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Project report

LCA study

Comparison of deep foundation systems consisting of bored piles and ductile cast-iron piles

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1 Introduction

The following LCA study aims to determine the Global Warming Potential (GWP – kg CO_2 equivalents per meter of foundation pile) of deep foundation systems consisting of (ungrouted or grouted) ductile cast-iron piles (Table 1) and bored piles (Table 2) by applying the Life Cycle Assessment (LCA) methodology according to ISO 14040 [1] and ISO 14044 [2].

Table 1: Analysed ductile cast-iron piles with material shares per meter

Pile tube diameter	Wall thickness	Cast-iron (mass)	Concrete filling (volume)	Concrete grouting 220 mm (volume)	Concrete grouting 270 mm (volume)	Concrete grouting 320 mm (volume)	Concrete grouting 370 mm (volume)
[mm]	*[mm]*	*[kg/m]*	*[m³/m]*	*[m³/m]*	*[m³/m]*	*[m³/m]*	*[m³/m]*
118	7,5	21,00	0,00959	0,02708	0,04632	0,06949	x
118	9	24,42	0,00933	0,02708	0,04632	0,06949	x
118	10,6	27,96	0,00906	0,02708	0,04632	0,06949	x
170	9	37,14	0,02036	x	0,03456	0,05773	0,08482
170	10,6	42,54	0,01996	x	0,03456	0,05773	0,08482
170	13	50,42	0,01936	x	0,03456	0,05773	0,08482

The reinforcement of the bored piles was set to the minimum reinforcement according Eurocode 2 *Design of concrete structures* (EN 1992-1-1) [3].

Table 2: Analysed bored piles with material shares per meter

Pile diameter	Concrete (volume)	Minimum reinforcement (mass)
[mm]	*[m³/m]*	*[kg/m]*
600	0,28	11,10
800	0,50	19,63
1000	0,79	19,63
620*	0,30	11,85
760*	0,45	17,81

*Pile diameter applied for analysed construction projects

Based on the results per meter, a Life Cycle Assessment comparing the GWP of ductile piles and bored piles applied as deep foundations for two construction projects is carried out (kg CO_2 equivalents per construction project).

2 Life cycle assessment

The LCA methodology analyses and observes environmental aspects and potential environmental impacts throughout the life cycle of a product or service. A complete LCA according to ISO 14040 and ISO 14044 includes the following elements:

- Goal and scope definition
- Life Cycle Inventory (LCI)
- Life Cycle Impact assessment (LCIA)
- Interpretation

2.1 Goal of the study

The main goal of the study is to determine basic GWP values (kg CO_2 equivalents per meter of pile) for (ungrouted or grouted) ductile cast-iron piles and bored piles applied as deep foundation. Based on these values, the GWP of future deep foundation projects, which apply one of the two assessed pile types, can be determined, respectively the project variant causing least GWP emissions can be defined.

2.2 Scope of the study

The deep foundation systems are analysed "from cradle to construction end", i.e. the assessment includes all life cycle modules and processes until the construction processes of the different piles are completed:

- Material production (A1-A3)
- Transport to building site (A4)
- Construction process (A5)

During the use phase of the deep foundation systems (module B1 – B7) generally no material and energy inputs are required. Therefor, this study does not analyse the use phase due to its irrelevance.

Due to the fact that after the "end of life" of the entire building the deep foundation piles will either be reused (in the next building) or be left in place (if no other structure is created), the end of life phase (module C1 – C4) of the analysed pile types is also not included in the study.

2.3 Life cycle inventory

The Life Cycle Inventory (LCI) quantifies relevant inputs and outputs of the analysed life cycle modules, i.e. material and energy resources applied as well as emissions and waste products.

The LCI data sets were taken from the Environmental Product Declaration (EPD) for TRM ductile pile systems [4] or were modelled with the LCA software SimaPro based on the LCI database ecoinvent (Swiss life cycle inventory database developed in the ETH domain providing datasets for energy production, transport services, material production as well as waste disposal) [5]. The TRM-EPD was also modelled with ecoinvent datasets. If ecoinvent standard datasets were utilised, the Austrian consumer electricity mix was applied for these datasets.

The concrete mixtures analysed were provided by a company specialised in foundation engineering. Firstly it was planned to analyse a variety of concrete types applicable for the different deep foundation techniques. In accordance with the construction company it was agreed that for bored piles only the in Austria (and Germany) generally applied concrete of strength class C25/30 and for ductile piles only a special concrete mix with 0/4 aggregates and a high proportion of CEM III / A is analysed (for both filling and grouting). The analysed concrete mixtures are shown in Table 3.

Table 3: Concrete mixtures – raw materials (A1)

Mixtures	*Bored piles C25/30*	*Filling and grouting ductile piles*
	[kg/m³]	*[kg/m³]*
Cement		
CEM II/A-M(S-L) 42,5 R	330	
CEM III/A- 32,5 R		480
Additives		
Latent hydraulic additives	61	80
Water	184	165
Aggregates		
Primary aggregates (0/32)	1775	
Primary aggregates (0/4)		1540
Admixtures		
Plasticiser	2	5
Retarder		3
Density	2352	2273

The transport distances and vehicles for raw materials applied within the specific concretes are shown in Table 4.

Table 4: Transport characteristics concrete raw materials (A2)

Material	Transport distance	Transport vehicle
	[km]	
Cement	100	Articulated lorry
Latent hydraulic additives	100	Articulated lorry
Admixtures	500	Articulated lorry
Primary aggregates	35	Four-axle lorry

For both concrete mixtures analysed, the LCI dataset for the concrete mixing process (A3) was modelled according to the production process of a standard concrete from the ecoinvent 2.2 database.

The production process (per kg) of cast-iron (A1-A3) was taken from the TRM-EPD published by Bau-EPD GmbH. The production of reinforcing steel (A1-A3) was taken from the ecoinvent database. The production of one kilogram cast-iron causes (taking the Austrian electricity mix into account) a GWP of 1.06 kg CO_2 equivalents.

Regarding material transport processes to the building site it was defined to distinguish between average transport distances for Europe (Table 5) and “outside of Europe” (Table 6). Since the average distances for "outside Europe" are difficult to define, the transport distances for the "Interchange" bridge project in South Africa (transport ductile piles from Tiroler Rohre (TRM – Hall, Tirol, Austria) via Rotterdam to Cape Town) were applied.

Table 5: Transport characteristics material transport to building site (A4) – Europe

Material	Transport distance	Transport vehicle
	[km]	
Cast-iron	300	Articulated lorry
Concrete for filling and grouting of ductile pile	30	Four-axle lorry
Concrete for bored pile	30	Four-axle lorry
Reinforcing steel bored pile	100	Four-axle lorry

Table 6: Transport characteristics material transport to building site (A4) – outside of Europe

Material	Transport distance	Transport vehicle
	[km]	
Cast-iron – road	925	Articulated lorry
Cast-iron – ship	12’160	Transoceanic freight ship
Concrete for filling and grouting of ductile pile	50	Four-axle lorry
Concrete for bored pile	50	Four-axle lorry
Reinforcing steel bored pile	250	Four-axle lorry

The LCI for the construction process (A5) of the ductile piles was modelled based on performance factors and approaches provided by Tiroler Rohre (TRM). Thereby, the fuel consumption per m pile and the production of all construction equipment were considered (taking into account the operating time for each pile in relation to the total provision time of the equipment).

Table 7: Performance factors and modelling of construction process for ductile piles (A5) – TRM

Installation performance	300	m per day
Fuel consumption excavator 150 kW	150	l per day
Extra fuel consumption concrete pump 30 kW for grouting	20	l per day

Fuel consumption excavator – ungrouted	0,5	l per m of pile
Extra fuel consumption for grouting	0,07	l per m of pile

Construction equipment – ungrouted	**Engine performance** *[kW]*	**Net weight** *[kg]*
Excavator	150	25.000
Total	**150**	**25.000**

Construction equipment – grouted	**Engine performance** *[kW]*	**Net weight** *[kg]*
Excavator	150	25.000
Concrete pump	30	2.300
Total	**150**	**25.000**

The construction processes for bored piles (fuel consumption and the impact of construction equipment) were modelled for a typical construction equipment constellation and based on standard performance factors (Table 8). Thereby, it was distinguished between processes depending on the pile length (drilling, concreting, etc.) and single incident processes (repositioning of equipment, reinforcing, etc.).

Table 8: Performance factors bored pile construction

<u>Bored pile – single incidents per pile</u>		
Preparation	0,21	h/pile
Cleaning of borehole	0,50	h/pile
Reinforcing	0,38	h/pile
Introducing concrete pouring tube	0,42	h/pile
Total	***1,50***	***h/pile***
<u>Bored pile – per m of pile</u>		
Excavation/ Installation of drilling pipe	0,083	h/m
Concreting/ Pulling	0,083	h/m
Total	***0,167***	***h/m***

Table 9: Modelling of construction processes for bored piles

Single incidents per pile						
Equipment	**Engine performance**	**Net weight**	**ÖBGL-Nr.**	**Operating hours**	**Operating month**	**Fuel consumption**
	[kW]	*[kg]*	*[-]*	*[h/pile]*	*[Mo/pile]*	*[kWh/pile]*
Drill and pile driver	140	40.000	K.2.00.0090			
Double top drive	-	3.000	K.2.02.0050			
Telescopic Kelly bar	-	2.300	K.2.04.0815			
Auger	-	3.200	K.7.01.0600			
Drill pipe	-	3.000	K.6.00.0624			
Cutting shoe	-	1.200	K.6.02.0622			
	140	52.700		1,50	0,008843	**210,47**
Total month of provision basic machine:	45					
Ratio to month of provision per pile:	**0,000196514**					
Per m of pile						
Equipment	**Engine performance**	**Net weight**	**ÖBGL-Nr.**	**Operating hours**	**Operating month**	**Fuel consumption**
	[kW]	*[kg]*	*[-]*	*[h/m]*	*[Mo/m]*	*[kWh/m]*
Drill and pile driver	140	40.000	K.2.00.0090			
Double top drive		3.000	K.2.02.0050			
Telescopic Kelly bar		2.300	K.2.04.0815			
Auger		3.200	K.7.01.0600			
Drill pipe		3.000	K.6.00.0624			
Cutting shoe		1.200	K.6.02.0622			
	140	52.700		0,167	0,000980	**23,33**
Total month of provision basic machine:	45					
Ratio to month of provision per pile:	**2,17865E-05**					

2.4 Life Cycle Impact Assessment

2.4.1 Environmental indicators

Global Warming Potential (GWP):

Mankind injectes a growing amount of greenhouse gases into the atmosphere. These greenhouse gases absorb thermal radiation from earth, what causes a change of the global radiation balance and results in a global climate change.

The quantitatively most important greenhouse gas is carbon dioxide. The global warming potential is therefore expressed as carbon dioxide equivalents (kg CO_2 eq), i.e. for each "global warming substance" an equivalent amount of carbon dioxide is calculated in kilograms. Thus, the impact on the global climate change is summerized to a single indicator.

2.4.2 Basic values for LCA of ductile and bored piles

The following data can be used as basis for LCA studies of ductile and bored piles applied a deep foundation. The results for transport processes are expressed per meter pile and kilometer transport distance.

Table 10: Basic values ductile pile – kg CO_2 eq per meter of pile – transport results per m of pile and km of transport

			Pile type	118/7,5	118/9	118/10,6	170/9	170/10,6	170/13
A1-A3	Material production	Concrete filling	*kg CO_2 eq per m of pile*	2,47	2,41	2,34	5,25	5,15	4,99
		Ductile pile		22,30	25,90	26,60	39,40	45,10	53,40
		Concrete grouting 220 mm		6,98	6,98	6,98	x	x	x
		Concrete grouting 270 mm		11,94	11,94	11,94	8,91	8,91	8,91
		Concrete grouting 320 mm		17,92	17,92	17,92	14,89	14,89	14,89
		Concrete grouting 370 mm		x	x	x	21,87	21,87	21,87
A4	Transport to building site	Ductile pile – road	*kg CO_2 eq per m of pile and km of transport*	0,002256884	0,002624433	0,003004879	0,00399146	0,004572	0,005419
		Ductile pile – ship		0,00022574	0,000262504	0,000300557	0,000399238	0,000457	0,000542
		Concrete filling		0,003637	0,003536	0,003435	0,007729	0,007578	0,007342
		Concrete grouting 220 mm		0,010272	0,010272	0,010272	x	x	x
		Concrete grouting 270 mm		0,017581	0,017581	0,017581	0,013101	0,013101	0,013101
		Concrete grouting 320 mm		0,026370984	0,026370984	0,026370984	0,021892	0,021892	0,021892
		Concrete grouting 370 mm		x	x	x	0,032181	0,032181	0,032181
A5	Construction process	Ungrouted	*kg CO_2 eq per m of pile*	1,90	1,90	1,90	1,90	1,90	1,90
		Grouted		2,15	2,15	2,15	2,15	2,15	2,15

Table 11: Basic values bored pile – kg CO_2 eq per meter of pile – transport results per m of pile and km of transport

			Diameter	600	800	1000	620	760
A1-A3	Material production	Concrete	*kg CO_2 eq per m of pile*	77,62	138,61	219,00	83,16	124,75
		Reinforcement		15,59	27,57	27,57	16,64	25,01
A4	Transport to building site	Concrete	*kg CO_2 eq per m of pile and km of transport*	0,111984	0,199045	0,311029	0,119562	0,179680
		Reinforcement		0,001869	0,003305	0,003305	0,001995	0,002999
A5	Construction process	Per m of pile	*kg CO_2 eq per m of pile*	10,89	10,89	10,89	10,89	10,89
		Single incidents	*kg CO_2 eq per m of pile*	98,27	98,27	98,27	98,27	98,27

2.4.3 LCA per meter of pile with European standard transport distances

In the next step the GWP per meter of pile type was determined with the previously defined average European transport distances.

Table 12: Results ductile pile type 118/7,5 – kg CO_2 eq per m pile – standard transport distances Europe

			Pile type - 118/7,5 *kg CO_2 eq per m of pile*			
	Transport ductile pile:	300 km				
	Transport concrete:	30 km	Ungrouted	Grouted 220 mm	Grouted 270 mm	Grouted 320 mm
A1-A3	Material production	Concrete filling	2,47	2,47	2,47	2,47
		Ductile pile	22,30	22,30	22,30	22,30
		Concrete grouting	x	6,98	11,94	17,92
		Total	**24,77**	**31,76**	**36,72**	**42,69**
A4	Transport to building site	Ductile pile - road	0,68	0,68	0,68	0,68
		Ductile pile - ship	x	x	x	x
		Concrete filling	0,11	0,11	0,11	0,11
		Concrete grouting	x	0,31	0,53	0,79
		Total	**0,79**	**1,09**	**1,31**	**1,58**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**27,46**	**35,00**	**40,19**	**46,42**

Table 13: Results ductile pile type 118/9 – kg CO_2 eq per m pile – standard transport distances Europe

Transport ductile pile: 300 km Transport concrete: 30 km			Pile type - 118/9 *kg CO_2 eq per m of pile* Ungrouted	Grouted 220 mm	Grouted 270 mm	Grouted 320 mm
A1-A3	Material production	Concrete filling	2,41	2,41	2,41	2,41
		Ductile pile	25,90	25,90	25,90	25,90
		Concrete grouting	x	6,98	11,94	17,92
		Total	**28,31**	**35,29**	**40,25**	**46,23**
A4	Transport to building site	Ductile pile - road	0,79	0,79	0,79	0,79
		Ductile pile - ship	x	x	x	x
		Concrete filling	0,11	0,11	0,11	0,11
		Concrete grouting	x	0,31	0,53	0,79
		Total	**0,89**	**1,20**	**1,42**	**1,68**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**31,10**	**38,65**	**43,83**	**50,06**

Table 14: Results ductile pile type 118/10,6 – kg CO_2 eq per m pile – standard transport distances Europe

Transport ductile pile: 300 km Transport concrete: 30 km			Pile type - 118/10,6 *kg CO_2 eq per m of pile* Ungrouted	Grouted 220 mm	Grouted 270 mm	Grouted 320 mm
A1-A3	Material production	Concrete filling	2,34	2,34	2,34	2,34
		Ductile pile	29,60	29,60	29,60	29,60
		Concrete grouting	x	6,98	11,94	17,92
		Total	**31,94**	**38,92**	**43,88**	**49,86**
A4	Transport to building site	Ductile pile - road	0,90	0,90	0,90	0,90
		Ductile pile - ship	x	x	x	x
		Concrete filling	0,10	0,10	0,10	0,10
		Concrete grouting	x	0,31	0,53	0,79
		Total	**1,00**	**1,31**	**1,53**	**1,80**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**34,84**	**42,39**	**47,57**	**53,81**

Table 15: Results ductile pile type 170/9 – kg CO_2 eq per m pile – standard transport distances Europe

Transport ductile pile: 300 km Transport concrete: 30 km			**Pile type - 170/9** *kg CO_2 eq per m of pile*			
			Ungrouted	Grouted 270 mm	Grouted 320 mm	Grouted 370 mm
A1-A3	Material production	Concrete filling	5,25	5,25	5,25	5,25
		Ductile pile	39,50	39,50	39,50	39,50
		Concrete grouting	x	8,91	14,89	21,87
		Total	**44,75**	**53,66**	**59,64**	**66,62**
A4	Transport to building site	Ductile pile - road	1,20	1,20	1,20	1,20
		Ductile pile - ship	x	x	x	x
		Concrete filling	0,23	0,23	0,23	0,23
		Concrete grouting	x	0,39	0,66	0,97
		Total	**1,43**	**1,82**	**2,09**	**2,39**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**48,08**	**57,64**	**63,88**	**71,17**

Table 16: Results ductile pile type 170/10,6 – kg CO_2 eq per m pile – standard transport distances Europe

Transport ductile pile: 300 km Transport concrete: 30 km			**Pile type - 170/10,6** *kg CO_2 eq per m of pile*			
			Ungrouted	Grouted 270 mm	Grouted 320 mm	Grouted 370 mm
A1-A3	Material production	Concrete filling	5,15	5,15	5,15	5,15
		Ductile pile	45,10	45,10	45,10	45,10
		Concrete grouting	x	8,91	14,89	21,87
		Total	**50,25**	**59,16**	**65,13**	**72,12**
A4	Transport to building site	Ductile pile - road	1,37	1,37	1,37	1,37
		Ductile pile - ship	x	x	x	x
		Concrete filling	0,23	0,23	0,23	0,23
		Concrete grouting	x	0,39	0,66	0,97
		Total	**1,60**	**1,99**	**2,26**	**2,56**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**53,75**	**63,31**	**69,54**	**76,84**

Table 17: Results ductile pile type 170/13 – kg CO_2 eq per m pile – standard transport distances Europe

Transport ductile pile: 300 km Transport concrete: 30 km			Pile type - 170/13 *kg CO_2 eq per m of pile* Ungrouted	Grouted 270 mm	Grouted 320 mm	Grouted 370 mm
A1-A3	Material production	Concrete filling	4,99	4,99	4,99	4,99
		Ductile pile	53,40	53,40	53,40	53,40
		Concrete grouting	x	8,91	14,89	21,87
		Total	**58,39**	**67,30**	**73,28**	**80,27**
A4	Transport to building site	Ductile pile - road	1,63	1,63	1,63	1,63
		Ductile pile - ship	x	x	x	x
		Concrete filling	0,22	0,22	0,22	0,22
		Concrete grouting	x	0,39	0,66	0,97
		Total	**1,85**	**2,24**	**2,50**	**2,81**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**62,14**	**71,70**	**77,94**	**85,23**

Table 18: Results bored pile – kg CO_2 eq per m pile – standard transport distances Europe

Transport concrete: 30 km Transport reinforcement: 100 km			**Diameter**	**600**	**800**	**1000**	**620**	**760**
A1-A3	Material production	Concrete	*kg CO_2 eq per m of pile*	77,62	138,61	219,00	83,16	124,75
		Reinforcement		15,59	27,57	27,57	16,64	25,01
		Total		**93,21**	**166,18**	**246,57**	**99,81**	**149,76**
A4	Transport to building site	Concrete	*kg CO_2 eq per m of pile*	3,36	5,97	9,33	3,59	5,39
		Reinforcement		0,19	0,33	0,33	0,20	0,30
		Total		**3,55**	**6,30**	**9,66**	**3,79**	**5,69**
A5	Construction process	**Total per m pile**	*kg CO_2 eq per m of pile*	**10,89**	**10,89**	**10,89**	**10,89**	**10,89**
		Single incidents per pile	*kg CO_2 eq per pile*	*98,27*	*98,27*	*98,27*	*98,27*	*98,27*
Total per m of pile*			*kg CO_2 eq per m of pile*	**107,65**	**183,37**	**267,12**	**114,49**	**166,34**

* without single construction incidents per pile

2.4.4 LCA per meter of pile with Non-European standard transport distances

Furthermore, the GWP per meter of pile type was determined for the average transport distances outside Europe (Interchange project in Southafrica).

Table 19: Results ductile pile type 118/7,5 – kg CO_2 eq per m pile – standard transport distances outside Europe

Transport ductile pile – road:		925 km	**Pile type - 118/7,5**			
Transport ductile pile – ship:		12'160 km	*kg CO_2 eq per m of pile*			
Transport concrete:		50 km	Ungrouted	Grouted 220 mm	Grouted 270 mm	Grouted 320 mm
A1-A3	Material production	Concrete filling	2,47	2,47	2,47	2,47
		Ductile pile	22,30	22,30	22,30	22,30
		Concrete grouting	x	6,98	11,94	17,92
		Total	**24,77**	**31,76**	**36,72**	**42,69**
A4	Transport to building site	Ductile pile - road	2,09	2,09	2,09	2,09
		Ductile pile - ship	2,74	2,74	2,74	2,74
		Concrete filling	0,18	0,18	0,18	0,18
		Concrete grouting	x	0,51	0,88	1,32
		Total	**5,01**	**5,53**	**5,89**	**6,33**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**31,69**	**39,44**	**44,77**	**51,18**

Table 20: Results ductile pile type 118/9 – kg CO_2 eq per m pile – standard transport distances outside Europe

Transport ductile pile – road:		925 km	**Pile type - 118/9**			
Transport ductile pile – ship:		12'160 km	*kg CO_2 eq per m of pile*			
Transport concrete:		50 km	Ungrouted	Grouted 220 mm	Grouted 270 mm	Grouted 320 mm
A1-A3	Material production	Concrete filling	2,41	2,41	2,41	2,41
		Ductile pile	25,90	25,90	25,90	25,90
		Concrete grouting	x	6,98	11,94	17,92
		Total	**28,31**	**35,29**	**40,25**	**46,23**
A4	Transport to building site	Ductile pile - road	2,43	2,43	2,43	2,43
		Ductile pile - ship	3,19	3,19	3,19	3,19
		Concrete filling	0,18	0,18	0,18	0,18
		Concrete grouting	x	0,51	0,88	1,32
		Total	**5,80**	**6,31**	**6,68**	**7,11**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**36,00**	**43,75**	**49,08**	**55,50**

Table 21: Results ductile pile type 118/10,6 – kg CO_2 eq per m pile – standard transport distances outside Europe

Transport ductile pile – road:		925 km	Pile type - 118/10,6			
Transport ductile pile – ship:		12'160 km	*kg CO_2 eq per m of pile*			
Transport concrete:		50 km	Ungrouted	Grouted 220 mm	Grouted 270 mm	Grouted 320 mm
A1-A3	Material production	Concrete filling	2,34	2,34	2,34	2,34
		Ductile pile	29,60	29,60	29,60	29,60
		Concrete grouting	x	6,98	11,94	17,92
		Total	**31,94**	**38,92**	**43,88**	**49,86**
A4	Transport to building site	Ductile pile - road	2,78	2,78	2,78	2,78
		Ductile pile - ship	3,65	3,65	3,65	3,65
		Concrete filling	0,17	0,17	0,17	0,17
		Concrete grouting	x	0,51	0,88	1,32
		Total	**6,61**	**7,12**	**7,49**	**7,92**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**40,44**	**48,19**	**53,52**	**59,94**

Table 22: Results ductile pile type 170/9 – kg CO_2 eq per m pile – standard transport distances outside Europe

Transport ductile pile – road:		925 km	Pile type - 170/9			
Transport ductile pile – ship:		12'160 km	*kg CO_2 eq per m of pile*			
Transport concrete:		50 km	Ungrouted	Grouted 270 mm	Grouted 320 mm	Grouted 370 mm
A1-A3	Material production	Concrete filling	5,25	5,25	5,25	5,25
		Ductile pile	39,50	39,50	39,50	39,50
		Concrete grouting	x	8,91	14,89	21,87
		Total	**44,75**	**53,66**	**65,13**	**72,12**
A4	Transport to building site	Ductile pile - road	3,69	3,69	3,69	3,69
		Ductile pile - ship	4,85	4,85	4,85	4,85
		Concrete filling	0,39	0,39	0,39	0,39
		Concrete grouting	x	0,66	1,09	1,61
		Total	**8,93**	**9,59**	**10,03**	**10,54**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**55,58**	**65,41**	**71,82**	**79,32**

Table 23: Results ductile pile type 170/10,6 – kg CO_2 eq per m pile – standard transport distances outside Europe

			Pile type - 170/10,6			
Transport ductile pile – road:		925 km	*kg CO_2 eq per m of pile*			
Transport ductile pile – ship:		12'160 km				
Transport concrete:		50 km	Ungrouted	Grouted 270 mm	Grouted 320 mm	Grouted 370 mm
A1-A3	Material production	Concrete filling	5,15	5,15	5,15	5,15
		Ductile pile	45,10	45,10	45,10	45,10
		Concrete grouting	x	8,91	14,89	21,87
		Total	**50,25**	**59,16**	**65,13**	**72,12**
A4	Transport to building site	Ductile pile - road	4,23	4,23	4,23	4,23
		Ductile pile - ship	5,56	5,56	5,56	5,56
		Concrete filling	0,38	0,38	0,38	0,38
		Concrete grouting	x	0,66	1,09	1,61
		Total	**10,17**	**10,82**	**11,26**	**11,77**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**62,31**	**72,13**	**78,55**	**86,05**

Table 24: Results ductile pile type 170/13– kg CO_2 eq per m pile – standard transport distances outside Europe

			Pile type - 170/13			
Transport ductile pile – road:		925 km	*kg CO_2 eq per m of pile*			
Transport ductile pile – ship:		12'160 km				
Transport concrete:		50 km	Ungrouted	Grouted 270 mm	Grouted 320 mm	Grouted 370 mm
A1-A3	Material production	Concrete filling	4,99	4,99	4,99	4,99
		Ductile pile	53,40	53,40	53,40	53,40
		Concrete grouting	x	8,91	14,89	21,87
		Total	**58,39**	**67,30**	**73,28**	**80,27**
A4	Transport to building site	Ductile pile - road	5,01	5,01	5,01	5,01
		Ductile pile - ship	6,59	6,59	6,59	6,59
		Concrete filling	0,37	0,37	0,37	0,37
		Concrete grouting	x	0,66	1,09	1,61
		Total	**11,97**	**12,63**	**13,06**	**13,58**
A5	Construction process	**Total**	**1,90**	**2,15**	**2,15**	**2,15**
Total per m pile			**72,26**	**82,08**	**88,50**	**96,00**

Table 25: Results bored pile – kg CO_2 eq per m pile – standard transport distances outside Europe

Transport concrete: 50 km Transport reinforcement: 250 km			Diameter	600	800	1000	620	760
A1-A3	Material production	Concrete	*kg CO_2 eq per m of pile*	77,62	138,61	219,00	83,16	124,75
		Reinforcement		15,59	27,57	27,57	16,64	25,01
		Total		**93,21**	**166,18**	**246,57**	**99,81**	**149,76**
A4	Transport to building site	Concrete	*kg CO_2 eq per m of pile*	5,60	9,95	15,55	5,98	8,98
		Reinforcement		0,47	0,83	0,83	0,50	0,75
		Total		**6,07**	**10,78**	**16,38**	**6,48**	**9,73**
A5	Construction process	**Total per m pile**	*kg CO_2 eq per m of pile*	**10,89**	**10,89**	**10,89**	**10,89**	**10,89**
		Single incidents per pile	*kg CO_2 eq per pile*	*98,27*	*98,27*	*98,27*	*98,27*	*98,27*
Total per m of pile*			*kg CO_2 eq per m of pile*	**107,65**	**183,37**	**267,12**	**114,49**	**166,34**

* without single construction incidents per pile

2.4.5 LCA for construction projects

In order to compare the different pile types in their application as deep foundation, for two construction projects a bored pile and ductile pile variant were compared.

2.4.5.1 Production and logistics centre company Zürn in Germany

The first analysed construction is the deep foundation system for the new production and logistics centre of the company *Zürn* in *Rain am Lech* in Germany.

The ductile pile variant consists of 43 piles of type 118/7.5 enveloped by 270 mm (diameter) grouting layer. The piles have a length of 10 m. The characteristic load for the complete deep foundation system is approximately 16,500 kN. The characteristic bearing capacity per pile is about 500 kN. Thus, 43 piles provide a characteristic bearing capacity of approximately 21,500 kN, i.e. the ductile variant is oversized by about 5,000 kN.

As a first step the detailed results for the individual piles (with a length of 10m) were calculated. Thereby, the transport distances correlate with the European average distances (concrete 30 km, ductile pile 300 km equal to distance Hall in Tirol – Rain am Lech).

Originally it was planned to model the material production and the construction process with the national energy mix of the country, where the construction project is executed. However, the influence of replacing the Austrian by the German electricity mix was determined to be about 1% of the overall result. Therefor and in order to avoid further effort, it was decided to compare the deep foundation variants with the Austrian electricity mix.

Table 26: Construction project Zürn – pile type 118/7.5, 270 mm grouting, length 10 m – kg CO_2 eq per ductile pile

		Dimension:	**118/7,5/10m**
		Transport ductile pile:	300 km
		Transport concrete:	30 km

			Pile type - 118/7,5
			kg CO_2 eq per pile
			Grouting 270 mm
A1-A3	Material production	Concrete filling	24,73
		Ductile pile	223,00
		Concrete grouting	119,45
		Total	**367,18**
A4	Transport to building site	Ductile pile - road	6,77
		Ductile pile - ship	x
		Concrete filling	1,09
		Concrete grouting	5,27
		Total	**13,14**
A5	Construction process	**Total**	**21,54**
Total per pile			**401,86**

In the next step, the overall result for the 43 ductile piles was determined.

Table 27: Construction project Zürn – 43 x pile type 118/7.5, 270 mm grouting, length 10 m – kg CO_2 eq

		Dimension:	**118/7,5/10m x 43**
		Transport ductile pile:	300 km
		Transport concrete:	30 km

			Pile type - 118/7,5
			kg CO_2 eq
			Grouting 270 mm
A1-A3	Material production	Concrete filling	1.063,42
		Ductile pile	9.589,00
		Concrete grouting	5.136,33
		Total	**15.788,75**
A4	Transport to building site	Ductile pile - road	291,14
		Ductile pile - ship	x
		Concrete filling	46,92
		Concrete grouting	226,79
		Total	**564,85**
A5	Construction process	**Total**	**926,29**
Total			**17.279,89**

The bored pile variant consists of 24 bored piles with a diameter of 620 mm and a length of 8 m. Again, the average European transport distances (concrete 30 km, reinforcement 100 km) were applied. The characteristic bearing capacity of the pile system was dimensioned according to the characteristic overall load of approximately 16,500 kN.

Table 28: Construction project Zürn – bored pile 620 mm, length 8 m – kg CO_2 eq per bored pile

	Dimension:	**620mm/ 8m**		Diameter
	Transport concrete:	30 km		
	Transport reinforcement:	100 km		**620**
A1-A3	Material production	Concrete	*kg CO_2 eq per pile*	665,31
		Reinforcement		133,15
		Total		**798,46**
A4	Transport to building site	Concrete	*kg CO_2 eq per pile*	28,69
		Reinforcement		1,60
		Total		**30,29**
A5	Construction process	**Total per m pile**	*kg CO_2 eq per pile*	**87,14**
		Single incidents per pile		*98,27*
Total per pile			*kg CO_2 eq per pile*	**1014,16**

Table 29: Construction project Zürn – 24 x bored pile 620 mm, length 8 m – kg CO_2 eq per bored pile

	Dimension:	**620mm/ 8m x 24**		**Diameter**
	Transport concrete:	30 km		
	Transport reinforcement:	100 km		620
A1-A3	Material production	Concrete	*kg CO_2 eq*	15.967,41
		Reinforcement		3.195,53
		Total		**19.162,94**
A4	Transport to building site	Concrete	*kg CO_2 eq*	688,68
		Reinforcement		38,31
		Total		**726,99**
A5	Construction process	**Total per m pile**	*kg CO_2 eq*	**2.091,47**
		Single incidents per pile		*2.358,39*
Total			*kg CO_2 eq*	**24.339,79**

2.4.5.2 Interchange project in South Africa

The second project analysed is the deep foundation system of a bridge structure for a motorway interchange in South Africa.

The ductile pile variant consists of 38 ungrouted type 118/9 piles. 20 piles have a length of 16 m and 18 of 11 m. This deep foundation variant can carry off a characteristic load of 22'800 kN.

The transport distances for this project have already been utilised previously for the transportation situation "outside Europe" and will lso be applied for this analysis.

Since there is no dataset for electricity production in South Africa in the ecoinvent 2.2 database (and also due to the expected minimal impact) the Austrian electricity mix is as well applied for both deep foundation variants of this construction project.

Table 30: Interchange project South Africa – pile type 118/9, ungrouted, length 16 m – kg CO_2 eq per pile

		Dimension:	**118/9/16m**
		Transport ductile pile – road:	925 km
		Transport ductile pile – ship:	12'160 km
		Transport concrete:	50 km
			Pile type - 118/9
			kg CO_2 eq per pile
			ungrouted
A1-A3	Material production	Concrete filling	38,50
		Ductile pile	414,40
		Concrete grouting	x
		Total	**452,90**
A4	Transport to building site	Ductile pile - road	38,84
		Ductile pile - ship	51,07
		Concrete filling	2,83
		Concrete grouting	x
		Total	**92,74**
A5	Construction process	**Total**	**30,39**
Total per pile			**576,03**

Table 31 Interchange project South Africa – pile type 118/9, ungrouted, length 11 m – kg CO_2 eq per pile

		Dimension:	**118/9/11m**
		Transport ductile pile – road:	925 km
		Transport ductile pile – ship:	12'160 km
		Transport concrete:	50 km
			Pile type - 118/9
			kg CO_2 eq per pile
			ungrouted
A1-A3	Material production	Concrete filling	26,47
		Ductile pile	284,90
		Concrete grouting	x
		Total	**311,37**
A4	Transport to building site	Ductile pile - road	26,70
		Ductile pile - ship	35,11
		Concrete filling	1,94
		Concrete grouting	x
		Total	**63,76**
A5	Construction process	**Total**	**20,90**
Total per pile			**396,02**

Table 32: Interchange project South Africa – pile type 118/9, ungrouted, length 20 x 16 m & 18 x 11 m – kg CO_2 eq

	Dimension: Transport ductile pile – road:	**118/9/16m x 20 + 11m x 18** 925 km	**Pile type - 118/9**
	Transport ductile pile – ship:	12'160 km	*kg CO_2 eq*
	Transport concrete:	50 km	**ungrouted**
A1-A3	Material production	Concrete filling	1.246,31
		Ductile pile	13.416,20
		Concrete grouting	x
		Total	**14.662,51**
A4	Transport to building site	Ductile pile - road	1.257,50
		Ductile pile - ship	1.653,48
		Concrete filling	91,58
		Concrete grouting	x
		Total	**3.002,56**
A5	Construction process	**Total**	**983,98**
Total			**18.649,06**

The bored pile variant of of the interchange project in South Africa consists of 16 bored piles with a diameter of 760 mm. 10 piles have a length of 18.5 m and 6 of 15 m. This deep foundation system can carry off a characteristic load of 22'900 kN.

Table 33: Interchange project South Africa – bored pile 760 mm, length 18,5 m – kg CO_2 eq per pile

	Dimension: Transport concrete:	**760mm/ 18,5m** 50 km		Diameter
	Transport reinforcement:	250 km		**760**
A1-A3	Material production	Concrete	*kg CO_2 eq per pile*	2307,79
		Reinforcement		462,76
		Total		**2770,55**
A4	Transport to building site	Concrete	*kg CO_2 eq per pile*	99,72
		Reinforcement		5,55
		Total		**105,27**
A5	Construction process	**Total per m pile**	*kg CO_2 eq per pile*	**201,52**
		Single incidents per pile		*98,27*
Total			*kg CO_2 eq per pile*	**3175,61**

Table 34: Interchange project South Africa – bored pile 760 mm, length 15 m – kg CO_2 eq per pile

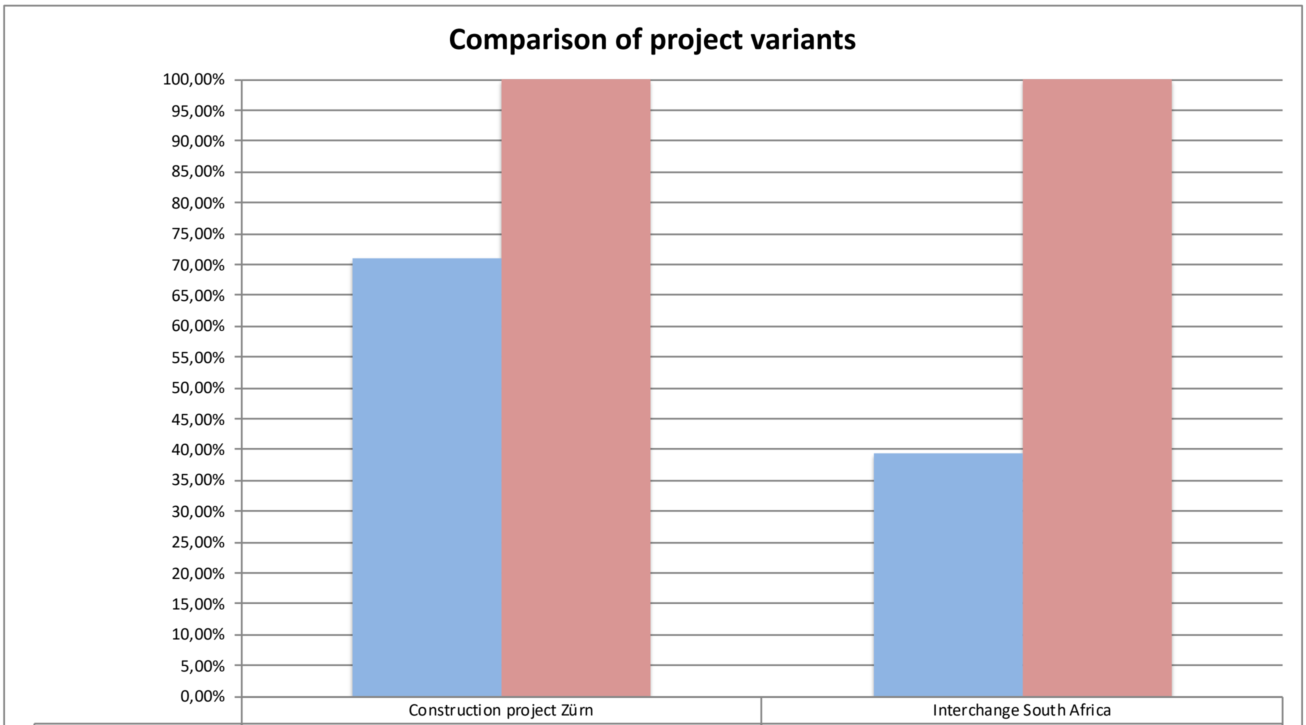
	Dimension:	**760mm/ 15m**		Diameter
	Transport concrete:	50 km		
	Transport reinforcement:	250 km		**760**
A1-A3	Material production	Concrete	*kg CO_2 eq per pile*	1871,18
		Reinforcement		375,21
		Total		**2246,39**
A4	Transport to building site	Concrete	*kg CO_2 eq per pile*	80,86
		Reinforcement		4,50
		Total		**85,35**
A5	Construction process	**Total per m pile**	*kg CO_2 eq per pile*	**163,40**
		Single incidents per pile		*98,27*
Total			*kg CO_2 eq per pile*	**2593,41**

Table 35: Interchange project South Africa – bored pile 760 mm, length 10 x 18,5 m & 6 x 15 m – kg CO_2 eq

	Dimension:	**760mm/ 18,5m x 10 + 760mm/ 15m x 6**		Diameter
	Transport concrete:	50 km		
	Transport reinforcement:	250 km		**760**
A1-A3	Material production	Concrete	*kg CO_2 eq*	34.304,98
		Reinforcement		6.878,91
		Total		**41.183,89**
A4	Transport to building site	Concrete	*kg CO_2 eq*	1.482,36
		Reinforcement		82,48
		Total		**1.564,83**
A5	Construction process	**Total per m pile**	*kg CO_2 eq*	**2.995,59**
		Single incidents per pile		*1.572,26*
Total			*kg CO_2 eq*	**47.316,58**

2.4.6 Detailed comparison of project variants

In this chapter the ductile pile and bored pile variants of the analysed construction projects are compared. Figure 1 shows the comparison of the overall results of the different deep foundation variants for each construction project.



	Construction project Zürn	Interchange South Africa
Ductile piles - percentage	70,99%	39,41%
Bored piles - percentage	100,00%	100,00%
Ductile piles - kg CO2 eq	17.279,89	18.649,06
Bored piles - kg CO2 eq	24.339,79	47.316,58

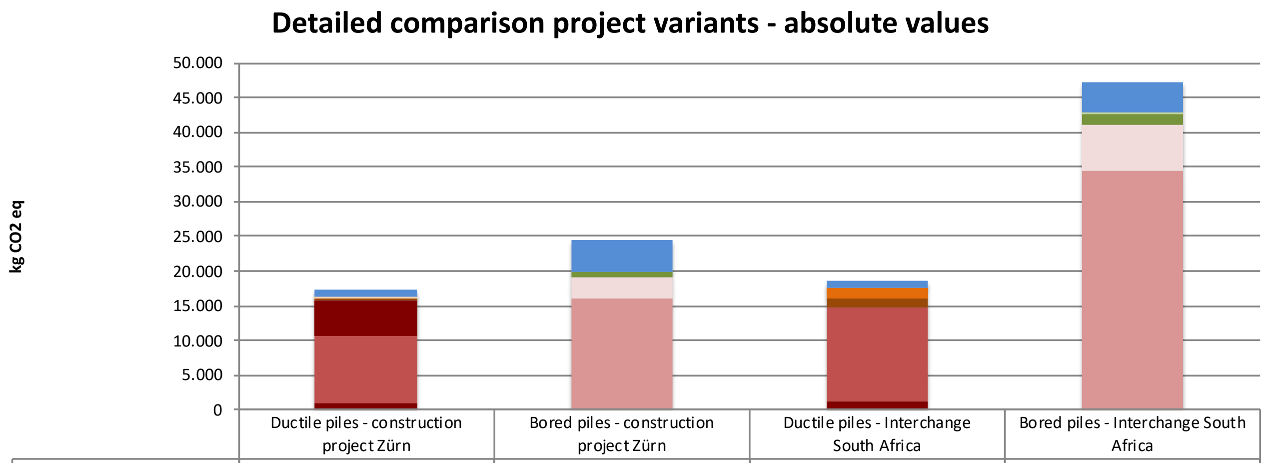
Figure 1: Comparison of ductile pile and bored pile variant of analysed construction projects – kg CO_2 eq

Figure 1 demonstrates that the ductile pile variants of both construction projects analysed offer great GWP saving potentials in comparison to the bored pile variants.

The ductile pile variant for the production and logistics centre of the company *Zürn* offers savings of around 30 %, the ductile pile variant for the interchange project in South Africa of around 60 %.

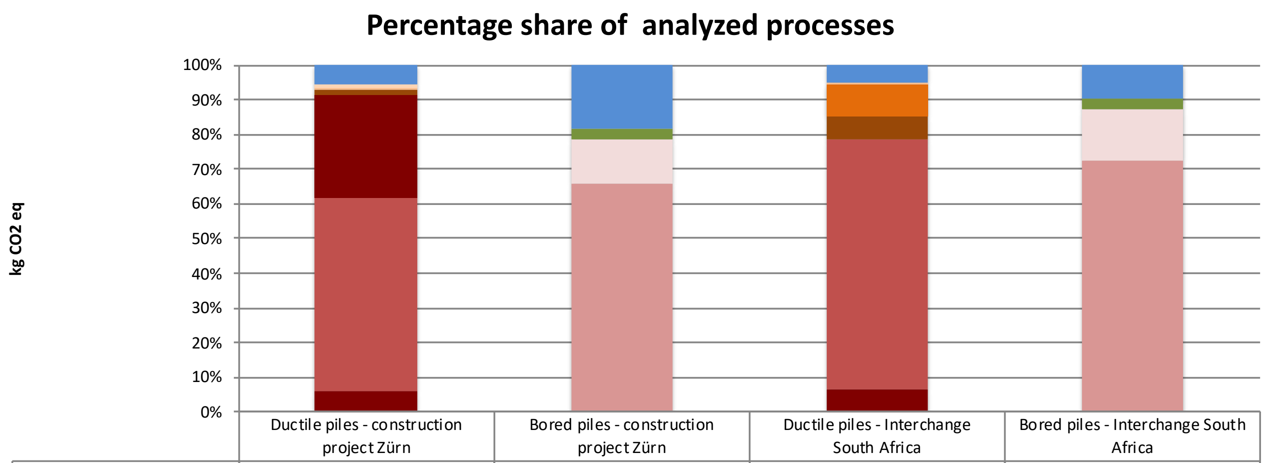
The lower GWP saving potential for the construction project in Germany shows the influence of the oversizing of the ductile pile variant and furthermore the influence of the 270 mm grouting on the overall result. The great potential of ungrouted ductile pile variant in South Africa demonstrates the low influence of transport processes (in this case transport by lorry and ship) in comparison to material production processes.

Figure 2 shows the influence of the specific processes analysed on the overall results for each project variant in absolute values. Figure 3 demonstrates the percentage share of the specific processes analysed for each deep foundation variant.



	Ductile piles - construction project Zürn	Bored piles - construction project Zürn	Ductile piles - Interchange South Africa	Bored piles - Interchange South Africa
Construction process	926,29	4.449,86	983,98	4.567,85
Transport concrete	0,00	38,31	0,00	82,48
Transport reinforcement	0,00	688,68	0,00	1.482,36
Transport concrete grouting	226,79	0,00	0,00	0,00
Transport concrete filling	46,92	0,00	91,58	0,00
Transport ductile pile - ship	0,00	0,00	1.653,48	0,00
Transport ductile pile - road	291,14	0,00	1.257,50	0,00
Reinforcement	0,00	3.195,53	0,00	6.878,91
Concrete	0,00	15.967,41	0,00	34.304,98
Concrete grouting	5.136,33	0,00	0,00	0,00
Ductile pile	9.589,00	0,00	13.416,20	0,00
Concrete filling	1.063,42	0,00	1.246,31	0,00
Total	17.279,89	24.339,79	18.649,06	47.316,58

Figure 2: Detailed comparison of deep foundation variants in absolute values – kg CO_2 eq



	Ductile piles - construction project Zürn	Bored piles - construction project Zürn	Ductile piles - Interchange South Africa	Bored piles - Interchange South Africa
Construction process	5,36%	18,28%	5,28%	9,65%
Transport concrete	0,00	0,16%	0,00	0,17%
Transport reinforcement	0,00	2,83%	0,00	3,13%
Transport concrete grouting	1,31%	0,00	0,00	0,00
Transport concrete filling	0,27%	0,00	0,49%	0,00
Transport ductile pile - ship	0,00	0,00	8,87%	0,00
Transport ductile pile - road	1,68%	0,00	6,74%	0,00
Reinforcement	0,00	13,13%	0,00	14,54%
Concrete	0,00	65,60%	0,00	72,50%
Concrete grouting	29,72%	0,00	0,00	0,00
Ductile pile	55,49%	0,00	71,94%	0,00
Concrete filling	6,15%	0,00	6,68%	0,00
Total	17.279,89	24.339,79	18.649,06	47.316,58

Figure 3: Percentage share of specific processes analysed for deep foundation variants – kg CO_2 eq

Figure 2 and Figure 3 underline the previous made statements and shows the great impact of material production processes, especially of concrete production processes. I.e., grouting of ductile piles causes its additional GWP emissions in comparison to ungrouted piles.

Moreover, the influence of oversizing the ductile pile variant for the production and logistics centre of the company *Zürn* is underlined. The approximately 5,000 kN of extra bearing capacity cause a correspondingly higher Global Warming Potential for this variant. Despite the oversized bearing capacity, the ductile pile variant still causes lower CO_2 eq emissions than the bored pile variant of this project (about 30 %).

The detailed analysis also shows the little influence of transport processes. Even long transport distances, e.g. for ductile piles from Austria to South Africa, have low effect on the overall result.

The influence of the construction process for bored piles is significantly higher than for ductile piles. This can be explained by the heavy and powerful equipment required for bored pile construction.

3 Conclusion

The determined results show that great GWP savings can be achieved by material reductions. The slimmer ductile piles consist of CO_2-intensive cast iron, which however, due to its technical characteristics, allows the construction of slim and material reduced deep foundation piles, resulting in immense savings of GWP emissions.

The influence of transport processes was determined to be very low even for projects outside Europe. The influence of the construction processes generally depends on the applied construction equipment.

4 References

1. ISO, *ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework*. 2006, International Standard Office: Geneva.
2. ÖN EN ISO 14040:2006, *Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen*. Wien.
3. ÖN EN 1992-1-1, *Eurocode 2: Design of concrete structures — Part 1-1: General rules and rules for buildings*. 2015: Wien.
4. Tiroler Rohre GmbH, *Umweltproduktdeklaration TRM Pfahlsysteme*. 2017, Bau-EPD GmbH: Wien.
5. Ecoinvent Center, *ecoinvent database*. 2017, Swiss Center for Life Cycle Assessment: Dübendorf, Schweiz.