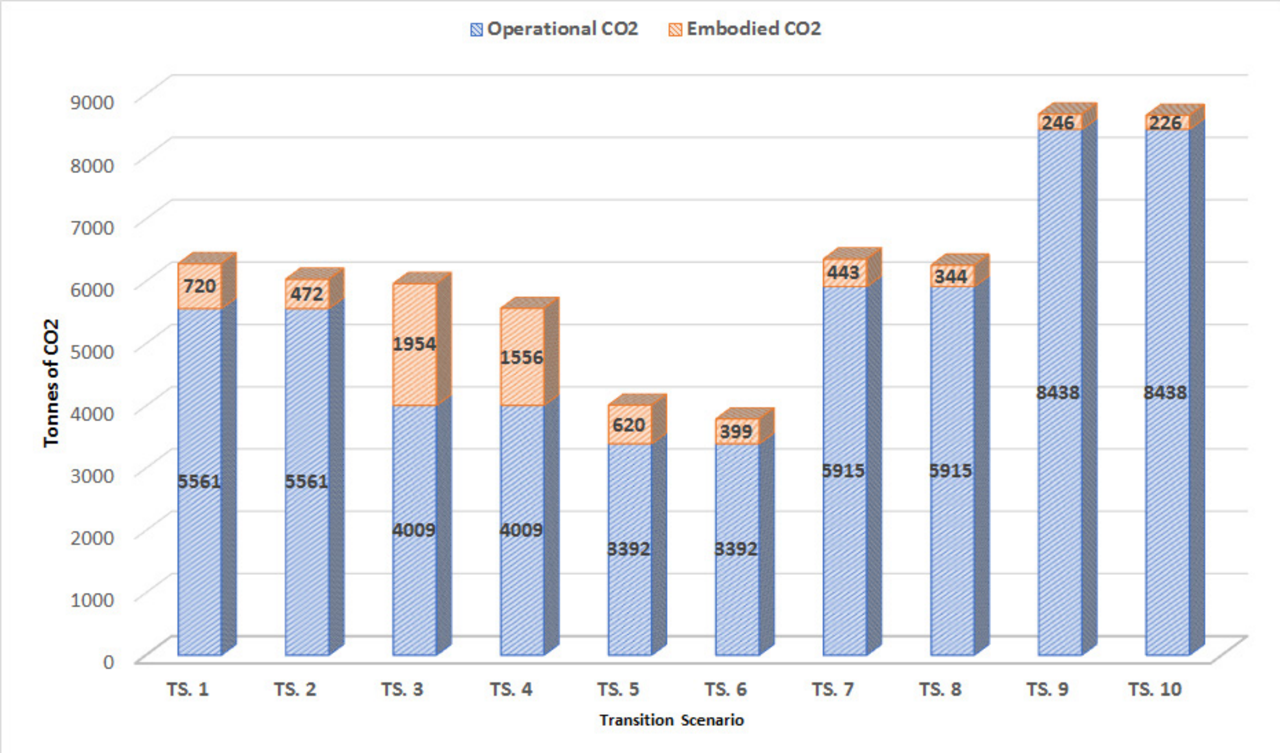

Figure 13: Operational vs. embodied CO2 (renovation) impacts for transition scenarios for the Lunetten neighborhood.

In earlier sections the conclusion was drawn that for all transition scenarios with regard to energy impacts except for the all-electric demolish & rebuild transition scenarios TS. 3 & TS. 4, the transition scenarios using standard renovation approaches perform better in terms of energy impacts then the transition scenarios using circular renovation strategies. Comparing this statement with the results depicted in this section in Figure 12 the same conclusion can be drawn again for results on the neighborhood level with TS. 5 holding with 71.4 TJ the lowest value for energy use. A small exception further is that the results suggest an equal performance for the high temperature heat network transition scenarios, the difference could however be present in the decimals, so the statement of lower energy impacts for standard renovation approaches can still hold true. The difference between these standard and circular renovation approaches was allocated to the use of circular mainly biobased materials in the transition scenario that have a circular renovation strategy. These biobased materials hold high shares of renewable embodied energy while having very low values for non-renewable embodied energy values. The renewable embodied energy (for instance caused by the sunlight absorbed a by a tree to grow) is thus responsible for the high values for total embodied energy. An in depth analysis in the CIMFA-Model with regard to embodied impacts further found values for embodied energy ranging 10-13% of the total energy use for standard homes, 15-27% of the total energy use for middle temperature retrofits (TS. 7 & 8), 28-44% of the total energy use for low temperature retrofits (TS. 1, 2, 5 & 6) and 30-53% of the total energy use for demolish & rebuild scenarios (TS. 3 & 4). This underlines the growing importance of embodied energy as share of the total energy.

Regarding CO2 impacts earlier sections concluded the opposite, transition scenario using a circular renovation / rebuild approach perform better in terms of CO2 emission reduction then transition scenarios using a standard renovation / rebuild approach. Comparing this statement with the results depicted in this section in Figure 13 the same conclusion can be drawn again with TS. 6 holding the lowest emissions (with 3,791 tonnes of CO2) of all transition scenarios. The differences in CO2 emissions were allocated to by caused by the use of circular building materials meaning that circular renovation / rebuild strategies save CO2 emissions.

5.2). Cumulative emissions for various 10 year transition scenarios

In the method section the creation of a 10 years scenario for Lunetten measuring cumulative CO2 emissions was described in detail. Below the results for this 10 year scenario are given in Figure 14 for all transition scenarios (for the full 10 years) and in Figure 15 for all transition scenarios (detail of a selection of the 10 year period). These figures give a impression of the results however, larger and better readable figures are available in the Appendix. Further elaboration follows after these figures.

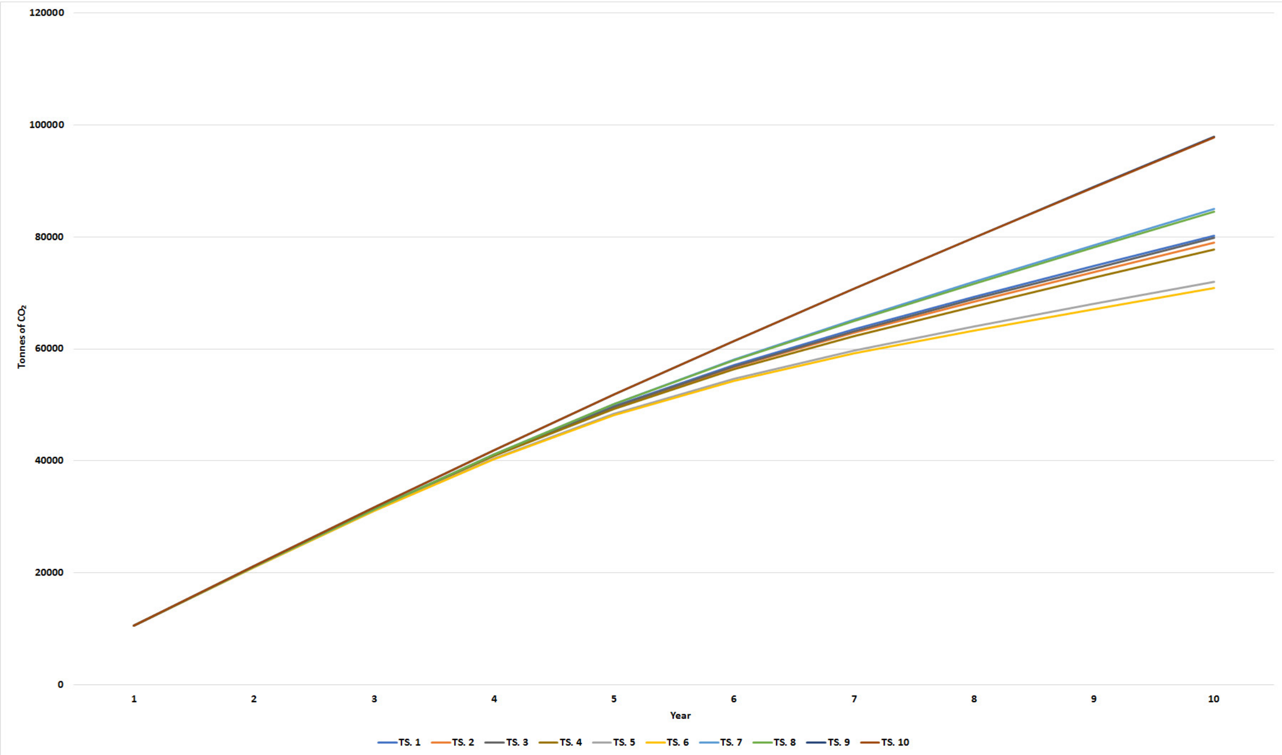

Figure 14: Cumulative CO2 emissions per year

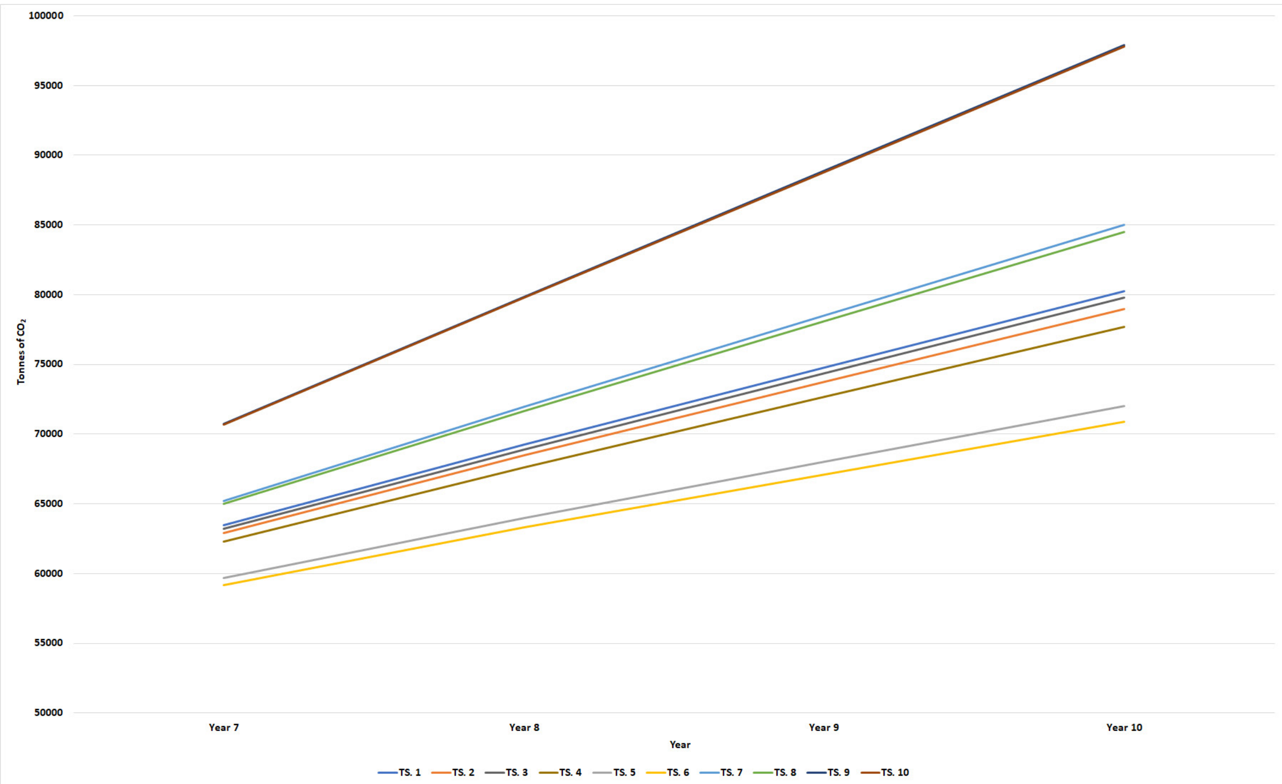

Figure 15: Cumulative CO2 emissions per year (detail)

Evaluating the results for cumulative CO2 emissions in Figure 14 & 15, one could see that TS. 6 performs best (with 70,882 tonnes of cumulative CO2 emissions in year 10) in terms of cumulative CO2 emissions, while TS. 9 performs worst (with 97,916 tonnes of cumulative CO2 emissions in year 10) of all transition scenarios. Further these figures shows that circular transition scenarios perform better in terms of CO2 emissions then standard transition scenarios. Finally when comparing the transition scenarios with the low temperature solutions with transition scenarios of other temperature ranges one could conclude that low temperature solutions (and associated intensive renovations) always pay themselves back in the long-term in Lunetten regarding CO2 emissions. More results can however be obtained, for this a further in depth analysis of the scenarios is made with Figures 16, 17, 18 & 19 and Table 24.

Figure 16 for TS. 6 and Figure 17 for TS. 9 show the progress of CO2 emissions during the ten year transition period for the two transition scenarios that form the extremes lowest vs. highest cumulative emissions (for the results for other transition scenarios, see CIMFA-Model, tab: Cumulative CO2 emission Results). Regarding operational CO2 emissions both Figures 16 & 17 show an equal decrease regarding operational CO2 for the not-renovated dwellings during the 10 year period. Simultaneously Figures 17 & 19 show the opposite happening for the emissions of renovated dwellings and embodied CO2. However while their starting points are equal their endpoints in the final year differ greatly for both operational CO2 emissions and embodied CO2. For TS. 9 (worst performing transition scenario) embodied CO2 emissions are barely noticeable while for the renovated dwellings the operational CO2 emissions grow to heights that almost equal the original energy use. For TS. 6 opposite is visible with embodied CO2 emissions seeing a noticeable rise, while renovated dwellings operational CO2 emissions see a limited rise (with less than half of the original CO2 emissions).

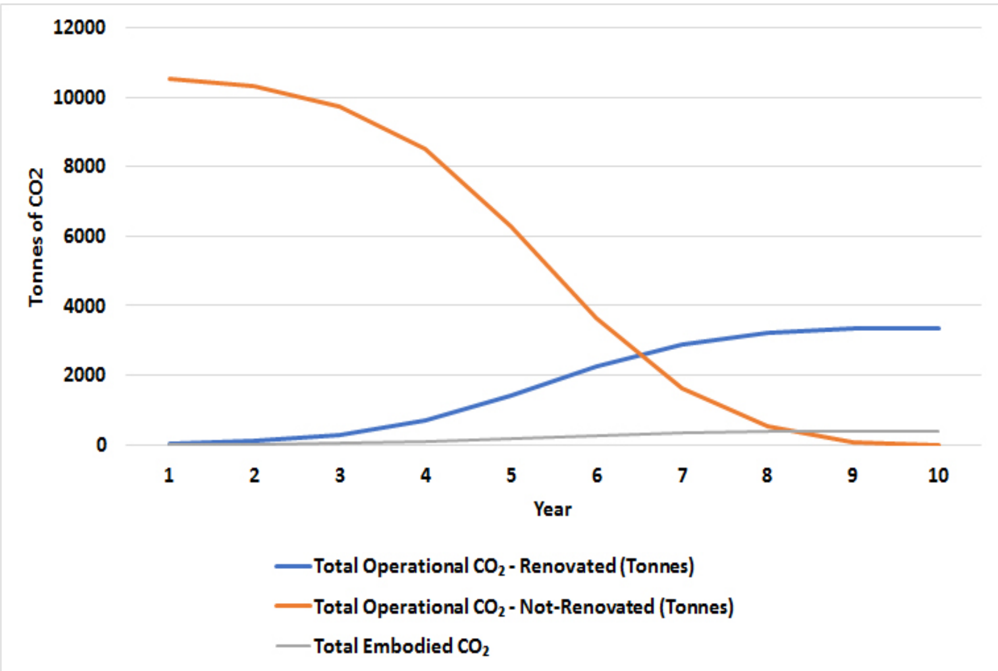

Figure 16: CO2 emissions (TS. 6)

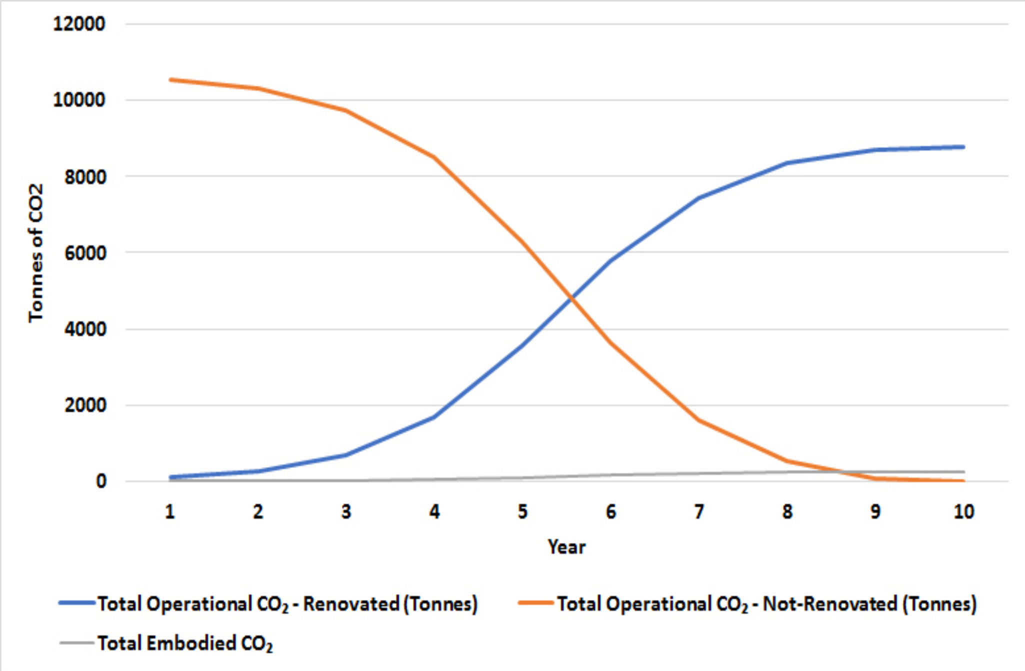

Figure 17: CO2 emissions (TS. 9)

Evaluating differences for these scenario when emissions are summed (see Figure 17 & 19), a considerable difference is also noticeable between TS. 6 & TS. 9. The emissions of the highest line at the starting year of this figure therefore represent the current situation (total emissions when no renovations have been performed) which is 10,651 Tonnes of CO2 / year for all transition scenarios. The emissions of the highest line at the final year of this figure represent the final situation (total emissions when all renovations have been performed). This value will differ for each transition scenario. Extracting those two values from one another gives the savings potential of the transition scenario. Large differences are noticeable in Figure 18 & 19 regarding this for TS. 6 & 9. The outcomes of other transition scenarios will range somewhere between the values obtained for TS. 6 & 9. (see Table 24 for an overview). Finally Table 24 also shows that circularity leads to more (cumulative) CO2 emissions reductions then the same heat supply alternative combined with a standard renovation approach. This difference is as in previous sections within this chapter attributed to the circular renovation / rebuild approaches used.

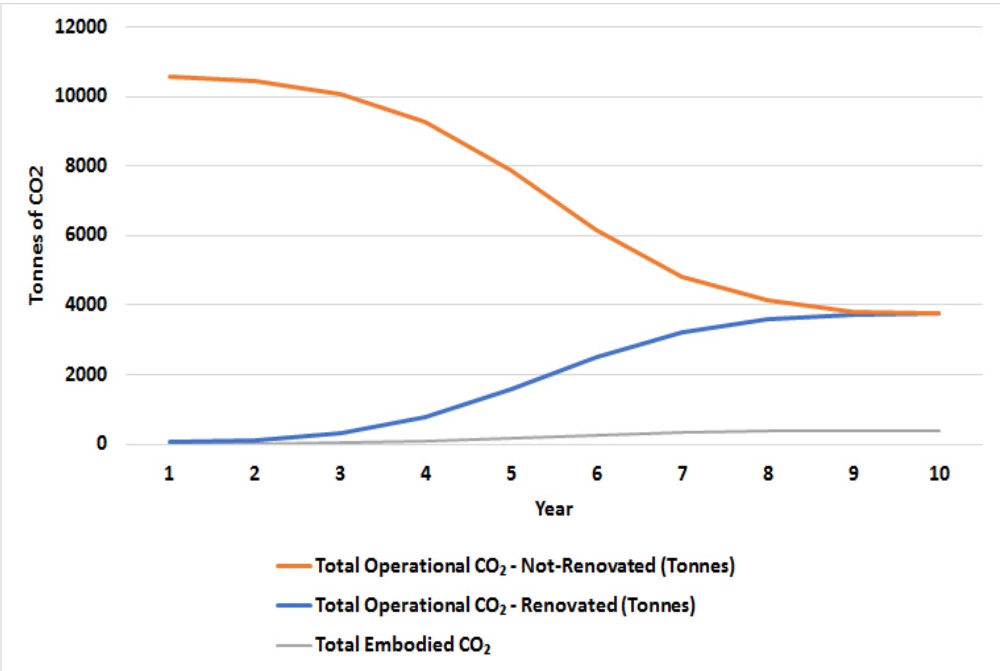

Figure 18: Summed CO2 emissions (TS. 6)

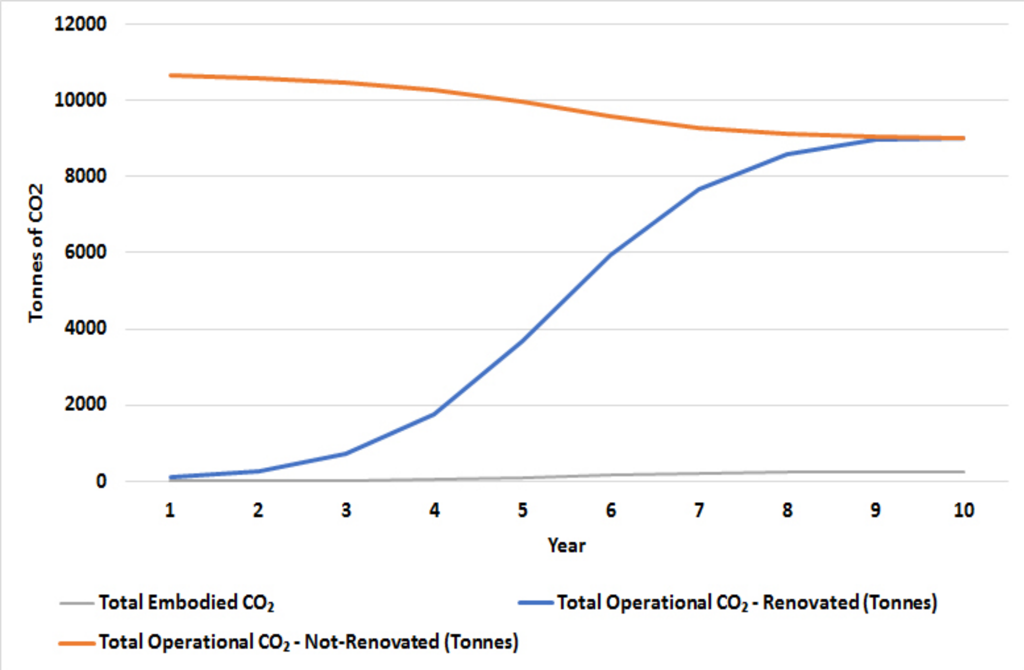

Figure 19: Summed CO2 emissions (TS. 9)

	Cumulative CO2 emissions after 10 years	Savings
Current	106,510 Tonnes of CO2	n.a.
TS. 1	80,253 Tonnes of CO2	5,179 Tonnes / year
TS. 2	78,965 Tonnes of CO2	5,427 Tonnes / year
TS. 3	79,786 Tonnes of CO2	5,239 Tonnes / year
TS. 4	77,700 Tonnes of CO2	5,537 Tonnes / year
TS. 5	72,017 Tonnes of CO2	6,670 Tonnes / year
TS. 6	70,882 Tonnes of CO2	6,891 Tonnes / year
TS. 7	85,019 Tonnes of CO2	4,139 Tonnes / year
TS. 8	84,515 Tonnes of CO2	4,238 Tonnes / year
TS. 9	97,916 Tonnes of CO2	1,628 Tonnes / year
TS. 10	97,816 Tonnes of CO2	1,648 Tonnes / year

Table 24: Cumulative CO2 emissions and savings in various transition scenarios.

Concluding on this section: taking all previous indicators and figures for energy use into account for both the embodied & operational CO2 impacts results show that TS. 6 with savings of 6,891 tonnes of CO2 achieve the highest savings of all transition scenarios (which is equal to the yearly building energy use related CO2 emissions of approximately 1570 households) (PBL, 2012).

Other notable results were that regarding CO2 emissions transition scenarios using a circular renovation / rebuild approach perform better in terms of CO2 emission reduction then transition scenarios using a standard renovation / rebuild approach. This differences in CO2 emissions is allocated to the use of circular building materials which led to larger savings in CO2 emissions. Further it was concluded that for the Lunetten case study low-temperature transition scenarios always pay themselves back with regard to

CO_2 emissions when comparing them with solution within other temperature ranges.

5.3). Sensitivity Analysis

The CIMFA-Model has more than a 100+ variables, consisting of variables such as values for the building dimensions, density and lambda values for materials, energy and CO_2 emissions factors for material production, re-use potential for materials, life-expectancy of materials, energy consumption estimates for various temperature scenarios and CO_2 factors for energy production given for various heat supply options. However most of these values are expected to have minimal influence on the final results because there was no fixed number, however there was a fixed range available (the case for some of the density and lambda values). Because these ranges were usually small influences on the eventual results are expected to be low.

For this it was decided to perform a sensitivity analysis for a selection of the variables delineating on those values that are considered to be the most important / hold the potential to have the biggest effects on the final results which are the values for life-expectancy of materials and the CO_2 factors for energy production (given for various heat supply options). These are further explained in the following two sections.

5.3.1). Sensitivity of life-expectancy variables

With regard to life-expectancy the upper values are set 20% higher than the standard values while the lower values are set 20% lower than the standard values. Results are given in Table 25 (for energy) and in Table 26 (for CO_2).

	Decrease (%)	Upper value	Current value	Lower value	Increase (%)
TS. 1	3.17%	76.4 TJ	78.9 TJ	82.7 TJ	4.82%
TS. 2	3.28%	76.6 TJ	79.2 TJ	83.1 TJ	4.92%
TS. 3	8.66%	87.5 TJ	95.8 TJ	108.1 TJ	12.84%
TS. 4	6.87%	73.2 TJ	78.6 TJ	86.7 TJ	10.31%
TS. 5	1.82%	70.1 TJ	71.4 TJ	73.3 TJ	2.66%
TS. 6	3.18%	76.1 TJ	78.6 TJ	82.3 TJ	4.71%
TS. 7	0.77%	129 TJ	130.0 TJ	131.4 TJ	1.08%
TS. 8	1.60%	135.1 TJ	137.3 TJ	140.5 TJ	2.33%
TS. 9	0.27%	187.6 TJ	188.1 TJ	189.0 TJ	0.48%
TS. 10	0.32%	187.6 TJ	188.2 TJ	189.0 TJ	0.43%

Table 25: Results (energy) of sensitivity analysis on variables for life-expectancy.

	Decrease (%)	Upper value	Current value	Lower value	Increase (%)
TS. 1	1.91%	6,161 Tonnes	6,281 Tonnes	6,461 Tonnes	2.87%
TS. 2	1.31%	5.954 Tonnes	6,033 Tonnes	6,151 Tonnes	1.96%
TS. 3	5.47%	5.637 Tonnes	5,963 Tonnes	6,451 Tonnes	8.18%
TS. 4	4.67%	5.305 Tonnes	5,565 Tonnes	5,954 Tonnes	6.99%
TS. 5	2.59%	3.908 Tonnes	4,012 Tonnes	4,166 Tonnes	3.84%
TS. 6	1.77%	3.724 Tonnes	3,791 Tonnes	3,891 Tonnes	2.64%
TS. 7	1.16%	6.284 Tonnes	6,358 Tonnes	6,468 Tonnes	1.73%
TS. 8	0.93%	6.201 Tonnes	6,259 Tonnes	6,344 Tonnes	1.36%
TS. 9	0.47%	8.643 Tonnes	8,684 Tonnes	8,745 Tonnes	0.70%
TS. 10	0.44%	8.626 Tonnes	8,664 Tonnes	8,721 Tonnes	0.66%

Table 26: Results (CO2) of sensitivity analysis on variables for life-expectancy.

In Table 25 decreasing impacts in energy emission in a range of 0.32% - 8.66% and increasing impacts in a range of 0.43% - 12.84% were observed while in Table 26 increasing impacts in CO2 emission in a range of 0.66% - 8.18% and decreasing impacts in a range of 0.44% - 5.47% were observed. Largest impacts were observed for TS. 3 and TS. 4 (because of the large material flows within these transition scenarios) while lowest impacts were observed in TS 9 & 10 (which are the transition scenarios with limited material flows). The influence on the results of changing parameters for life-expectancy of materials and installations are with the ranges given above relatively limited.

5.3.2). Sensitivity of CO2 emissions variables for energy production

With regard to CO2 factors for energy production the upper value is considered to be the current value (because for the future CO2 emissions are only expected to decline), while the lower value is assumed to be zero (the eventual national goal for CO2 factors). Results are given in Table 27.

	Upper Value	Lower Value	Decrease (%)
TS. 1	6,281 Tonnes of CO2	720 Tonnes of CO2	88.5%
TS. 2	6,033 Tonnes of CO2	472 Tonnes of CO2	92.2%
TS. 3	5,963 Tonnes of CO2	1954 Tonnes of CO2	67.2%
TS. 4	5,565 Tonnes of CO2	1556 Tonnes of CO2	72.0%
TS. 5	4,012 Tonnes of CO2	620 Tonnes of CO2	84.5%
TS. 6	3,791 Tonnes of CO2	399 Tonnes of CO2	89.5%
TS. 7	6,358 Tonnes of CO2	443 Tonnes of CO2	93.0%
TS. 8	6,259 Tonnes of CO2	344 Tonnes of CO2	94.5%
TS. 9	8,684 Tonnes of CO2	246 Tonnes of CO2	97.2%
TS. 10	8,664 Tonnes of CO2	226 Tonnes of CO2	97.4%

Table 27: Results of sensitivity analysis on CO2 factors for energy production.

In Table 27 decreasing CO2 impacts were found ranging between 67.2% - 97.4%. Lowest decreases are achieved for transition scenarios that use a demolish & rebuild approach, therefore decrease in CO2 emissions is somewhat limited because there remains a considerable amount of embodied CO2 impacts. Highest decreases are achieved for transition scenarios that use high temperature heat supply strategies. These transition scenarios hold minimal embodied CO2 impacts, which means that when bringing the operational CO2 impacts to zero remaining CO2 impacts will be very low because of the low embodied CO2 impacts. Based on this, one could see the sensitivity of the parameters for CO2 emissions for energy production. While the parameters for electricity production are average values for the Netherlands, the parameters for heat networks can vary per location. Based on the results for this sensitivity analysis in a hypothetical situation for another location in the Netherlands that has a fully sustainable high temperature heat source available it is that outcomes for that specific location show that in terms of CO2 emissions high temperature heat network will perform best. The results for a neighborhood analysis performed with the CIMFA-Model can thus vary from one another based on geographical location of the neighborhood that is analyzed.

Concluding for this section: changing parameters for life-expectancy of materials and installations led to relatively limited changes in energy and CO2 impacts (increases in a range of 0.43% - 12.84% for energy and 0.66% - 8.18% for CO2, while decreases in a range of 0.32% - 8.66% for energy and 0.44% - 5.47% for CO2 were observed). With regard to the sensitivity of the parameters for CO2 emissions for energy production large sensitivities were found ranging from 67.2% - 97.4%. Further an important conclusion was made that that the results for a neighborhood analysis performed with the CIMFA-Model can vary from one another based on geographical location of the neighborhood that is analyzed.

6). Discussion

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Within this chapter the research project will be further discussed starting off with a section that mentions the limits of this study, followed up by a section that lines out the contribution to literature of this study and finishing with a section that gives recommendations for future research. This final section partly holds a connection with the limits because it offers perspective to solve some of the earlier limits of the current research with future adjustments.

6.1). Limits of the study:

In this study various limits could be distinguished, these limits can be subdivided into three categories namely limits related to the geometric model, limits related to data quality and finally a category with (other) limitations that could not be placed in one of the earlier mentioned categories but also don't relate to another.

First of all limits with regard to the geometric model can be found in the fact that not the entire existing building is captured by the CIMFA-Model. Not taken into account are for instance things like stairs, gutter, windowsills and wall paper because they were deemed to be too much detail for the model. Further the foundation was left out because in all scenarios no changes to the existing foundation were assumed (also in case of demolish & rebuild the new dwelling would be built on top of the old foundation). Finally internal walls and doors were left out of the model because the measures of this model focus on insulation. For this reason internal walls were deemed to be too much detail. However all things mentioned above will influence the accuracy and / or completeness of the CIMFA-Model and it's results.

Besides exclusions upfront, further limits in the CIMFA-Model also occur because of the way data is inserted into the model. First of all the sub-archetypes are scaled and materials assigned based on a interaction between the reference archetype and input regarding dimension of the building obtained from existing construction drawings. The CIMFA-Model however only allows to insert dimensions of rectangular buildings. This approach was for Lunetten not a real problem because almost all dwellings had a rectangular floor plan. Influence of this on the model results is thus assumed to be minimal, however when the CIMFA-model is used for other neighborhoods this could become considerable.

Looking further into the CIMFA-model thickness values from things like floors, walls and roofs were derived from the GPR-archetype model in order to finally derive m^3 of materials. However for a few materials thicknesses were not available, in this case assumptions had to be made which leads to inaccuracies in the CIMFA-model. Further the material thicknesses and material types that were obtained from either the GPR-archetype or assumptions were used as the standard values for all dwellings within Lunetten. However these values that were obtained from the archetypes do not necessarily exactly represent the real situation for each dwelling in Lunetten. Illustrating this with an example the inner facing for row houses were assumed to be a 100mm thick limestone wall because this was most common for this period. However although most common for this period this could still mean that the inner facing of a wall of a row house in Lunetten can be of a different thickness and / or material. Using standardized values could in potential thus have led to further inaccuracies in the CIMFA-model compared to exact reality.

Further regarding the determinations of the existing stock inaccuracies could occur because the stocks are based on a situation immediately after construction of the building. During the years however the original building could have been changed with for instance extensions to the existing building and / or later additional insulation measures. The CIMFA-Model will not account for these later changes therefore leading to further inaccuracies in the model.

Last to mention regarding the geometric model is that exact material needs for renovations are calculated. These however do not account for things like cutting losses and other losses that occur during the assembling of various components of a building.

Shifting from limits related to the geometric model towards the limits with regard to data quality several factors that influence the study with regard to data quality can be distinguished. All these factors were related to the NMD.

First of all a limit that was observed during the research was that for certain categories only limited amount of materials / installation options were available in GPR-gebouw. Examples were for instance with regard to air-sourced heat pumps (only one option available) and with circular insulation materials (usually multiple were available however several had such poor data that caused them to be excluded and therefore limiting down the options). This so called poor data is the second concern within the limits regarding data quality. For several materials (mainly bio-based (wood) materials) negative values were obtained for embodied energy and / or embodied CO2. This embodied energy also holds the last limit, the value consist within the GPR-tool out of three types of energy impacts namely 1). Total embodied energy which was composed of 2). renewable embodied energy and 3). non-renewable embodied energy. Adding up renewable embodied energy with non-renewable embodied energy should give the total embodied energy. This is however not always the case, therefore combined with all earlier factors raising concerns about the NMD data quality.

Left to mention are three limitations that hold no connection with the two categories above or with one another. First of all a rather specific limit to the current research it that it doesn't account for the fact that some materials are landfilled before the actual end of life, additional energy and CO2 impacts should therefore be allocated to the buildings stock). This however doesn't happen.

Secondly this research shows that in terms of CO2 impacts, circular low-temperature strategies hold the best performance. However how realistic are those scenarios? What can be said about the labor requirements? And what can be said about the costs? Nothing is said about these factors either in this research while they could be of equally important decision criteria just like energy and CO2.

Finally the sensitivity analysis that was performed was a rather limited sensitivity analysis which only took account for a few of the variables, testing them only for a situation that changed them individually.

6.2). Contribution to Literature:

This study aimed to fill in the literature gap of: ''Getting insights into the potential benefits in terms of operational and embodied energy and CO2 impacts for circular transition scenarios in the energy transition from a built environment using natural gas, to one using natural gas free alternatives for the existing residential building stock in The Netherlands''.

To measure these potential benefits the CIMFA-Model was constructed, which was designed in such a way that it could also be re-used with minimal changes for other neighborhood studies with regard to this topic. A major conclusion that could be made is that with transition scenarios using circular renovation / rebuild strategies more CO2 emissions could be saved then when using a standard renovation / rebuild approach. Using circular renovation / rebuild approaches thus contribute to two important targets namely: climate targets such as the Paris agreement (United Nations, 2015) and national and international targets / laws with regard to circularity, for instance (EU, 2018; SER, 2016; Rijksoverheid, 2016b; Rijksoverheid, 2018).

Comparing results with other studies, one study was available that specifically investigated the operational and embodied energy impacts for various retrofit scenarios within the Netherlands. In this study Koezjakov, Urge-Vorsatz, Crijns-Graus & van den Broek (2018) found values for embodied energy for with a range of 10-12% of the total energy use for standard homes, 15-18% of the total energy use for retrofit homes, 31-35% of the total energy use for advanced retrofits and 31-46% for advanced new build. This research found values ranging 10-13% of the total energy use for standard homes, 15-27% of the total energy use for retrofits (TS. 7 & 8), 28-44% of the total energy use for advanced retrofits (TS. 1, 2, 5 & 6) and 30-53% of the total energy use for advanced new build (TS. 3 & 4). Most values obtained within this research are in line with the findings of Koezjakov, Urge-Vorsatz, Crijns-Graus & van den Broek (2018). Different however is that this research shows larger ranges, this can be attributed to the special attention for circular materials which holds high embodied energy values. Overall however the findings of this research support findings of earlier research.

6.3). Recommendations for future research:

First of all as already came forward out of the of the study several limits regarding the geometric model exist. While some are already optional and allow the flexibility of the model (for instance the default values for wall thicknesses and material types), others like for instance not taking account for things like foundation and internal walls as well as the fact that the CIMFA-Model only works for dwellings with rectangular floor plans are fixed limits without an additional use. Improvement on these factors should thus be the goal for future research. This means that a future version of the CIMFA-Model should thus for the sake of completeness also include elements as foundation and internal walls. Further an geometric-model should be developed that also allows the exact calculation of non-rectangular buildings. For this could be thought about a calculation methodology that is based on the use of the shoelace algorithm. First test were already performed within this project and it was found out that using a shoelace algorithm theoretically would work and also allow the exact calculation of a large variation of non-rectangular buildings.

A second series of recommendations is specifically addressed towards the GPR-Gebouw tool that was used. First of all, as mentioned before in the limits not all material flows for each archetype could be accurately derived from the GPR-Gebouw tool. This was because for a few materials the material thicknesses were not given and therefore had to be based on assumptions. Besides this the GPR-Gebouw tool also made use of the NMD database to account for energy and CO2 impacts of various materials This database however had for some categories rather limited choices, while for other categories there were concerns about the data-quality. Finally this database also missed vital data needed to asses certain circular aspects of the materials. An upcoming update for the NMD which will be included into the GPR-Gebouw is expected to solve the problems with regard to mentioned data-quality issues and accounting for circular aspects. Further possible future version of the NMD as well as an entire new version of the GPR-Gebouw tool could possibly also improve data availability by adding more choices for materials and installations as well as adding clear thicknesses for al dimensions. In case any of this named updates will come available it is thus immediately advised to update the existing CIMFA-Model with this data.

A third recommendation could be made with regard to future versions of the CIMFA-Model. For these future versions it would be recommended that they include more data which for instance also allow to measure the impacts of infrastructural adjustments needed in the neighborhood for each heat supply scenario. Further data that makes accounting for the energy and CO2 impacts of landfilling materials before the actual end of life should be added. Finally also adding data with regard to cost and labor requirements would be a great contribution to improving the model since these things would allow broader and more accurate assessments of the various transition scenarios.

A last recommendation is to make more neighborhoods analyzes by using the CIMFA-Model. First of all because this would allow comparisons between multiple neighborhoods that use the same methodology / tool. Secondly more analysis would probably also lead to more knowledge about the drawbacks of the CIMFA-Model which on its turns would could contribute to future improvements of the CIMFA-Model.

7). Conclusion

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This research aimed to gain insights into the potential benefits in terms of operational and embodied energy and CO2 impacts for circular transition scenarios in the energy transition from a built environment using natural gas, to one using natural gas free alternatives for the existing residential building stock in The Netherlands". To fulfill in this research aim the following main research question was formulated for this research: "What are the differences in operational and embodied energy and CO2 impacts when comparing circular transition scenarios with non-circular transition scenarios for a situation of an energy transition where natural gas free heat supply alternatives replace natural gas as main source for heat supply in existing dwellings in the Netherlands?"

Within this research an example study for the Utrecht-Lunetten neighborhood was used to analyze this. For this research a special model to measure impacts of a circular energy transition (the CIMFA-Model) was created with input data being based on RVO-archetypes. For the Lunetten neighborhood special sub-archetypes were made that scaled the archetypes to the specific situation of Lunetten. Then a set of 10 transition scenarios (TS. 1-10) was formed that differ from one another with regard to heat supply option using either all-electric or a heat network with varying temperature ranges as heat supply option, further they differed with regard to renovation / rebuild strategy using either a standard renovation / rebuild strategy or a circular renovation / rebuild strategy. For each of these transition scenarios an overview of material flows was obtained. Combining these results with energy and CO2 impacts for each individual material gave an overview of embodied impacts for the various transition scenarios. Adding operational energy and operational CO2 impacts in the final stage allowed further comparisons for the case study of Lunetten neighborhood. The main results that were obtained in this research are visualized in Table 28.

	Operational	**Embodied (renovation)**	**Unit**	**Cumulative CO2 (10 years scenario)**	**Unit**
Current	181	n.a.	TJ	106,510	Tonnes CO2
	10,651	n.a.	Tonnes CO2		
TS. 1	63.7	15.2	TJ	80,253	Tonnes CO2
	5,561	720	Tonnes CO2		
TS. 2	63.7	15.5	TJ	78,965	Tonnes CO2
	5,561	472	Tonnes CO2		
TS. 3	46.4	49.2	TJ	79,786	Tonnes CO2
	8,438	1954	Tonnes CO2		
TS. 4	46.4	32.3	TJ	77,700	Tonnes CO2
	8,438	1556	Tonnes CO2		
TS. 5	63.7	7.7	TJ	72,017	Tonnes CO2
	4,009	620	Tonnes CO2		
TS. 6	63.7	14.9	TJ	70,882	Tonnes CO2
	4,009	399	Tonnes CO2		
TS. 7	124.2	5.8	TJ	85,019	Tonnes CO2
	3,392	443	Tonnes CO2		
TS. 8	124.2	13	TJ	84,515	Tonnes CO2
	3,392	344	Tonnes CO2		
TS. 9	184.8	3.4	TJ	97,916	Tonnes CO2
	5,915	246	Tonnes CO2		
TS. 10	184.8	3.4	TJ	97,816	Tonnes CO2
	5,915	226	Tonnes CO2		

Table 28: Overview of the main results of this research (neighborhood level).

Concluding on these main results with regard to the research question, regarding energy the transition scenarios using standard renovation approaches showed better performances with regard to embodied energy impacts then the transition scenarios using circular renovation approaches (with an exception for TS. 3 & 4). The difference between these standard and circular renovation approaches was allocated to the use of circular mainly biobased materials in the transition scenarios that have a circular renovation strategy. These biobased materials hold high shares of renewable embodied energy while having very low values for non-renewable embodied energy values. The renewable embodied energy (for instance caused by the sunlight absorbed a by a tree to grow) is thus responsible for the high values for total embodied energy. The exception for TS. 3 & 4 was allocated to the fact that the re-used materials in TS. 4 compensated for the additional energy impacts of the circular materials. Regarding operational energy all low temperature heat transition scenarios (TS.1-6) perform better than the transition scenarios operating in other temperature ranges (TS. 7-10). Of the low temperature transition scenarios TS. 3 & 4 (demolish & rebuild) perform best, this is caused by the fact that rebuild allows a better optimization of insulation capabilities then renovation.

Concluding with regard to CO2 impacts, the results proved that in terms of CO2 impacts transition scenario using circular renovation / rebuild strategies work when it comes to reducing environmental impacts. Embodied CO2 impacts of circular materials were found to be lower than the CO2 impacts for standardly applied materials, therefore a circular transition scenarios allow greater CO2 reductions. Regarding operational CO2 impacts large variations were found for the various transition scenarios. These differences were allocated to the CO2 emissions for energy use which vary depending on the heat supply option that is used. For the specific case study of Lunetten the low-temperature heat network led to the most favorable results in terms of operational CO2 emissions. When evaluating all transition scenarios on a longer term (10 years) results further suggested that for the specific Lunetten case study low temperature heat supply solutions always pay themselves back on the long term in terms of CO2 emissions compared to transition scenarios which have middle or high temperature heat supply sources installed.

Translating these results of the specific case study of Lunetten to the scale of the Netherlands the following things can be concluded for the Netherlands:

1). Regarding operational energy, impacts will vary for various transition scenarios were those scenarios using low temperature heat are expected to have the best energy performance.

2). Regarding embodied energy, standard renovation / rebuild approaches have a lower embodied energy use then circular renovation / rebuild approaches. However, it has to be noted that within this research this was observed when using values of total embodied energy (and not non-renewable embodied energy) for the separate materials.

3). Regarding operational CO2 impacts it was found that each situation is unique. Some of the values found for CO2 emissions for energy use (e.g. heat network) can vary for each neighborhood within the Netherlands. Therefore the results of Lunetten cannot be generalized for the Netherlands since they can differ for each individual neighborhood.

4). Circular renovation / rebuild strategies work. The embodied CO2 impacts of circular materials were found to be than the CO2 impacts for standardly applied materials, therefore a circular transition scenarios allow greater CO2 reductions within the Netherlands.

5). The results of this study show the growing importance of embodied energy as share of the total energy for the Lunetten case study. These results can also be generalized for the Netherlands.

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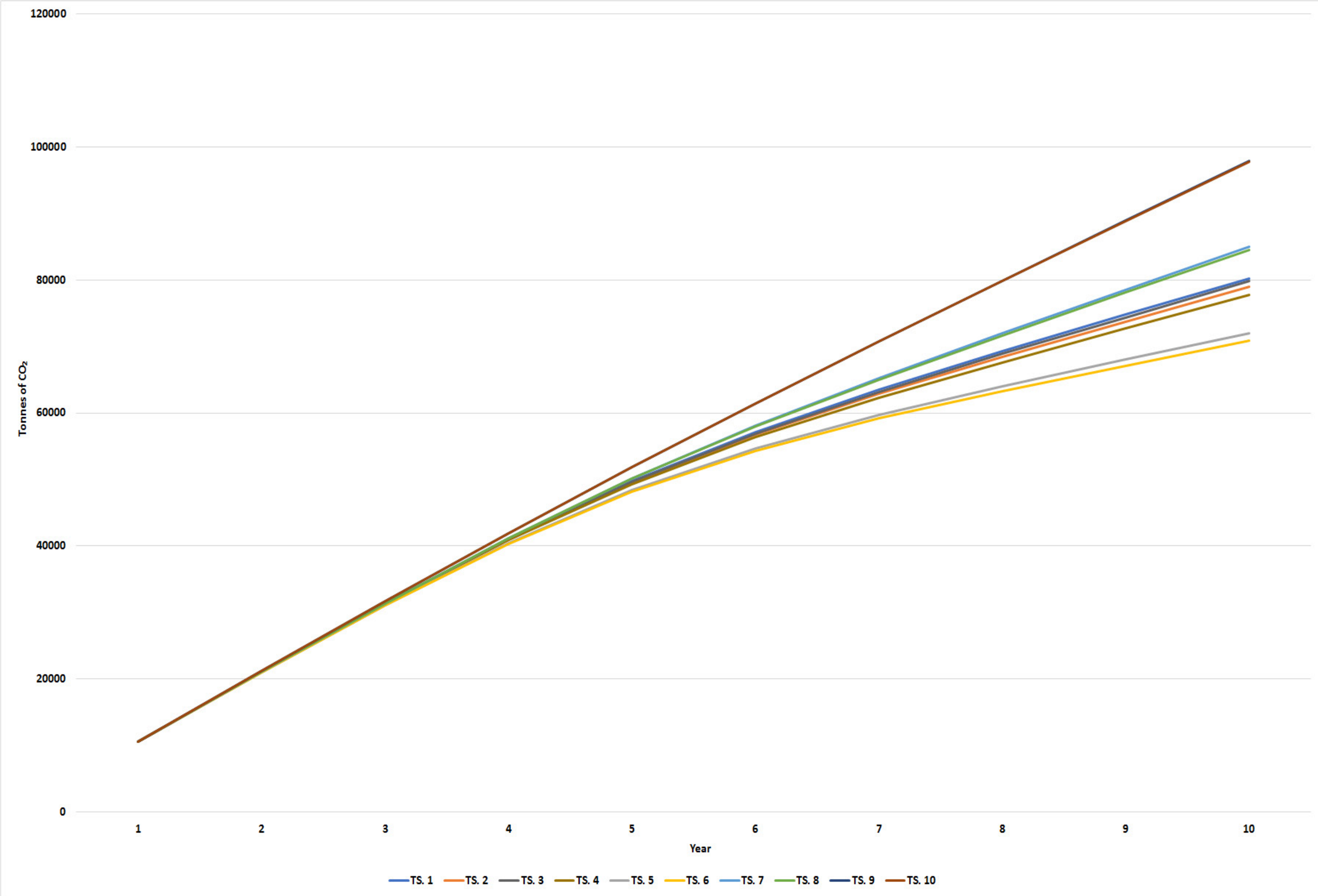
Appendix



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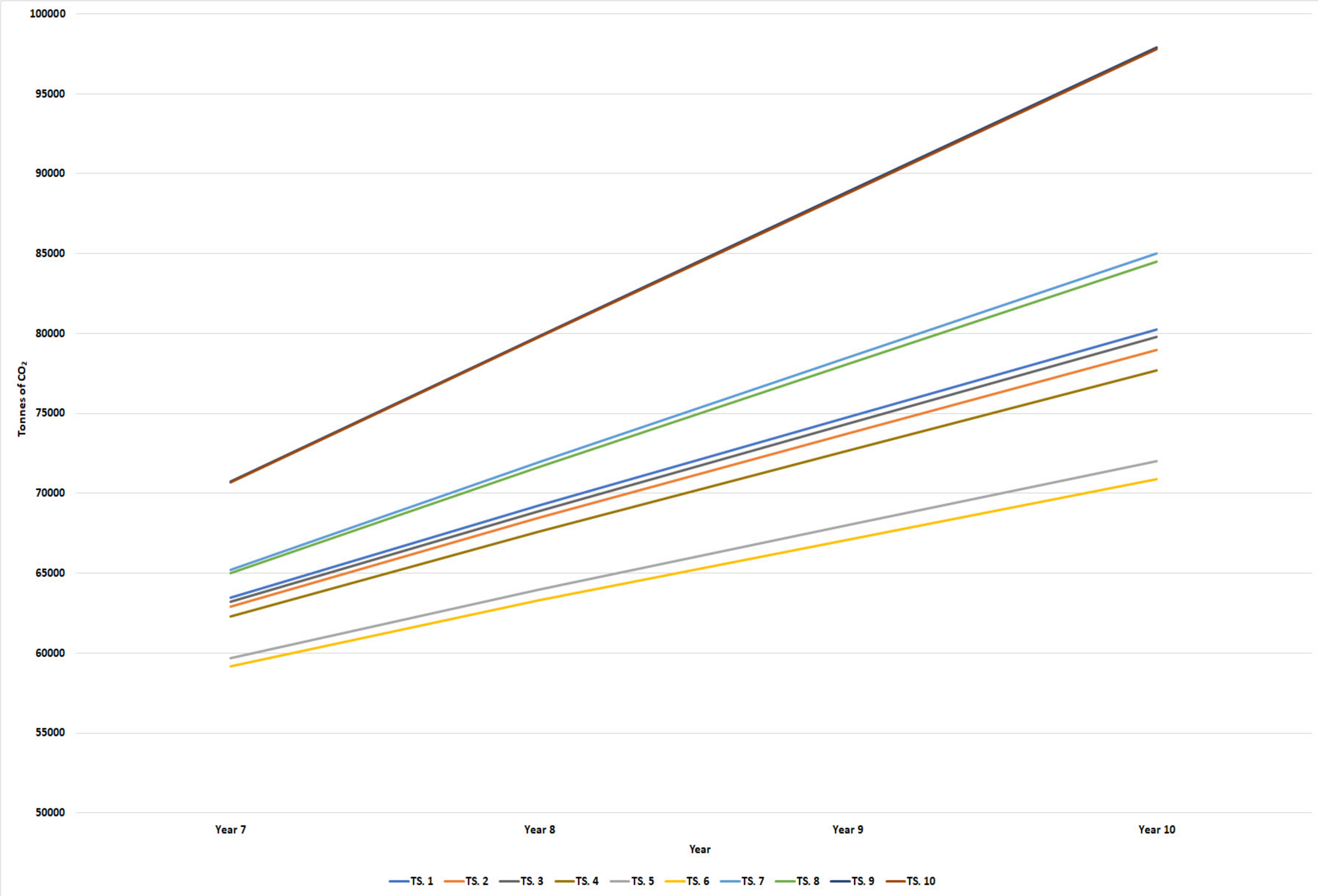
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