

Gearbox Life Cycle Assessment

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Abstract: Sustainable production has been attracting more and more attention nowadays. Gearbox is a widely applied mechanical engineering product. However, little work of life cycle assessment (LCA) aimed at the gearbox could be found in the literature. This paper presents a LCA of gearbox to fill in the gap. The life cycle of the gearbox is modelled parametrically with a three-tier approach. Eco-impact caused by human labour is considered in the LCA. The LCA is conducted using a popular LCA software, SimaPro, and a widely accepted LCIA method, ReCiPe. Based on analysis of the results, optimisation plans are proposed at the end.

Keywords: Life cycle assessment, life cycle impact assessment, Gearbox, LCA, LCIA, SimaPro, ReCiPe, Environmental impact, Machinery, parametric modelling.

1 Introduction

In recent years, sustainable development have been risen as a popular topic, and sustainable production has been attracting more and more attention. Life cycle assessment (LCA) of mechanical engineering products has been considered as an important aspect of the sustainable production. Gearbox is a widely applied mechanical product in industry. However, according to the literature survey conducted by the authors, little work has been done for LCA of gearboxes. This paper presents a LCIA of representative single-stage gearbox to fill the gap.

In this research, a popular LCA software, SimaPro, and a well-known LCA method, ReCiPe, are used to conduct the LCA of the gearbox.

SimaPro has number of advanced features for LCA, such as friendly user interface, specific presentation of LCA results, and embedded ecoinvent database, which is a comprehensive Life Cycle Inventory (LCI) database. Furthermore, its parameter function provides the foundation of parametric modelling of the gearbox.

ReCiPe is a Life Cycle Impact Assessment (LCIA) method which comprises harmonised category indicators at the midpoint and the endpoint level. This method is an improvement on CML 2001 method [1] and Eco-indicator 99 method [2]. The method calculates eighteen midpoint indicators and sum up these midpoint indicators into three endpoint indicators. Because the eighteen midpoint indicators are not easy to interpret, the three endpoint indicators are more understandable. User can choose at which level it wants to have the result. [3]

2 Parametric Modelling of the Gearbox Life Cycle

A single-stage industrial gearbox, as shown in Fig. 1, is taken as the object of the LCA. The modelling mainly consists of two stages, modelling of the assembly and its production, and the rest of phases within the product life cycle, including transport, disposal, disassembly, and waste scenario.

The parameter function provided within the SimaPro has two modules, 'input parameters' and 'calculated parameters'. Parameters' name and their values can be defined by user in the 'input parameters'. In the calculated parameters, new complicated parameters can be defined as expressions of input parameters listed previously. Meanwhile, these parameters will be calculated simultaneously and automatically by SimaPro. The function offers the foundation of the parametric modelling of the life cycle.

The parametric modelling of the assembly and its production are divided into two aspects, material extraction and mechanical process. The ecoinvent database contains life cycle inventory of mainstream material extractions and mechanical processes. With the help of ReCiPe LCIA method, these inventories can be converted into environmental impact per unit of mass. Therefore, mass of material extraction and mechanical process of each part should be defined firstly. All geometry dimensions of each part are defined in the input parameters module and volume of blanks and processed parts are expressed as formations of input parameters in calculated parameters module. With density of each kind of material, the mass can be obtained accordingly.

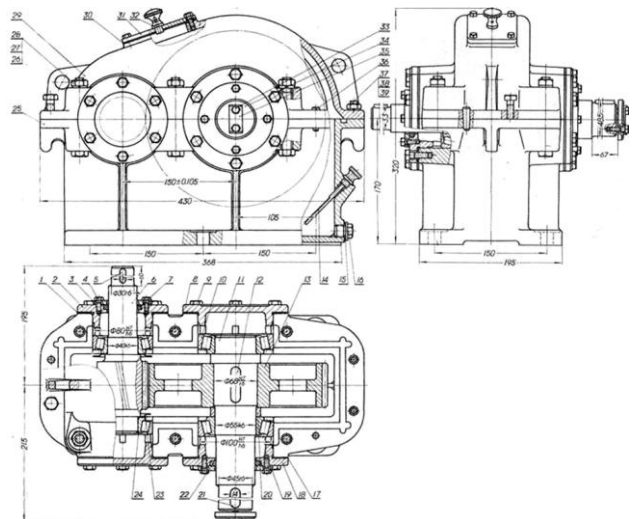


Fig. 1. Gearbox assembly drawing [4]

Following the Three-tiers approach for calculation of LCIA scores proposed in [5], the gearbox assembly is broken into three tiers as shown in Fig. 2: (1) parts, including one spur gear, one high speed shaft, one low speed shaft, two bearings for low speed shaft, two bearings for high speed shaft, five kinds of bolts, two kinds of nuts, one case base, one case cover, and four bearing end caps, etc. (2) sub-assemblies, including high speed shaft assembly, low speed shaft assembly, case, bolts, and nuts; and (3) assembly, i.e., the gearbox. All the parts, subassemblies, and assembly are set up as parametric models in mentioned method. The impact of them will be summed up tier by tier to form the impact of the assembly.

After that, all amounts that the materials used for blanks of parts and cut off by each manufacture process are taken into account. All these mass data are inputted in corresponding extraction or manufacture process in input/output module of the SimaPro. In addition, human labour impact [5] involved in the production of each part are considered as well.

The modelling of the rest phases within the life cycle, including transport, disposal, disassembly, and waste scenario of gearbox are completed in corresponding modules provided by SimaPro. For the disposal of the gearbox after the end of its life, all the parts are assumed to be treated as waste scenario, which is a waste distribution list indicated different waste treatments for different waste types in England, provided by PRé in SimaPro.

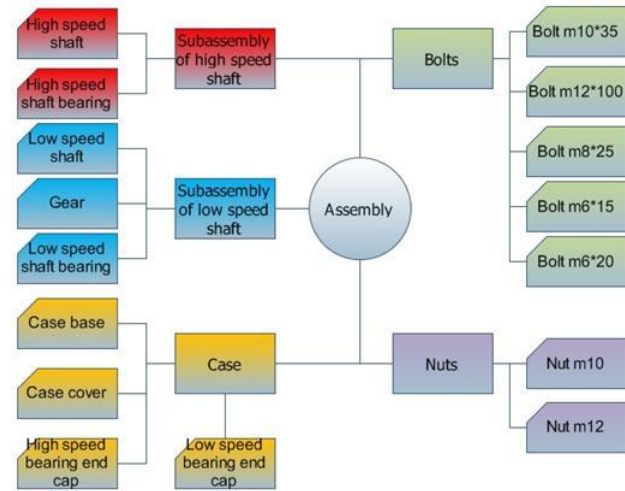


Fig.2. Gearbox assembly breakdown structure

2.1 Modelling of the gearbox assembly

As shown in Fig. 2, the gearbox assembly is consist of five subassemblies. Each subassembly has number of parts. There are sixteen kinds of parts. Some subassemblies have more than one piece of a kind of part. Such as bearings and bearing end caps, they are always assembled in couples. Also, numbers of bolts and nuts are assembled to tighten the case base and case cover. Completed list of parts is illustrated in Table 1. In total, there are 68 parts. In each stage of modelling, number of parts will be multiplied and taken into account of whole results of LCIA.

Subassembly	Part	Piece
subassembly of high speed shaft	high speed shaft	1
	high speed shaft bearing	2
subassembly of low speed shaft	low speed shaft	1
	low speed shaft bearing	2
	gear	1
case	case base	1
	case cover	1
	high speed bearing end cap	2
	low speed bearing end cap	2
Bolts	bolt m10*35	3
	bolt m12*100	6
	bolt m8*25	24
	bolt m6*20	2
	bolt m6*15	12
Nuts	nut m10	2
	nut m12	6
Total		68

Table 1 Parts list of each subassembly

2.1.1 Part modelling

Modelling in SimaPro uses parametric manner as mentioned. Each parameter must have a unique name in the whole project to avoid confusion. The ecological impact comes from two sections, material extraction and process. The modelling of parts is based on this principle. The extraction of used material and manufacture process amount will be modelled for each part.

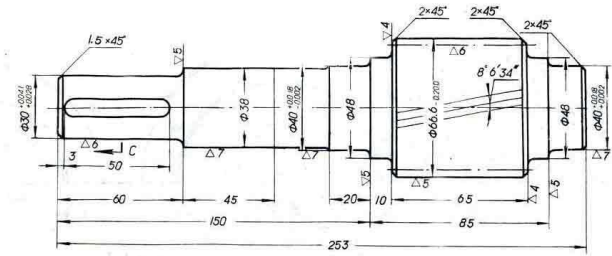


Fig. 3 drawing of the shaft [4]

High speed shaft is a gear-shaft made by low-alloyed steel as shown in Fig. 3. Mass of material used for blank is a calculated parameter named *blank_mass*, which is calculated from input parameters below as Table 2. The *blank_mass* is obtained by *blank_volume* multiples density of the material, AISI1040, which is estimated as $7.85e-6$ kg/mm³. The density is valued by the average value of the range of density from $7.8e-6$ to $7.9e-6$ kg/mm³. *Blank_volume* is the volume of a cylinder metal blank. The formula to calculate the volume is shown below and in Table 2.

$$blank_volume = \frac{\pi}{4} * blank_diameter^2 * blank_length \quad (1)$$

Input parameters include the length and diameter of the blank, *blank_length* and *blank_diameter*, and five different length and diameter of each stage of the gear-shaft, *gs_L1*, *gs_L2*, *gs_L3*, *gs_L4*, *gs_L5*, *gs_d1*, *gs_d2*, *gs_d3*, *gs_d4*, *gs_d5*. Calculated parameters include the volume and mass of the blank, and the volume of gear-shaft, *gear-shaft_volume*, which is calculated from input parameters as shown in formula (2).

$$gearshaft_volume = \frac{\pi}{4} * (gs_d1^2 * gs_L1 + gs_d2^2 * gs_L2 + gs_d3^2 * gs_L3 + gs_d4^2 * gs_L4 + gs_d5^2 * gs_L5) \quad (2)$$

And then, the scrap cut off during the process of gear-shaft manufacture is obtained. *gs_scrap_v* is the volume of the scrap which is equal to the difference between that of the blank and that of the gear-shaft. The mass of the

scrap, gs_scrap_m , is acquired by multiplying the density of the material.

Name	Value	Unit
high speed shaft		
Materials/Assemblies		
Steel, low-alloyed, at plant/RER U	blank_mass	kg
Processes		
Turning, steel, conventional, average/RER U	$gs_scrap_m-0.1$	kg
Milling, steel, average/RER U	0.1	kg
Human labour	1	hr
Input parameters		
blank_length	253	mm
blank_diameter	70	mm
gs_L1	60	mm
gs_L2	70	mm
gs_L3	38	mm
gs_L4	20	mm
gs_L5	65	mm
gs_d1	30	mm
gs_d2	38	mm
gs_d3	40	mm
gs_d4	48	mm
gs_d5	65	mm
Calculated parameters		
blank_volume	$\pi/4 * \text{blank_diameter}^2 * \text{blank_length}$	mm ³
gear-shaft_volume	$\pi/4 * (gs_d1^2 * gs_L1 + gs_d2^2 * gs_L2 + gs_d3^2 * gs_L3 + gs_d4^2 * gs_L4 + gs_d5^2 * gs_L5)$	mm ³
gs_scrap_v	blank_volume-gear-shaft_volume	mm ³
blank_mass	blank_volume*7.85e-6	kg
gs_scrap_m	gs_scrap_v*7.85e-6	kg

Table 2 High speed shaft modelling parameters

Low speed shaft is a shaft as shown in the bottom of Table 3. Material of blank is same as the high speed shaft. Mass of material used for blank is a calculated parameter named $blank_m$, which is calculated from input parameters below as Table 3. The $blank_m$ is obtained by $blank_v$ multiples density of the material, which is same as the high speed shaft. The $blank_v$ is the volume of a cylinder metal blank. The formula to calculate the volume is shown below and in Table 3.

$$blank_v = \frac{\pi}{4} * blank_d^2 * blank_l \quad (3)$$

Input parameters include the length and diameter of the blank, $blank_l$ and $blank_d$, and five different length and diameter of each stage of the shaft, s_L1 , s_L2 , s_L3 , s_L4 , s_L5 , s_d1 , s_d2 , s_d3 , s_d4 , s_d5 . Calculated parameters include the volume and mass of the blank, and the volume of shaft, $shaft_v$, which is calculated from input parameters through formula 4.

$$shaft_v = \frac{\pi}{4} * (s_d1^2 * s_L1 + s_d2^2 * s_L2 + s_d3^2 * s_L3 + s_d4^2 * s_L4 + s_d5^2 * s_L5) \quad (4)$$

And then, the scrap cut off during the process of shaft manufacture is obtained. s_scrap_v is the volume of the scrap which is equal to the difference between that of the blank and that of the shaft. The mass of the scrap, s_scrap_m , is acquired by multiplying the density of the material. During the process of shaft manufacture, the scrap is cut off by turning and milling. 0.1 kg is estimated as the mass of milling, which is finishing processing. The remind mass of scrap is the mass of turning. As the table

shows, turning mass is equal to $s_scrap_m-0.1$ kg. Human labour used for manufacture of low speed shaft is about one hour.

Name	Value	Unit
low speed shaft		
Materials/Assemblies		
Steel, low-alloyed, at plant/RER U	blank_m	kg
IProcesses		
Turning, steel, conventional, average/RER U	$s_scrap_m-0.1$	kg
Milling, steel, average/RER U	0.1	kg
Human labour	1	hr
Input parameters		
blank_l	255	mm
blank_d	65	mm
s_L1	62	mm
s_L2	67	mm
s_L3	57	mm
s_L4	57	mm
s_L5	12	mm
s_d1	45	mm
s_d2	52	mm
s_d3	55	mm
s_d4	58	mm
s_d5	65	mm
Calculated parameters		
blank_v	$\pi/4 * \text{blank_d}^2 * \text{blank_l}$	
shaft_v	$\pi/4 * (s_d1^2 * s_L1 + s_d2^2 * s_L2 + s_d3^2 * s_L3 + s_d4^2 * s_L4 + s_d5^2 * s_L5)$	
s_scrap_v	blank_v-shaft_v	
blank_m	blank_v*7.85e-6	
s_scrap_m	s_scrap_v*7.85e-6	

Table 3 Low speed shaft modelling parameters

Gear is perforated as shown in the bottom of Fig. 3. Material of blank is the same as the high speed shaft. Mass of material used for blank is a calculated parameter named b_m . The b_m is obtained by b_v multiples density of the material, which is same as the high speed shaft. The b_v is the volume of a cylinder metal blank, which is calculated from input parameters through formula 5 shows below and in Table 4.

$$b_v = \frac{\pi}{4} * b_d^2 * b_l \quad (5)$$

Input parameters include the length and diameter of the blank, b_l , b_d , amount, length and diameter of holes, h_a , h_l , h_d , two diameters and depth of the ring groove, r_d1 , r_d2 , r_l , length and diameter of centre hole, ch_l , ch_d . Calculated parameters include the volume and mass of the blank and the gear, and the volume of holes, ring groove, and centre hole, h_v , r_v , ch_v . which are calculated from input parameters through formula 6, 7 and 8.

$$h_v = \frac{\pi}{4} * h_d^2 * h_l * h_a \quad (6)$$

$$r_v = \frac{\pi}{4} \times (r_{d2} - r_{d1})^2 \times r_l \quad (7)$$

$$r_v = \frac{\pi}{4} \times (r_{d2} - r_{d1})^2 \times r_l \quad (8)$$

$$g_v = b_v - (h_v + r_v + ch_v) \quad (9)$$

And then, the volume of gear, g_v is calculated by the volume of the blank minus the sum of the volume of the holes, ring groove, and centre hole. The formula 9 is shown above. Then, the scrap cut off during the process of the gear manufacture is obtained. $scrap_m$ is the mass of the scrap which is equal to the difference between that of the blank and that of the gear.

Name	Value	Unit
gear		
Materials/Assemblies		
Steel, low-alloyed, at plant/RER U	b_m	kg
Processes		
Turning, steel, conventional, average/RER U	scrap_m-1	kg
Milling, steel, average/RER U	1	kg
Human labour	1	hr
Input parameters		
b_l	60	mm
b_d	237	mm
h_d	35	mm
h_a	6	mm
h_l	15	mm
r_d1	210	mm
r_d2	90	mm
r_l	45	mm
ch_d	58	mm
ch_l	60	mm
Calculated parameters		
b_v	$\pi/4 * b_d^2 * b_l$	
h_v	$\pi/4 * h_d^2 * h_l * h_a$	
r_v	$\pi/4 * (r_{d2} - r_{d1})^2 * r_l$	
ch_v	$\pi/4 * ch_d^2 * ch_l$	
g_v	$b_v - (h_v + r_v + ch_v)$	
b_m	$b_v * 7.85e-6$	
g_m	$g_v * 7.85e-6$	
scrap_m	$b_m - g_m$	

Table 4. Gear modelling parameters

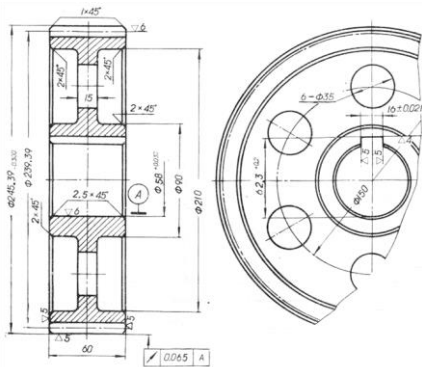


Fig. 3. Gear [4]

Case base is the base of the gearbox as shown in Fig. 4. Material used is cast iron. Mass of material used is a calculated parameter $cb_m - bec_m$, which is the difference from mass of case base and mass of the holes cut off for assembling bearing end caps. They are all calculated from input parameters below as Table 5. The cb_m is obtained by cb_v multiples density of the material, which is estimated as $7.125e-6$ kg/mm³. The density is valued by the average value of the range of

density from $7.05e-6$ to $7.2e-6$ kg/mm³. The cb_v is the volume used to make cast iron. The formula to calculate the volume is shown below and in Table 5. The volume is equal to the difference from the cube outside to the cube inside of the case.

$$cb_v = cb_l \times cb_w \times cb_h - (cb_l - cb_t) \times (cb_w - cb_t) \times (cb_h - cb_t) \quad (10)$$

Input parameters include the length, cb_l , width, cb_w , height, cb_h , and thickness, cb_t , of the case base, and five different lengths of bolts, $l1, l2, l3, l4, l5$, which are assembled in the case to tighten the case base and case cover. For convenient calculation, all the bolts are calculated with the case base but not case cover. Two diameters of two holes for assembling bearing end caps, $sbec_d, lbec_d$, are also included in the input parameters. Calculated parameters include the volume and mass of the case base, all the holes for assembling the bolts, $hole_v, hole_m$, and bearing end caps, bec_v, bec_m . They are all calculated from input parameters. The $hole_v$ and bec_v is calculated from formula shown below.

$$hole_v = \frac{\pi}{4} \times 6^2 \times (l2 \times 2 + l1 \times 12) + \frac{\pi}{4} \times 8^2 \times 24 \times l3 + \frac{\pi}{4} \times 10^2 \times l4 \times 3 + \frac{\pi}{4} \times 12^2 \times l5 \times 6 \quad (11)$$

$$bec_v = \frac{\pi}{4} \times cc_t \times (sbec_d^2 + lbec_d^2) \quad (12)$$

During the process of case base manufacture, the mass of holes, $hole_m$, is processed by drilling. Before drilling holes, the case base should be processed by heat treatment. Turning is the finish process to plain the surface of the case base. The weight processed by turning is 1 kg. Human labour used for manufacture of case base is two hours.

Name	Value	Unit
case base		
Materials/Assemblies		
Cast iron, at plant/RER U	$cb_m - bec_m$	kg
Processes		
Drilling, conventional, cast iron/RER U	hole_m	kg
Heat treatment, hot impact extrusion, steel/RER U	$cb_m - bec_m$	kg
Turning, cast iron, conventional, average/RER U	1	kg
Human labour	2	hr
Input parameters		
cb_l	428	mm
cb_w	190	mm
cb_h	170	mm
cb_t	8	mm
l1	15	mm
l2	20	mm
l3	25	mm
l4	35	mm
l5	100	mm
sbec_d	80	mm
lbec_d	100	mm
Calculated parameters		
cb_v	$cb_l * cb_w * cb_h - (cb_l - cb_t) * (cb_w - cb_t) * (cb_h - cb_t)$	
cb_m	$cb_v * 7.125e-6$	
hole_v	$\pi/4 * 6^2 * (l2 * 2 + l1 * 12) + \pi/4 * 8^2 * 24 * l3 + \pi/4 * 10^2 * l4 * 3 + \pi/4 * 12^2 * l5 * 6$	
hole_m	$hole_v * 7.125e-6$	
bec_v	$\pi/4 * cb_t * (sbec_d^2 + lbec_d^2)$	
bec_m	$bec_v * 7.125e-6$	

Table 5 Case base modelling parameters

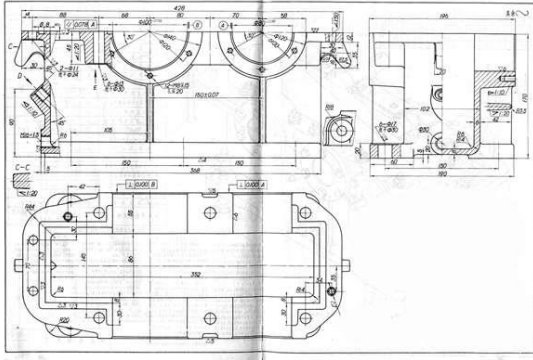


Fig. 4. Case base [4]

Name	Value	Unit
case cover		
Materials/Assemblies		
Cast iron, at plant/RER U	cc_m- <i>bec_m</i>	kg
Processes		
Heat treatment, hot impact extrusion, steel/RER U	cc_m- <i>bec_m</i>	kg
Turning, cast iron, conventional, average/RER U	1	kg
Human labour	2	hr
Input parameters		
cc_l	428	mm
cc_w	196	mm
cc_h	140	mm
cc_t	8	mm
sbec_d	80	mm
lbec_d	100	mm
Calculated parameters		
cc_v	$cc_l * cc_w * cc_h - (cc_l - cc_t) * (cc_w - cc_t) * (cc_h - cc_t)$	mm ³
cc_m	$cc_v * 7.125e-6$	
bec_v	$\pi/4 * cc_t * (sbec_d^2 + lbec_d^2)$	
bec_m	$bec_v * 7.125e-6$	

Table 6 Case cover modelling parameters

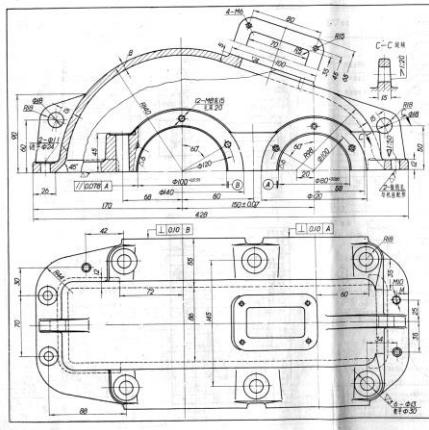


Fig. 5. Case cover [4]

Case cover is the cover of the gearbox as shown in Fig. 5. Material used is cast iron. Mass of material used is a calculated parameter $cc_m - bec_m$, which is the difference from mass of case cover and mass of the holes cut off for assembling bearing end caps. They are all calculated from input parameters below as Table 6. The cc_m is obtained by cc_v multiples density of the material,

which is estimated as $7.125e-6 \text{ kg/mm}^3$. The density is valued by the average value of the range of density from $7.05e-6$ to $7.2e-6 \text{ kg/mm}^3$. The cc_v is the volume used to make cast iron. The formula to calculate the volume shows below and in Table 6. The volume is equal to the difference from the cube outside to the cube inside of the case.

$$cc_v = cc_l * cc_w * cc_h - (cc_l - cc_t) * (cc_w - cc_t) * (cc_h - cc_t) \quad (13)$$

Input parameters include the length, cc_l , width, cc_w , height, cc_h , and thickness, cc_t , of the case cover. For convenient calculation, all the bolts assembled in the case are calculated with the case base but not case cover. Two diameters of two holes for assembling bearing end caps, $sbec_d$ and $lbec_d$, are also included in the input parameters. Calculated parameters include the volume and mass of the case base, cc_v and cc_m , all the holes for assembling the bolts and bearing end caps, bec_v and bec_m . They are all calculated from input parameters. The formula for calculate bec_v is same as that in case base.

During the process of case cover manufacture, the case cover should be processed by heat treatment. Turning is the finish process to plain the surface of the case cover. The weight processed by turning is 1 kg. Human labour used for manufacture of case base is two hours.

High speed bearing end cap is the end cap of the bearing as shown in Table 7. Material used is cast iron. Mass of material used is a calculated parameter, m , which is calculated from volume of material used and the density of cast iron, $7.125e-6 \text{ kg/mm}^3$. The v is the volume used to make cast iron. The formula to calculate the volume shows below and in Table 7. The volume is equal to the sum of a cylinder in left and a ring in right.

$$v = \frac{\pi}{4} * d1^2 * l1 + \frac{\pi}{4} * l2 * (d2^2 - d3^2) \quad (14)$$

Input parameters include the length of the cylinder and the ring, $l1$ and $l2$, and three, diameters of them, $d1$, $d2$, $d3$. Calculated parameters include the volume and mass of the bearing end cap, v and m . They are all calculated from input parameters.

Name	Value	Unit
high speed bearing end cap		
Materials/Assemblies		
Cast iron, at plant/RER U	m	kg
Processes		
Turning, cast iron, conventional, average/RER U	0.1	kg
Human labour	0.5	hr
Input parameters		
d1	120	mm
d2	80	mm
d3	60	mm
l1	10	mm
l2	50	mm
Calculated parameters		
v	$\pi/4 * d1^2 * l1 + \pi/4 * l2 * (d2^2 - d3^2)$	
m	$v * 7.125e-6$	

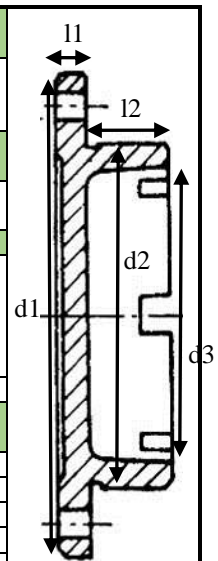


Table 7 High speed bearing end cap modelling parameters

During the process of end cap manufacture, turning is the finish process to plain the surface of the end cap. The weight processed by turning is 0.1 kg. Human labour used for manufacture of end cap is half an hour. The modelling of low speed bearing end cap is similar as that of high speed bearing end cap.

High speed shaft bearing is the bearing of high speed shaft as shown in Table 8. It is a 7208c angular contact ball bearing of GB/T 292-1994 standard. Material used is chromium steel. Mass of material used is a calculated parameter, m , which is calculated from volume of material used and the density of the chromium steel, which is estimated as $8e-6$ kg/mm³. The density is valued by the average value of the range of density from $7.93e-6$ to $8.09e-6$ kg/mm³. The v is the volume used to make chromium steel blank. The formula to calculate the volume shows below and in Table 8. The volume of blank is equal to the volume of whole cylinder.

$$v = \frac{\pi}{4} \times b \times (cd^2 - d^2) \quad (15)$$

Input parameters include four diameters, d , $d2$, cd , $cd2$, and the thickness of the bearing, b . Calculated parameters include the volume and mass of the blank, v and m . Based on the GB/T 292-1994 standard of 7208c angular contact ball bearing. The mass of the final bearing is about 0.37kg.

Name	Value	Unit
high speed shaft bearing		
Materials/Assemblies		
Chromium steel 18/8, at plant/RER U	m	kg
Processes		
Milling, chromium steel, small parts/RER U	m-0.37-0.1	kg
Turning, chromium steel, conventional, average/RER U	0.1	kg
Human labour	0.5	hr
Input parameters		
d	40	mm
d2	52.8	mm
cd	80	mm
cd2	67.2	mm
b	18	mm
Calculated parameters		
v	$\pi/4 * b * (cd^2 - d^2)$	mm ³
m	$v * 8e-6$	

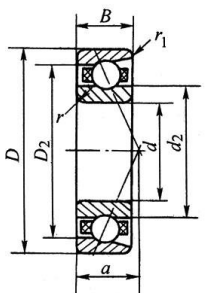


Table 8 High speed shaft bearing modelling parameters

During the process of bearing manufacture, milling is the finish process. The weight processed by milling is m-0.37-0.1. Which is equal to the mass of blank subtracts the mass of the bearing, 0.37, and mass processed by turning, 0.1 kg. Human labour used for manufacture of bearing is half an hour. The modelling of low speed shaft bearing is similar as that of high speed shaft bearing.

2.1.2 Subassembly and assembly modelling

As shown in Table 1, there are five subassemblies in the gearbox including subassembly of high speed shaft, subassembly of low speed shaft, case, bolts, and nuts. As Table 11 shows, each subassembly defines kind and amount of part and time spend of human labour for assembling parts together.

Modelling of subassembly in the SimaPro is to integrate all parts and time spent for assembling these parts together. For example, modelling of subassembly of bolts consists of two steps including add corresponding amounts of five different types of bolts into the subassembly and add time spend for assembling these bolts to the case. The subassembly of bolts consists of three m10*35 bolts, six m12*100 bolts, twenty-four m8*25 bolts, 2 m6*20 bolts, 12 m6*15 bolts, and $15 * (3+6+24+2+12) = 705s$ human labour.

Time spends of assembling one bolt and one nut are estimated as 15 and 10 seconds respectively. Other modelling of subassembly have similar processes. Totally, there are 68 parts in all of these subassemblies, and 17min5s is spent to assemble these subassemblies.

Subassembly	Part	Piece	Human labour
subassembly of high speed shaft	high speed shaft	1	1min
	high speed shaft bearing	2	
subassembly of low speed shaft	low speed shaft	1	2min
	low speed shaft bearing	2	
	gear	1	
case	case base	1	1min
	case cover	1	
	high speed bearing end cap	2	
	low speed bearing end cap	2	
bolts	bolt m10*35	3	705s
	bolt m12*100	6	
	bolt m8*25	24	
	bolt m6*20	2	
	bolt m6*15	12	
nuts	nut m10	2	80s
	nut m12	6	
Total		68	17min5s

Table 11 Subassembly modelling

The assembly is the gearbox. As Table 12 shows, modelling of assembly integrates all of the subassemblies together and add processes used during assembly. Assembly includes one for each subassembly modelling above. Processes used include 2 min human labour for assemble and 0.01 kWh electricity for lifting parts up.

Name	Value	Unit
Original Gearbox		
Materials/Assemblies		
case	1	p
subassembly of low speed shaft	1	p
subassembly of high speed shaft	1	p
Bolts	1	p
Nuts	1	p
Process		
Human labour	2	min
Electricity, medium voltage, production GB, at grid/GB U	0.01	kWh

Table 12 Assembly modelling

2.2 Modelling of the life cycle

The life cycle of original gearbox includes one piece of gearbox, transport to retailer by van, disposal of the gearbox, and one additional life cycle of lubricating oils and greases. The transport is operated by a van with less than 3.5 ton weight load. Distance from factory to the retailer is 10 kilometres. The additional life cycle of lubricating oils and greases lasts one year. It will be replaced by new lubricating oils and greases once per year.

Name	Value	Unit
Original Gearbox life cycle		
Assembly		
Original Gearbox	1	p
Processes		
Operation, van < 3,5t/RER U	10	km
Waste/Disposal scenario		
disposal of original gearbox		

Table 13 Life cycle modelling

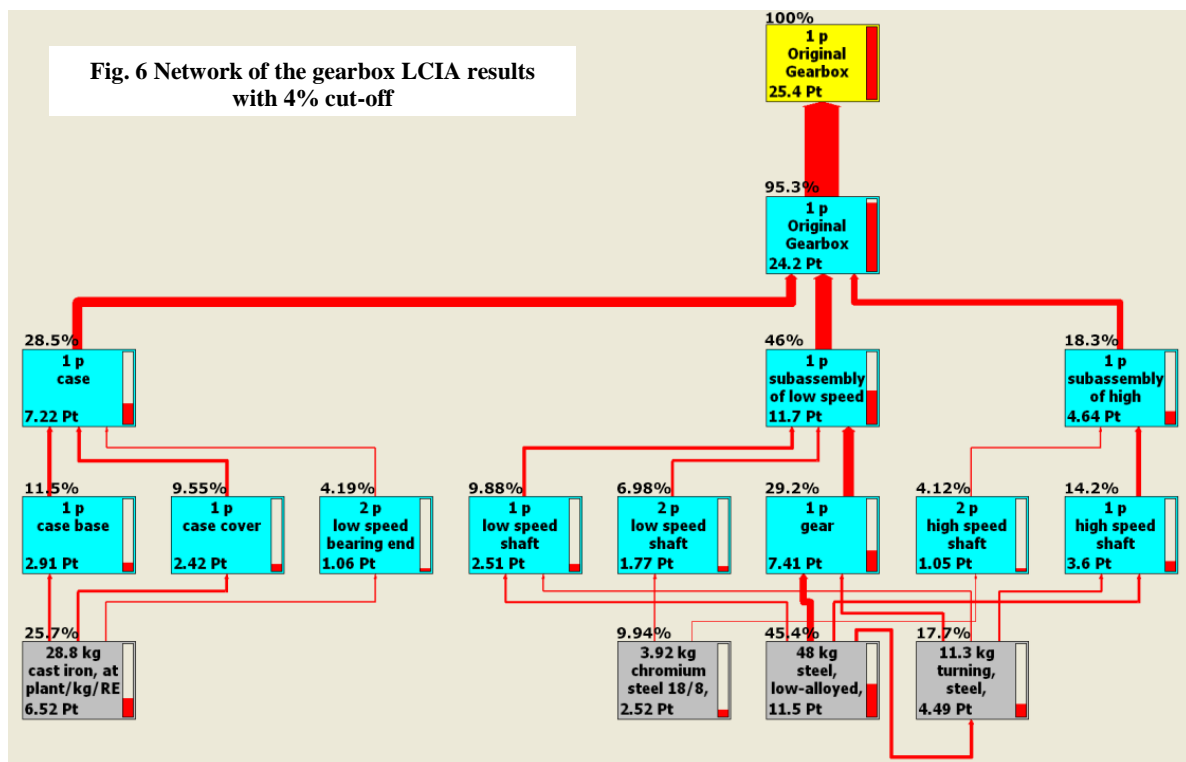
Disposal of original gearbox refers to the gearbox assembly. Two hours human labour during the disposal process is added into the disposal as well. The waste scenario is estimated as 100% disassembly of the gearbox. The disassembly of the gearbox is referred to the assembly to set up connection between it to the assembly. One hour human labour is consumed during the process of disassembly of the gearbox. The separation of sub-assemblies is not considered for the original gearbox. All the waste for the original gearbox is treated by waste scenario for England. The waste scenario for England indicates waste flow for different type of waste in the end life of the product in England.

3. LCA Results Interpretation

After the modelling of the gearbox life cycle, hierarchist version of the ReCiPe method with normalisation value of world and the average weighting set are selected to assess the model.

The network results of LCIA are shown in Fig. 6. Yellow box in figure refers to the life cycle of original gearbox. Light blue boxes refer to subassemblies and parts. The grey boxes refer to processes used. For better present of the network, 4% cut-off is applied. That means any impact less than 4% of all have been cut off and hide. Each process has a numerical reading of eco-indicator in left bottom and a red colour bar indicator diagram in right side. A larger reading and larger red bar represent a larger ecological impact that the process generated. Also, a wider arrow represents larger ecological impact flows in and out. Percentage of each box clearly indicates how much impact is shared by individual process, part, or subassembly. As the figure shows, cast iron, chromium steel, low-alloyed steel and turning process on steel has the most of ecological impact among all the processes and material used in the gearbox life cycle. They score 6.52Pt, 2.52Pt, 11.5Pt, and 4.49Pt and 25.5%, 9.86%, 45%, 17.6% of all ecological impact respectively. Obviously, the low-alloyed steel has the most impact. Nearly half impact is contributed by the extraction of the low-alloyed steel. The cast iron contributes to case base, case cover, and low speed bearing end. Actually, it also contributes to high speed bearing end but it is not displayed since the 4% cut-off. The chromium steel contributes to low speed shaft bearing and high speed shaft bearing. The low-alloyed steel contributes to low speed shaft, gear, and high speed shaft. And it also processed by turning besides it. The turning contributes to the gear, the low speed shaft, the high speed shaft. And it also contributes to the low-alloyed steel as mentioned before.

Focusing on parts, which are light blue boxes shown above the grey process boxes, the gear shares the most ecological impact among them. Which is 7.41Pt sharing 29.2% of all. The high speed shaft bearing and low speed bearing end have almost the least ecological impact, which are 1.05 Pt. sharing 4.12% and 1.06 Pt. sharing 4.19% respectively. The high speed shaft has the second high ecological impact of all these subassemblies, which



is 3.6 Pt. sharing 14.2 %.The case base has the third high ecological impact of all these subassemblies, which is 2.91 Pt. sharing 11.5%. The ecological impact of case cover and low speed shaft are almost the same, which are 2.42 Pt. sharing 9.55 % and 2.51 Pt. sharing 9.88 %. The two pieces of low speed shaft bearing has 1.77 Pt. ecological impact, which shares 6.98 %.

Focusing on subassemblies, the subassembly of low speed has the highest impact as 11.7 Pt. sharing 46%. The main reason is the gear has the highest ecological impact. The case and the subassembly of high speed got second and third high ecological impact score, which are 7.22 Pt. sharing 28.5 % and 4.64 Pt. sharing 18.3 %.

The manufacture of gearbox assembly which is shown as the light blue box named original gearbox contains 95.3 % ecological impact of all processes in the gearbox life cycle. That means transport, disposal of gearbox, disassembly of gearbox, additional life cycle of lubricating oils and greases have remaining 4.7 % of ecological impact.

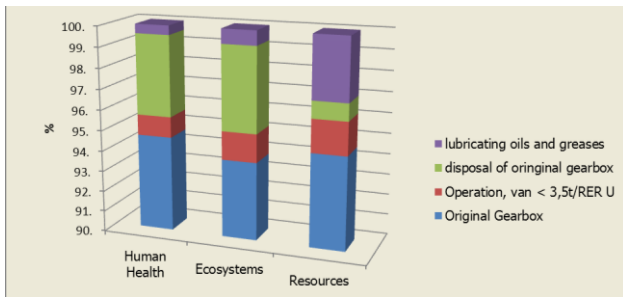


Fig. 7 Damage assessment result

Fig. 7 shows the damage assessment result in endpoint categories including human health, ecosystems, and resources. The original gearbox shares the largest ecological impact, which is shown as blue bar sharing from 93% to 94% of all three categories, among others. In resources category, the additional life cycle of lubricating oils and greases shares about 3%. Disposal of original gearbox shares about 1%. Operation of van shares about 2%. In human health category, operation of van shares about 1%, disposal of original gearbox shares about 4%. The additional life cycle of lubricating oils and greases shares less than 1%. In ecosystems category, the situation is similar as that in the human health but these three shares a little bit more than that in the human health.

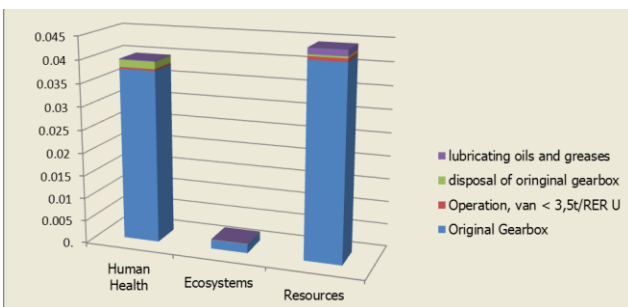


Fig. 8 Normalisation assessment result

Fig. 8 shows normalisation assessment result which is normalised by different normalisation values of each endpoint category defined by ReCiPe endpoint method Hierarchist version. In world ReCiPe endpoint hierarchist version 1.04, the normalisation values are shown in Table 14. After normalisation, the result turns into the bar chart

as shown in the Fig. 8. The ecological impact of human health and resources is much higher than that of ecosystems. The original gearbox still shares the largest ecological impact in both categories. Disposal of original gearbox shares most of remaining ecological impact in human health. And the additional life cycle of lubricating oils and greases shares most of remaining ecological impact in resources. After weighting using the factor shown in the Table 14, resources reduces half of ecological impact as shown in Fig. 9. Because the weighting factor for resources is 200 and that of other two categories are 400.

Normalization-Weighting set	World ReCiPe H/A
Normalization	
Human Health	74.6
Ecosystems	1170
Resources	0.0000456
Weighting	
Human Health	400
Ecosystems	400
Resources	200

Table 14 normalisation and weighting values defined in the ReCiPe endpoint world hierarchist version 1.04 [6]

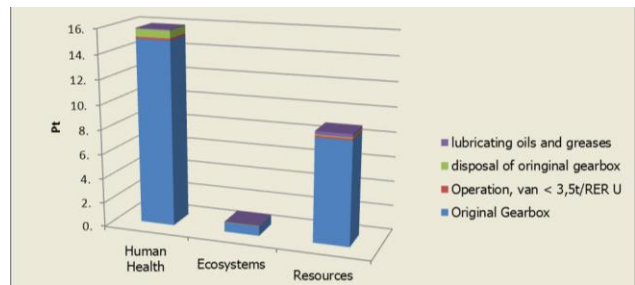


Fig. 9 Weighting assessment result

Fig. 10 shows a single score assessment result of each life cycle stage in endpoint categories. Original gearbox has the largest ecological impact, almost 25Pt in total. For original gearbox, ecological impact of human health shares the largest part, about 14 Pt. ecological impact of resources shares the second large part, about 10 Pt. ecological impact of ecosystems shares the remaining Pt., about 1 Pt. Other three have a little ecological impact only.

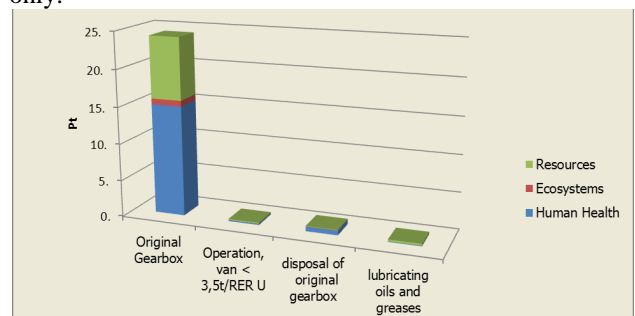


Fig. 10 Single score assessment result

Fig. 11 shows bar chart and pie chart of process contribution, which indicate the most contributed processes or materials in the life cycle. 3% cut-off is applied to these two charts to make the presentation clearly. Pig iron and hard coal share 8% for each. They are the most contributed materials and get about 2Pt of ecological impact for each. Iron ore with 46% Fe shares 7% as the third place. Hard coal shares 5% as the fourth

place. Sinter of iron and cast iron are tied for the fifth place, sharing 3%. Remaining processes share other 66%.

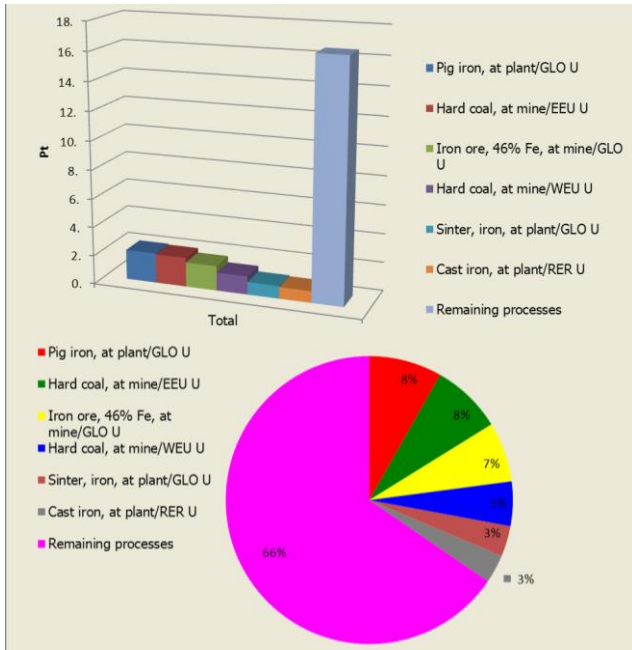


Fig. 11 Single score of process contribution

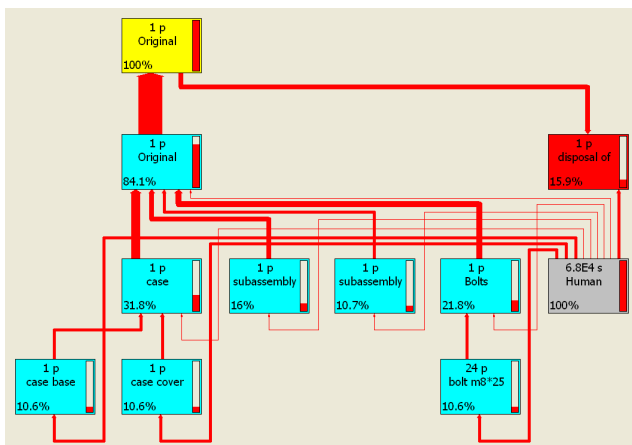


Fig. 12 Single process flow of human labour (8% cut-off)

Human labour contributes 0.684Pt and shares 2.7% of the ecological impact of original gearbox life cycle, which is 25.4Pt. In total, human labour involved 6.8E4 seconds' working time. The distribution of human labour in the whole gearbox life cycle shows in Fig. 12. The values below 8% have been cut off. Red bar in right side of each box indicates the ecological impact of human labour in every part or subassembly. Manufacture of gearbox shares 84.1% of all ecological impact of human labour. The disposal of gearbox shares remaining 15.9% of all. The subassembly of case including case base and case cover, shares the most ecological impact, 31.8% of all subassemblies. Each of the case base and the case cover shares 10.6%. The subassembly of low speed shaft shares 16%. The subassembly of high speed shaft shares 10.7%. The subassembly of bolts shares 21.8%. 24 pieces of bolt m8*25 shares 10.6%, which has the largest ecological impact of all bolts.

4 Analysis of results and proposal of optimisation

After the interpretation of the LCIA results, there are several points should be highlighted below.

- Turning process on steel has the most of ecological impact among all the processes used in the gearbox life cycle.
- The low-alloyed steel has the most ecological impact among the all materials used in the gearbox life cycle. Nearly half of all, 45%.
- Most of the low-alloyed steel is used for manufacture of gear.
- The gear has the most ecological impact among all the parts, 29.2%.
- The subassembly of low speed has the highest ecological impact, because the gear within it has the highest ecological impact.
- The manufacture of gearbox assembly produces 95.3% ecological impact in the gearbox life cycle in this case.
- The disposal of gearbox has the second high ecological impact besides the manufacture of gearbox in the whole life cycle.
- To arrange the ecological impacts in endpoint categories in descending order are human health, resources, and ecosystems.
- The human labour contributes 0.684Pt and shares 2.7% of the ecological impact of original gearbox life cycle, which is 25.4Pt.

Based on the results obtained, redesign or optimisation should be carried out in order to reduce the gearbox's ecological impact. Potential plans of optimisation may include:

- ✓ To extend the service life of gearbox
- ✓ To increase the recycle rate of used material
- ✓ Optimisation design of gearbox structure and life cycle with eco-constraints

5. Conclusion

A LCA of industrial gearbox has been successfully conducted and reported in this paper. After structure analysis of the gearbox, three-tier method and parametric modelling are used to model the life cycle of the gearbox in SimaPro. The ecological impact of human labour is also involved in the LCA. A parametric approach is utilised in the modelling of gearbox life cycle. Based on the life cycle model of gearbox, the LCIA has been implemented using SimaPro with ReCiPe LCIA method. The results of LCIA consist of network, characterisation, damage assessment, normalisation, weighting, and single score. The results obtained illustrate the ecological impact of gearbox throughout its life cycle. In addition, the ecological impact of human labour is presented. Based on the analysis of results, optimisation plans are proposed at the end.

References

- [1] Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van, Wegener Sleswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H. de, Duin, R. van, and Huijbregts, M.A.J. LCA - An operational guide to the ISO-standards - Part 1: LCA in perspective (Final report, May 2001), 2001.

- [2] Baayen H. Eco-indicator 99, Manual for Designers, A damage oriented method for Life Cycle Impact Assessment, 2000.
- [3] <http://www.lcia-recipe.net/project-definition>, January 2015.
- [4] Gong G., Pan P., Chen X., and Yan L. Illustrated catalogues of Mechanical Component Curriculum Design, Harbin Institute of Technology, 1981.
- [5] Su, D. and Ren, Z. Ecological Impact Assessment and Eco-design of Industrial Gearboxes, Key Engineering Materials Vol. 486 (2011) pp 197-200, 2011.
- [6] ReCiPe Mid/Endpoint method, <http://sites.google.com/site/lciarecipe/project-definition>, June 2011.