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An eco-impact design metric for water lubricated bearings based on anticipatory Life Cycle Assessment

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ABSTRACT

Water lubricated bearings have been named in literature as a sustainable alternative to their oil-based counterparts. In order to clarify when water lubricated bearings are or are not a sustainable alternative, and inform design decisions, an analytical design tool is introduced based on anticipatory Life Cycle Assessment (LCA). This model is based on data from the bearing geometries, materials, and material combinations that have been the subject of research attention in the past 20 years in water lubricated bearing design. The model provides simple equations, fed with data from literature on materials, production and their tribological combination to provide initial insight on the sustainability of these types of bearings and future designs. A case study illustrates that quantifying environmental impacts can help determine when lubricant loss is more important than material choice, or vice-versa. The method aids bearing designers towards more sustainable designs.

1. Introduction

Tribology is one of the key components when it comes to the continuous search for sustainability improvements within engineering. It covers the studies on friction, wear, lubrication and adhesion (Nosonosky and Bhushan, 2010). Although the name tribology was only introduced in the 1960's, research concerning full film lubricated bearings can be considered to have started close to a century before, with the derivation of Reynolds equation (Downson, 1962), followed by for instance the Michell/Kingsburgy tilting-pad bearing patent granted in 1905. The aptly named Rayleigh step bearing was investigated by Lord Rayleigh in 1918 (Rayleigh, 1918). Full film bearings, or fluid bearings, use a thin layer of liquid to support significant loads. Because of the separation of the solid elements between the liquid, these types of bearings possess superior friction and wear characteristics in comparison to their roller and sliding counterparts. When it comes to the lubricant used, the most common solution to date continues to be some form of oil-based lubricant.

The natural alternative to these oil-based lubricants would be to use one of the most abundant resources on the planet, water. Water as a lubricant has a rich history in the field of full film tribology. Going back to as early as 1840 (Orndorff, 1985) it has been used in many systems where water is the obvious choice, such as many maritime applications and water-hydraulic systems (Hother-Lushington, 1976). There is however also a different view on water in tribology, as it is also commonly seen as an undesired pollutant in the lubricant, as both stated by Smith (1973) as well as Machrafi (2012). The general view for the majority of history has been that water is more of a nuisance, than a sustainable alternative to oil-based lubrication, mainly because of its corrosive effects on metals and polluting effects on the more conventional lubricant, oil. This becomes more clear when looking at Fig. 1. Here, scientific journal publications from 1955 to 2020 focusing on bearing design with water were investigated for the mention of water as a environmentally friendly solution, containing the terms 'environmentally friendly' OR 'pollution free' OR 'eco friendly' OR 'ecological' OR 'sustainability'. This resulted in the first mentions of sustainability being found starting around the 1990's.

Until the 1990's no mention of any of these synonyms for sustainability were found. It was not until Clarke (Clarke and Allen, 1991) mentioned sustainability, however in his case mostly considering the hydraulic medium, not the lubricant. The importance of tribology on sustainability of engineering can be observed in several ways. On a global level, an estimated 103 EJ and 7040 Mt CO_2 is lost in friction (Holmberg and Erdemir, 2017). Some other key impact factors are the losses of oil-based lubricants into the environment (Nowak et al., 2019) or their end of life disposal (Coy et al., 1995). Improvements within these fields in terms of sustainability can result in valuable improvements. The concept of sustainable or 'green tribology' has been

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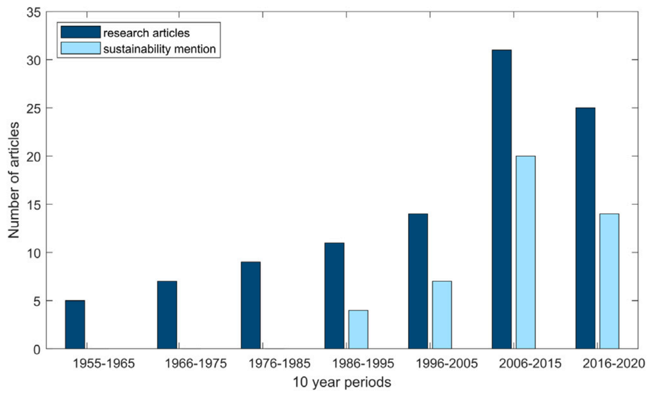

Fig. 1. Mention of sustainability in articles on bearing designs with water lubrication. The last period, only being 4 years in length, already has almost similar sustainability mentions as the complete preceding decade.

defined specifically with this in mind as 'the science and technology of tribological aspects of ecological balance and of environmental and biological impacts' (Nosonosky and Bhushan, 2010). Green tribology has been suggested to potentially lead to energy savings, environmental benefits, cost reduction and social progress (Tzanakis et al., 2012). To achieve this, Nosonosky and Bhusian noted twelve principles of green tribology. Amongst them are (1) minimization of heat and energy dissipation, (2) minimization of wear, (3) natural lubrication, (4) biodegradable lubrication, and (5) sustainable energy applications. These objectives align to those presented by Tzanakis et al. (2012), and provide a clear set of research objectives. The minimization of heat and energy dissipation as well as the minimization of wear align perfectly with the inherent properties of full film lubricated bearings.

However, when looking at published literature and the statements found therein concerning 'water', it is used synonymous with 'sustainable lubricant' (Machrafi, 2012). At first glance this might indeed seem like a valid statement, the general perception of water is, of course, that water is a more sustainable medium than any form of oil. This can also been seen in the carbon footprint of water (Rothausen and Conway, 2011) which is very low compared to that of lubricant oil (Ishizaki and Nakano, 2018). There are however other critical components that define the sustainability of a bearing system, including embodiment, material combination and wear performance. In order to make well founded arguments concerning sustainability of a particular bearing design, these components have to be taken into account.

Given the worldwide engineering trends, it will become required for engineers, designers and researchers to take into account sustainability when developing novel systems as early as possible in the design process. These types of sustainability analyses are currently performed at the end of the design cycle, when more data is available, but when the choices have already been made and the 'damage' is done. Having a method available for the sustainability analysis early in the design process can greatly improve the motivation for choosing water lubricated bearings and the decision for the most sustainable design. An anticipatory sustainability metric could thus be used to improve the motivation on sustainable water lubricated bearing design. The main objective is thus to define a framework to analyze the sustainability of water lubricated bearings such that in this aspect they can be compared fairly with their oil lubricated counterparts.

Several metrics can be used to define sustainability. A well known and often cited metric is that of ReCiPe by Goedkoop et al. (2009), which used a large set of parameters. A different approach is that of Culaba and Purvis (1999), which presented a more computational approach to the use of the LCA. The problem however that generally arises with LCA approaches is the lack of reliable data, especially when more exotic materials and production processes are involved. The choice is therefore made to utilize solely the following metrics:

1. Global Warming Potential (GWP), defined by the carbon dioxide equivalent [CO_2eq],
2. Primary energy use [MJ].

These metrics are widely available for the large majority of components used in the bearing applications under study and are widely understood by a large spectrum of the engineering field. They are thus favored over other important impact categories such as acidification, eutrophication, particulate emissions, or resource depletion that would have required estimations and are usually compared to each other with given weight factors. Since the materials analyzed here are not likely to exhibit important differences in their impact category profiles (such as one material having very high GWP impacts but very low acidification, with another material having the reverse), the metric of GWP should provide a reasonable comparison between alternatives, even if it provides an incomplete picture.

In this article, a sustainability design metric is presented based on anticipatory Life Cycle Assessment (LCA) (Wender et al., 2014a), in the form of simple equations for engineers to calculate the environmental impacts of different design options, and compare the results to decide what design(s) to pursue. The data needed for the calculations come from literature on full film water lubricated bearings, based on primary topology, production steps and material combinations, observed in the past 20 years of research literature. Finally, this metric is used in a design case to compare how water lubricated bearings can perform compared to their classic oil-based counterparts in terms of sustainability. The model is provided in the supplementary material in the form of a spreadsheet, which can directly be used for these calculations.

2. Methods

An LCA is a validated approach for sustainability analyses. The approach has been described in detail in the ISO14040 standard (Standard, 2014). The problem with conventional LCA approaches, is that they usually require data from mature industries, supply chains and products. They are therefore usually performed in retrospect. A different approach is to use this type of analysis as an anticipatory metric as presented by Wender et al. (2014a). This anticipatory approach allows for the LCA resulting metric to be used during development to make more quantitative based statements concerning the sustainability of a certain design. The construction of the metric follows initial identification steps performed in. Of these steps, the most fundamental is how to define sustainability for the type of system under consideration, which can vary greatly.

Taking into account the primary scope of the assessment, a general system boundary has been determined (Standard, 2014). The visualization of the general bearing system used in this work can be seen in Fig. 2. The system consists of the two main components crucial to full film lubricated bearing design, the bearing system and lubricant. The lubricant directly influences the material choices and thereby also the production of the bearing system. Its presence directly influences the performance obtained in operation, and therefore the lifetime of the system. Resulting decommissioning of the bearing system is linked to the time-to-maintenance of the bearing (Hase et al., 2016). The following assumptions are made for the analysis of different types full film lubricated systems:

1. Transport, water and energy used between all processes are not taken into account for this analysis. Motivation for this choice is two-fold. Firstly, these steps are necessary for all bearings independent of their type (water or oil-based), and thus the impact for these steps will be more or less equal. This means that their impact will only effect the total magnitude, but hardly influence relative differences between bearing types. The difference between lubricants will be taken into account in the raw material acquisition comparison. Secondly, based on an extensive description of a roller bearing LCA (Ekdahl, 2001)

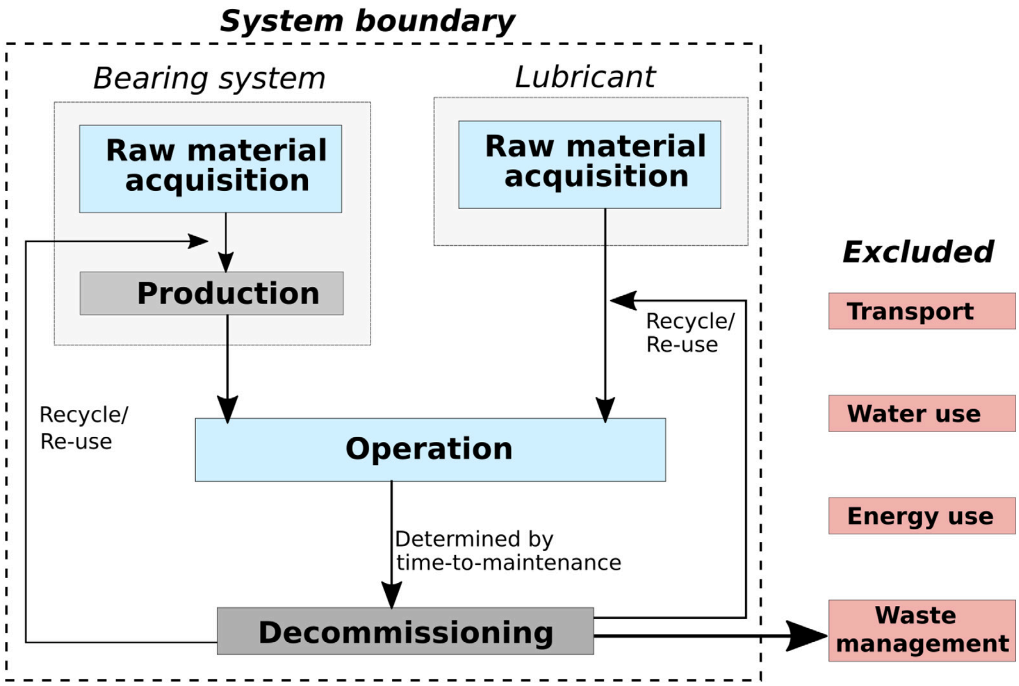

Fig. 2. Visualization of the boundary system used for the analysis. Transport is not taken into account, and water use is not taken into account except in the form of lubricant leakage when water lubricated systems are considered.

which are comparable systems in comparable applications, it was concluded that the influence of transport on the total system is small compared to the significantly more dominant effects of materials and production. Waste management is not taken into account because it again is assumed to be similar for all bearing types.

2. Operation, maintenance and decommissioning depend primarily on bearing lifetime and lubricant leakage. For bearings this can directly be expressed using the wear of the bearing and the leakage from the bearing. The higher the wear of the bearing, the sooner maintenance will have to be provided or decommissioning occurs. Simultaneously, the higher the leakage from the bearing, the larger the relevance of the lubricant on the sustainability of the system. Both wear and leakage are dependent on several factors including velocity, load and temperature.

The environmental impact contributions are thus captured in the following 4 attributes: The bearing, lubricant, lifetime and leakage. The system visualized in Fig. 2 is therefore redefined using these main factors. Please note that the model thus simplifies a more complex system in favor of a model consisting of a limited set of well defined parameters.

2.1. Eco-impact metric

The functional unit used in this work is the eco-impact of a given bearing design for a given service life. Because of the desire for an anticipatory assessment, the impact contributors have been simplified to the following main components: Bearing mass and production, lubricant use and loss, and bearing lifetime. These components are relatively easily identified, but still describe the system with an acceptable degree of accuracy. Secondly, environmental impact parameters are usually expressed as function of weight, further motivating the choice of using bearing mass compared to alternatives. Note that bearing geometry is an important factor in functionality, affecting load capacity, lifetime and friction. The proposed model does not directly include bearing geometry, because it is anticipatory—it is intended to be fast and simple, for use in early-stage development. However, to avoid sacrificing rigor, it does indirectly account for geometry by counting bearing mass and lubricant use and loss. Bearing mass depends directly on the geometry and size, thus acting as a fast and simple proxy for geometry. Lubricant use and loss also depends on geometry, and is relatively easily obtainable through analytical and finite element method approaches in current day bearing development. Together, these factors should adequately represent the impacts of different geometries without requiring the time and effort to directly model them, thus enabling decision support in earlier development stages. Fig. 3 visualizes the main contributors and their system components needed for determining an impact assessment. The bearing and lubricant impacts are used to represent a bearing design at the start of its operation life. The second component is defining the effects of operation. This effect is dominated by the wear of the bearing and the loss of lubricant through leakage. The wear of the bearing is determined by its material combination, lubricant and load condition, while the leakage is primarily based by the design of the bearing geometry and its operation condition. Based on these system components, the following relations are proposed:

$$C_{\mathrm{Bear}} = \frac{M_{\mathrm{total}} \cdot (c_{\mathrm{mat}} + c_{\mathrm{prod}})}{\Delta_o} \tag{1}$$

$$C_{\mathrm{Lub}} = c_{\mathrm{lub}} \cdot (V_0 + \dot{V}_{\mathrm{day}} \cdot t) \tag{2}$$

$$E_{\mathrm{Bear}} = \frac{M_{\mathrm{total}} \cdot (e_{\mathrm{mat}} + e_{\mathrm{prod}})}{\Delta_o} \tag{3}$$

$$E_{\mathrm{Lub}} = e_{\mathrm{lub}} \cdot (V_0 + \dot{V}_{\mathrm{day}} \cdot t) \tag{4}$$

where M_{total} is the total bearing mass [kg], c_{mat} the specific CO_2 impact of the bearing material [kg CO_2/kg], c_{prod} the specific production contribution of the bearing [kg CO_2/kg], Δ_o the operation factor defined by the material combination. V_0 is initial lubrication volume [ltr], $\dot{V}_{\mathrm{day}}$ is the daily leakage volume rate [ltr/day], t [days] is time scaling factor coupled to the leakage and c_{lub} the CO_2 impact per liter of the lubricant. The lubricant is defined in carbon equivalent per volume expressed in liter, since this is more common practice in literature. Lastly e_{mat}, e_{prod} and E_{Lub} are the primary energy equivalents. The impact of lubricant loss through degradation and leakage is effectively captured in the defined volume rate $\dot{V}_{\mathrm{day}}$ and the initial volume V_0. Because the leakage volume rate $\dot{V}_{\mathrm{lub}}$ has to be replaced in order to guarantee operation, and

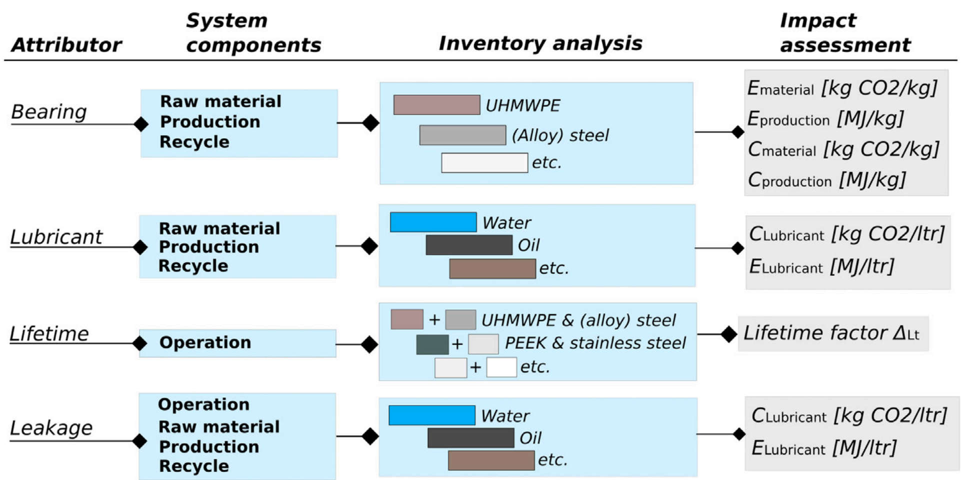

Fig. 3. A visual representation of the impact assessment parameters as related to the bearing system.

replacing the entire lubricant volume V_0 is required when degradation has occurred, they effectively capture both effects. The lifetime factor Δ_o [-] presented in Eqs. (1) and (3) is a measure of incorporating wear effects of the bearing, and is meant as a comparative method between material combinations. The use of this lifetime factor is based on the following assumptions to provide a fair comparison.

1. When comparing material combinations, the same load case has to be considered.
2. The mass M_{total} is only defined by the one part of the bearing that is susceptible to wear in the material combination, as it is assumed that the counter surface has effectively infinite lifetime by comparison.

To objectively make a anticipatory comparison, it is needed to simplify a general bearing system. By determining the sustainability component of only that specific component of the bearing that wears, a more general comparison can be made. The addition of other components of the bearing system might make the model more complete, but would also introduce additional uncertainties. The mass M_{total} will thus be defined solely by the mass of the wearing material, as seen in Fig. 4. Using Eq. (1) to (4), a CO_2 equivalent and primary energy representative impact metrics can be defined:

$$C_{\text{Total}} = C_{\text{Bear}} + C_{\text{Lub}} \quad (5)$$

$$E_{\text{Total}} = E_{\text{Bear}} + E_{\text{Lub}} \quad (6)$$

Where C_{Total} and E_{Total} are the CO_2 equivalent and primary energy representative impact factors respectively. These two metrics can be used to give an anticipatory impact assessment for a given bearing configuration. It can thus be used to compare bearing systems with different lubricants and material choices.

For different bearing materials and lubricants, material combinations, and manufacturing methods used to produce these bearings and lubricants, input data is required in order to be able to perform this analysis.

2.2. Data collection

Previously, the approach to define an impact metric has been defined. The metrics defined in Eqs. (6) and (6) are dependent on various material properties and bearing dimensions. This work focuses on water lubricated full film bearings. Bearing designers can also use this work to directly evaluate the differences of a water lubricated design with an oil lubricated alternative. However, the wide variety in materials combinations used for water lubricated bearings makes them the primary focus of this work.

To find the required input data, a literature analysis on bearing development of the past 20 years has been performed. Articles focused on water lubricated bearings from the past 20 years are collected, characterized by design, principal materials and material combinations. The materials are then described in terms of their sustainability and performance characteristics such that they can be implemented in the introduced sustainability metric. This analysis is performed in three steps, namely:

1. The identification and categorization of literature focusing on water lubricated bearings.
2. Identify used materials, material combinations and bearing designs.
3. Determine characteristics required for sustainability metric.

An analysis framework was constructed for the first step, being identification and categorization of literature. This approach is similar to the approach performed in Syahir et al. (2017).

The choice was made to analyze water lubricated bearing development from the year 2000 onward in which sustainability was explicitly mentioned. The literature investigation has been divided into a search for work focused on design and performance, and a search for work focused on materials. This in order to get an overview on the relative focus performed on both components within the full film bearing design. The literature analysis strategy can be seen in Table 1. Only English written sources were analyzed. As for other inclusion criteria, all papers concerning water lubrication with additional additives in the lubricant were excluded. Roller bearings were excluded as well. In case of duplicates, such as for instance in work presented in both a dissertation and a journal publication, only the journal publication is included. The approach is visualized in Fig. 5.

2.3. Inventory analysis

The analysis strategy is thus used to identify the materials, material combinations and bearing designs used in full film water lubricated bearing design. It therefore differs from a conventional review, in that the focus is not to broadly identify the field in different aspects, but instead to map only these crucial parameters:

- The c_{mat} and e_{mat} parameters for the bearing materials found using the analysis.
- The c_{prod} and c_{prod} parameters, specified for the material archetypes found in the analysis. The archetypes are defined as polymers, metals, ceramics and composites.
- The Δ_o factor, depending on material combinations found in literature.

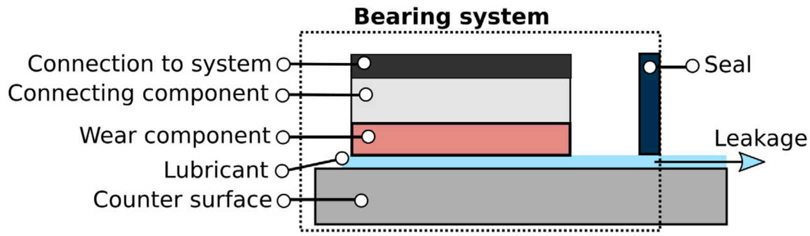

Fig. 4. Basic embodiment representation of bearing system, where the wear component dominates the sustainability analysis. The seal is only modeled through its effect on limiting the daily leakage volume $\dot{V}_{day}$.

Table 1
Literature data collection strategy.

Literature data collection strategy	
Search keywords (focus on design)	1) “Water” AND “lubricated” AND “bearing” 2) “Water” AND “hydrostatic” AND “bearing” 3) “Water” AND “hydrodynamic” AND “bearing” 4) “Water” AND “slider” AND “bearing” 5) “Water” AND “lubricated” AND “XXX” 6) “Water” AND “slipper” 7) “Water” AND “journal” AND “bearing” Where “XXX” is a range of applications: Spindle, pump, motor, systems.
Search keywords (focus on material)	(1) “Water” AND “lubricated” AND “Bearing” AND “materials” (2) “Water” AND “lubricated” AND “material” AND “combinations” (3) “Water” AND “lubricated” AND “materials” (4) “Water” AND “lubricated” AND “YYY” Where “YYY” is a material archetype: plastic, metal, composite, ceramic
Used Databases	Elsevier, ASME, Sagepub, Springer, Google Scholar, Scopus
Year range	2000–2020
Language	English
Included Publication types	Original research article, conference article, review article, book, reports
Inclusion criteria	(1) In English language (2) water without additives as lubricant (3) sliding contact at boundary or mixed lubrication
Exclusion criteria	(1) duplicates

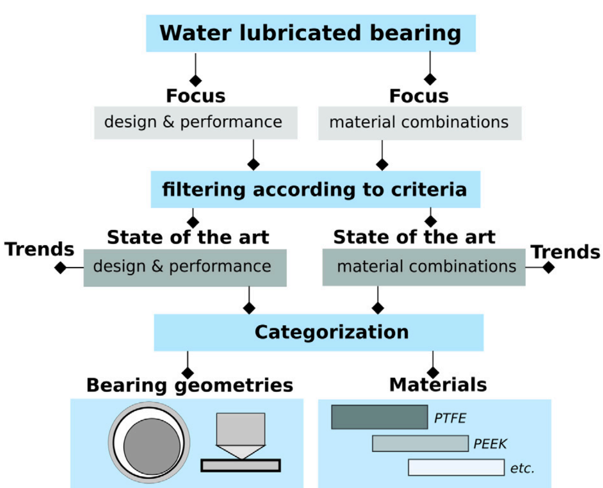

Fig. 5. Approach used to differentiate between geometry and material focused literature.

- The c_{lub} and e_{lub} parameters for the lubricant.

After identification of the materials, the production steps and subsequent environmental impacts are determined.

The impact parameters for bearing materials, production processes, material combinations and lubricant are obtained by the combination of available literature, CES Edupack (Cebon et al., 2009) and ecoinvent 3.6 (Wernet et al., 2016). These parameters are generally expressed as a function of weight. To model the environmental impact per kg of final formed material as a result of specific manufacturing processes, the Eco Audit tool in CES edupack has been used. In case of manufacturing methods that require the removal of material, it has been assumed that 20 % has been removed. Because this removal is heavily dependent on design, the examples here can only be used as an indication to show the share of manufacturing on the sustainability of a system. This however is acceptable because in general the contribution of production is low in contrast to the virgin material and time-to-maintenance effects captured by the lifetime factor Δ_o. For this reason, the effect of production is modeled as a function of the material archetypes. Finally, the material combination impact value is determined through the use of the so-called ‘triboregister’, which is a library by the Dutch ministry of traffic and water management (Ros, 1996). It provides an extensive overview of tribological material combinations loaded under equal conditions, with most of the data in this reference being obtained in water lubricated systems.

3. Results

A total of 127 articles was found matching the previously identified criteria. The review resulted in 53 articles with a focus on design or performance, and 74 with a focus on material combinations. Because this list of articles found is already fairly small, no articles were discarded based on journal ranking or (lack of) citations. In accordance with the review approach visualized in Fig. 5, a categorization of both bearing geometries and materials present in both groups was performed. It is important to note that in the case of a material focused research, a functional bearing geometry is often not necessary. This means that in the majority of cases, research is performed using either a pin-on-disc or ball/pin-on-ring type tribometer. These are thus not taken into consideration when investigating bearing geometries.

3.1. Bearing geometries

The bearing geometries are divided into one of three main groups: journal bearing, (translational) thrust bearing and (rotational) thrust bearing. Within these main categories, 14 different archetype embodiments of bearing geometries were found in literature. In case of an author having two articles in the same year concerning the same bearing geometry, only one is stated in the overview. The geometries and subsequent sources can be found in Table 2.

The majority of the literature found focuses on the conventional journal bearing geometry, with a rotating shaft (A.0). Other geometries are the rubber housing (A.1), stave bearing (A.2) and rubber stave bearing (A.3). This geometry group is the one with the most attention in research, and is one of the most commonly used bearing designs. Please note that slightly different versions of the same presented archetype have been observed in the analyzed literature, but that a higher level categorization is made to maintain overview of the field.

The most investigated bearing in the translational thrust bearing category is the one with a pocket embodiment (B.3). Other occurring embodiments are those with a rubber support (B.1) and a hybrid bearing with a porous land area (B.2).

Rotational thrust bearings come in two main categories: those with fixed geometries (C.0) and those with tilting pads (D.0). For the fixed geometry, different embodiments were found in the shape of multiple pockets (C.1), radial microgrooves (C.2) and spiral microgrooves (C.3). For the tilting pad embodiment (D.0), a step tilting pad variant (D.1), rubber supported (D.2) and grooved pad (D.3) have been observed.

3.2. Materials

All identified articles were investigated in terms of presented materials. The articles with a specific focus on materials used in this work are Wang and Gao (2013), Sukumaran et al. (2012), Abdelbary et al. (2013), Dong et al. (2014), Golchin et al. (2014), Liu et al. (2012), Wang and Zhang (2012), Chen et al. (2013a), Deleanu and Georgescu (2015), Chen et al. (2013b), Nguyen et al. (2013), Li et al. (2015), Dong et al. (2015), Wang et al. (2014a,c), Wang and Gao (2014a), ling Qin et al. (2015), Dong et al. (2016), Gao et al. (2016), Ali et al. (2017), Golchin et al. (2016), Chang et al. (2019), Chen et al. (2001b), Li et al. (2001), Wang et al. (2018), Chen et al. (2001a), Davim et al. (2001), Dong et al. (2017), Yamamoto and Hashimoto (2004a), Wang et al. (2005), Chen et al. (2017), Wang et al. (2017b,a), Guo et al. (2017), Golchin et al. (2017), Vadivel et al. (2018), Gao et al. (2018), Sumer et al. (2008), Unal and Mimaroglu (2006), Wang et al. (2006), Wu and Cheng (2006), Wang et al. (2009b), Yu et al. (2008), Jia et al. (2003), Meng et al. (2009), Wang et al. (2009a, 2004), Jia et al. (2004), Yamamoto and Hashimoto (2004b), Jordi et al. (2004), Ginzburg et al. (2006), Chen et al. (2012b), Jia et al. (2005), Ginzburg et al. (2011b), Wang et al. (2011d), Ginzburg et al. (2011a), Chen et al. (2012a), Zhao et al. (2011), Dong et al. (2013), Chen et al. (2010, 2012c), Feng et al. (2020), Chauhan et al. (2010), Gebhard et al. (2010), Iliev (2010), Tang et al. (2010), Chauhan et al. (2011), Rasheva et al. (2010), Chen et al. (2011), Golchin et al. (2013), Litwin and Olszewski (2013), Mimaroglu et al. (2013), Niu et al. (2013), Wang and Gao (2014b), Wang et al. (2011a). It has to be noted, that for articles focusing on design a material combination was often not expressed, since this is not crucial for certain design topics. Since a wide variety of material are used in bearing design, a characterization was made based on the following previously mentioned archetypes: metals, ceramics, polymers and composites. All materials present in literature have been mapped within these archetypes in terms of their occurrence. The resulting overview of materials can be seen in Fig. 7. Materials with only a single occurrence in literature, have a combined representation stated in the archetypes as ‘other’. Also, certain variations of the same material are all combined into a single representation into the overview. This means various types of stainless steel are all captured under the same representation “stainless steel”. This generalization is chosen to favor overview over detail. Secondly, the eco-impact properties for various versions of the same primary material are very similar, and moreover, the properties for these various versions of a material are usually not identified in literature.

The most common polymers present in literature are PEEK, Nitrile Butadiene rubber (NBR) and Ultra High Molecular Weight PolyEthylene (UHMWPE) respectively. The single occurrence polymers found in Golchin et al. (2013) have been combined into a single representation defined as ‘other’.

The most common metals present in literature are stainless steels, steel alloys and bronze. Several different types of stainless steels are presented in literature, with the most common being type 316 with 17 occurrences. The group steel alloys covers a wide variety of different steels, including tool steel, type 45 structural carbon steel and 34CrMo1. Often however in design focused articles, the specific steel type is not given. To obtain an improved overview and because the exact metal is not required for later sustainability impact assessment, the different steels have been grouped. Furthermore, the metals in literature that have been mentioned only once are tin–copper alloy (Zhao et al., 2011) and cobalt chrome alloy (Golchin et al., 2016).

By far the most common ceramics for water lubricated bearings are silicon carbide and silicon nitride. In addition tungsten carbide is mentioned once (Niu et al., 2013). This material type is in most cases a self paired archetype, meaning that either a combination of the same materials or the same material archetype is used.

Composites most found in literature are multiple forms of filled PEEK, followed by filled UHMWPE and filled PTFE. This closely follows the trend of most common polymers presented in literature. The additional materials in literature that are mentioned once are filled vinyl ester and filled PPS. These are usually compared with respect to their virgin/unfilled counterparts in literature to determine where the performance increase is obtained.

3.2.1. Material impact

To obtain the necessary data required for the use of the equivalent impact factors as assessment tools, the previously presented materials in Fig. 7 are used. The CO_2 equivalent is presented in Fig. 8, while the primary energy is presented in Fig. 9. In all cases both a best and worst case scenario have been presented. The best case means the embodiment energy and CO_2 equivalent have been determined for material that will be recycled, while the worst case scenario is determined by its virgin production without any recycling, down cycling or landfill procedures.

3.3. Material combinations

To visualize the occurrence of certain material combinations, an overview is presented in Fig. 10. 83 unique material type combinations have been observed in literature. The choice is made to cluster material combinations consisting of metals or ceramics with a specific counter surface material that occur only once in literature in their respective “other” groups. As seen also in the presence of materials in literature, primarily polymers–metals and composite–metal combinations have been observed. Virgin and filled PEEK in combination with stainless steel is by far the most common material combination observed. Silicon carbide is the most self-mated material combination in literature.

Table 2
Overview of literature research with a focus on geometry. The literature is organized relative to their main bearing geometry.

A.0	A.1	A.2	A.3
Andersson (2003) Hirani and Verma (2009) Litwin (2009) Wang et al. (2011c) Litwin (2011) Gengyuan et al. (2015) Gao et al. (2014) Zhang et al. (2015) Ye et al. (2016) Zhang et al. (2016) liang Xie et al. (2017) Feng et al. (2018)	Li et al. (2015) Liu and Yang (2015) Liu and Li (2020)	Majumdar et al. (2003) Pai and Pai (2008a) Pai and Pai (2008b) Wang et al. (2014) Feng et al. (2014) Cheng and Ji (2016) Lu et al. (2016) Gong et al. (2019) Li et al. (2019)	Cabrera et al. (2005) Orndorff et al. (2005) Hua et al. (2008) Peng et al. (2011) Wang et al. (2011b) Wang et al. (2013) Zhou et al. (2017a) Zhou et al. (2017b) Yang et al. (2018)
B.0	**B.1**	**B.2**	**B.3**
	Van Ostayen et al. (2004)	Hanawa et al. (2017)	Nie et al. (2006) Huanlong et al. (2006) Kang et al. (2011) Yin et al. (2013) Xu et al. (2016)
C.0	**C.1**	**C.2**	**C.3**
	Gohara et al. (2014) Rohmer et al. (2018)	Xiang et al. (2019)	Yoshimoto et al. (2002) Lin et al. (2018)
D.0	**D.1**	**D.2**	**D.3**
Dabrowski and Wasilczuk (2004) Song et al. (2018)	Nakano et al. (2009) Zhang et al. (2014) Zhang et al. (2018)	Liang et al. (2016) Liang et al. (2019) Ning (2019)	Boonlong and Jeenkour (2017)

3.3.1. Lifetime factor

In case of a comparison between material combinations, the load case is crucial for the subsequent analysis. To provide the reader with material for such a comparison, a library of different tribological material combinations has been analyzed based on those found in the triboregister Ros (1996).

In Table 3, several water lubricated material combinations and their load-conditions have been presented. The amount of wear is used to determine the lifetime factor for these material combinations. In the table presented, material 1 is the one that wears down, while material 2 is the counter-surface. Operation factor Δ_o is based on determining the effectiveness of the material combination. The wear rate, although more difficult to obtain as a general property of material combinations, is used since it is the best representation of bearing lifetime performance. This parameter is also used for full film lubricated bearings, since even though ideally they experience no wear due to their full film lubrication, in practice they often do not have perfect full films, so mixed or boundary lubrication occurs instead. This results in wear, which thus impacts the bearing lifetime. This has been done by normalizing the wear relative to the most effective water-lubricated material combination. Any material with a $\Delta_o < 1$ indirectly means the time-to-maintenance would be lower with respect to the reference material combination, which is UHMWPE to Stainless steel (SS). Simultaneously, a value $\Delta_o > 1$ would be an increase of time-to-maintenance of the same bearing sleeve. To give an example of how this could be implemented, a comparison between UHMWPE to stainless steel and HDPE to stainless steel in Table 3 can be made. If a system has been designed such that the lifetime is dictated by the lifetime of UHMWPE to stainless steel ($\Delta_t = 1$), using a HDPE bearing sleeve instead would mean that in that given lifespan, the HDPE sleeve would have to be replaced more then 44 times, because the material combination is less effective against wear. Although a simplification of the real life situation, which is dependent on significantly more variables, this lifetime factor Δ_o allows for a systematic comparison of the effects of different material combinations.

3.4. Production impact

Fig. 11 shows the overview of production methods analyzed in this work. The presented figure is based on using 4 materials per material archetype found in literature to define an average production cost per archetype group and production method. The data is obtained from CES Edupack (Cebon et al., 2009). The plot shows both the median in all cases, as well as the outliers to determine the range. For the archetypal material of polymers, PEEK, UHMWPE, PTFE, and POM have been used as typical examples. For the metals, stainless steel, bronze, medium carbon steel, and inconel 625 have been used. For the ceramics, silicon nitride, silicon carbide, boron nitride, and zirconium dioxide have been utilized. Finally, GF PEEK, GF PTFE, CF PI and GF UHMWPE has been analyzed to obtain the typical values for the composite manufacturing archetype. For polymer fine machining, the medians are 0.18 [kg Co2/kg] and 1.905 [MJ/kg].

For Polymer molding, these are 2.125 [kg CO_2/kg] and 30.5 [MJ/kg]. Polymer grinding has medians of 12 [kg CO_2/kg] and 2.67 [MJ/kg]. For forging and casting these are 0.325 [kg CO_2/kg], 4.36 [MJ/kg] and 1.02 [kg CO_2/kg], 13.55 [MJ/kg] respectively. Metal fine machining has medians of 0.075 [kg CO_2/kg], 1.14 [MJ/kg]. Composite molding has medians of 2.07 [kg CO_2/kg] and 30.39 [MJ/kg]. Finally, composite fine machining and ceramic grinding have medians of 0.24 [kg CO_2/kg], 2.35 [MJ/kg] and 1.76 [kg CO_2/kg], 23.5 [MJ/kg] respectively.

3.5. Lubricant impact

The lubricant is an integral part of the sustainability determination of the bearing system. Although the main focus in this work is water, several types of oil have also been presented in order to make the comparison between these different lubricant systems. The ecological impact of water is dependent on its treatment processes, and a wide variety of sources can be found in literature (Stokes and Horvath, 2009). In total three relatively expensive water sources have been identified for comparison, being desalinated groundwater, desalinated seawater and recycled water, all presented in the previously mentioned article. It is directly compared with mineral (Pusavec et al., 2010), synthetic (Ishizaki and Nakano, 2018) and a hydraulic rapeseed oil (McManus et al., 2003). The resulting values can be found in Fig. 12. A description of the embodied energy of synthetic oil has not been observed in literature. Therefore an estimate value of synthetic oil has presented based on the relative similarity between synthetic and

Table 3
Lifetime factor for several material combinations.

Mat 1	Mat 2	Ra	[MPa]	[mm/s]	[C]	wear $* 10^{-9}$ [mm^2/N]	Δ_0
Water lubricated							
UHMWPE (CF)	SS	0.8	2.7	10	20	0.429	1
UHMWPE	SS	0.4	2.5	10	20	1	0.429
PEEK	SS	0.1	2.5	500	20	1.5	0.286
PA 6	SS	0.8	2.4	10	20	4.4	0.0975
PTFE (CF)	SS	0.8	2.5	10	20	7.0	0.06128
UHMWPE	Steel	2.5	2.7	10	20	9.7	0.044
HDPE	SS	0.5	2.5	10	20	19	0.0226
PET	SS	0.8	2.5	10	20	20.1	0.021
PTFE	SS	0.8	2.5	10	20	37	0.0116
PTFE (GF)	SS	0.8	2.5	10	20	45	0.0095
POM	SS	0.8	2.5	10	20	46	0.0093
Bronze	Steel	1.6	2.5	10	20	34	0.0088
Thordon	SS	0.8	2.5	10	20	93.1	0.0046
Aluminum br.	SS	0.8	2	10	20	219	0.00195
SBR	SS	0.8	2	10	20	451	0.0009
Oil lubricated							
UHMWPE	SS	1.8	2.5	10	<70	0.001	429
UHMWPE	Steel	2.5	2.5	10	<70	0.01	42.9
Steel	Steel	2.5	2.5	10	20	2	0.214
Bronze	SS	0.8	2.5	10	20	5.7	0.0753
Aluminum br.	SS	2.5	2.5	10	<70	6	0.0715

mineral oil. It is important to note that the lubricant impact only looks at the direct environmental impact of the lubricant production. The lifetime factor addresses the effect of the lubricant on the lifetime properties. Because of the similar impact of the different presented type of water sources, recycled drinking water is used to represent the lubricant in the model.

4. Anticipatory impact analysis

In this work an analytical sustainability metric has been presented that can be used as a design tool when designing water lubricated bearings. To show the potential use of the approach, an example case is presented. The calculator spreadsheet that is provided in the supplementary material accompanying this paper can be used to perform this type of calculation, and encapsulates all previously mentioned model components as well as a primary bearing geometry calculator for simple bearing shapes.

4.1. Case: ship journal bearing

In ship propulsion systems journal bearings are widely used, and known for leaking lubricant even though continuous efforts are being made to limit this leakage. To prevent (sea)water from entering the ship's hull, the system is designed such that the lubricant is pressurized, thus preventing leakage of the environment into the ship. Even though seals are widely used to limit this, an estimated yearly 4.6 to 28.6 million liters of lubricant leaks from stern tubes (Etkin, 2010). And although water lubricated systems are present in this industry, many more are still oil lubricated because of better lifetime performance. The presented sustainability metric can prove a valuable tool when weighing the benefit of water lubrication, and can be used to identify the difference in environmental impact between oil lubricated and water lubricated systems. Dimensions presented in Roldo et al. (2013) have been used for this design case to determine the difference. The majority of these initial dimensions could otherwise be determined with the initial models used in the design process, based on the type of primary bearing geometry identified in Fig. 6.

The dimensions of bearings for so-called bulk carrier ships will be used for this example comparative analysis. For this analysis, the A.0 conventional journal bearing geometry of Fig. 6 has been used, consisting of bearing sleeve and counter surface axle. Also as previously stated, only the component susceptible to wear, which in this case is the bearing sleeve, will be used for the impact assessment. The inner bearing diameter is 469 mm, with a thickness of 25 mm and a bearing length of 960 mm (Roldo et al., 2013). This results in a total volume of 0.0237 m^3. In all cases the propulsion shaft is made of a steel alloy. This analysis will compare UHMWPE, PEEK, Steel and bronze as possible bearing sleeve materials. Using the densities of $931\,\mathrm{kg/m^3}$ for UHWMPE, $1300\,\mathrm{kg/m^3}$ for PEEK, $7800\,\mathrm{kg/m^3}$ for steel and $8800\,\mathrm{kg/m^3}$ for bronze results in bearing sleeve masses of 22.065 kg, 30.81 kg, 184.86 kg and 208.56 kg respectively. In order to determine the initial bearing lubrication volume, the bearing clearance presented in Roldo et al. (2013) will be used, being 0.8 mm and 1.59 mm for metal and polymer bearings respectively. The daily stern tube leakage is also presented in the previously mentioned, and is equal to 6 liters per day for bulk carrier ships. This leakage may be significant, and it is assumed that all lubricant is effectively replaced by replenishment of this loss. The lubricant volume V_0 is thus modeled solely by the initial volume of lubricant present in the bearing gap, and not the volume of any additional lubricant reservoir. Two production steps have been taken into account in accordance with the material archetypes that have been used. For all materials and production processes, the median values of Fig. 11, 9, 8 have been used. Finally, for UHMWPE and PEEK the lubricant is assumed to be water, while for steel and bronze its assumed to be synthetic oil as stated in Fig. 12. The operation time (time-to-maintenance) t is assumed to be equal to 24 months, meaning 730 days, and is the time between subsequent instances of dry docking and maintenance/renewal of the bearing system. Finally, in order to take the effect of material scenario (recycled or virgin) into account, two cases will be presented for all material combinations accordingly. The parameters used for this case study are summarized in Table 4. The resulting impact factors can be calculated using Eqs. (5) and (6) respectively, resulting in the comparison between cases as seen in Fig. 13. Fig. 13 shows that in this case, the total GWP impacts of oil-lubricated bearings are much worse than the total impacts of water-lubricated bearings for all material combinations, even when the impacts of manufacturing the bearings are smaller. It also shows when the environmental impacts of oil lubricant are larger than the impacts of bearing material and production, versus when they are smaller. Note that, in addition to the climate change impacts calculated here, oil leakage into water would also cause ecotoxicity. Such impacts could be calculated with LCA using the same methods as shown here for GWP, and could be weighed against the impacts of climate change using single score LCA methodologies such as Eco-Cost or ReCiPe (Goedkoop

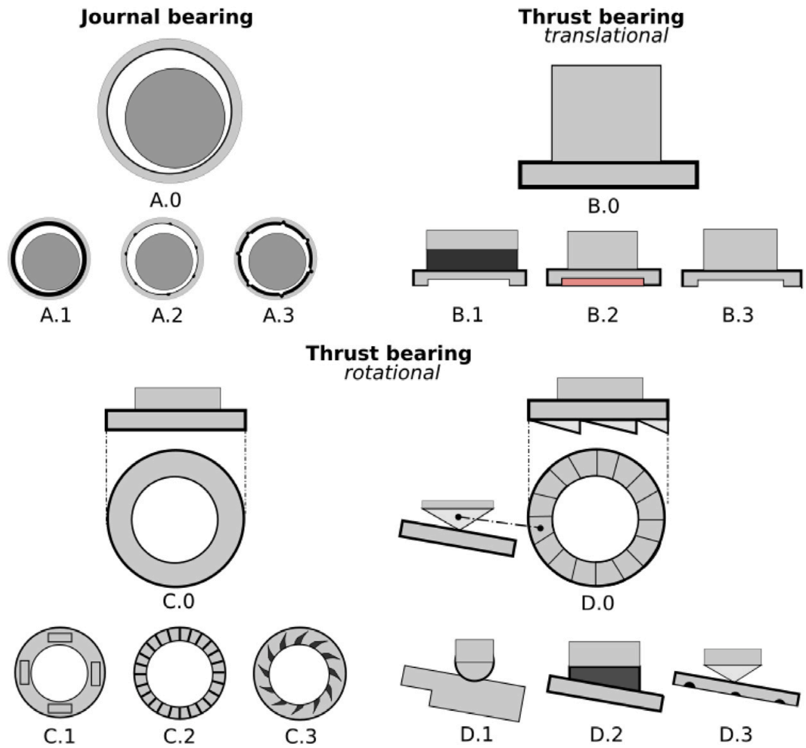

Fig. 6. Primary geometries of bearings observed in literature, as well as their specialized embodiment.

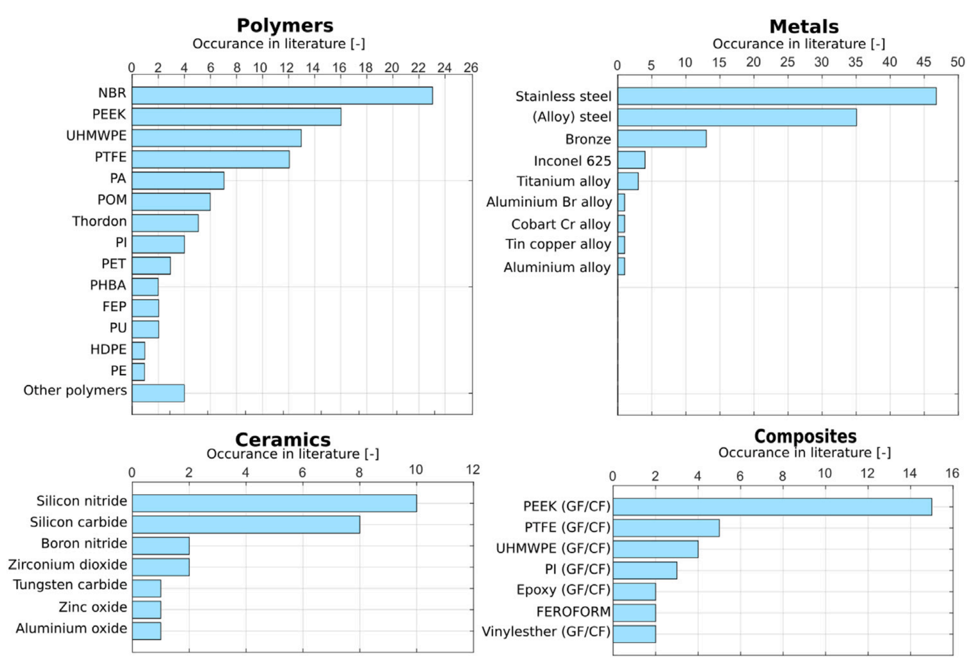

Fig. 7. Materials found in literature and their occurrence. For the polymer archetype presented in this figure, the full names of the presented materials are: Nitrile Butadiene Rubber (NBR), Polyether ether ketone (PEEK), Ultra-high-molecular-weight polyethylene (UHMWPE), Polytetrafluoroethylene (PTFE), Polyamide (PA), Polyoxymethylene (POM), Polyimide (PI), Polyethylene terephthalate (PET), polyhydroxybenzoic acid (PHBA), fluorinated ethylene propylene (FEP), Polyurethane (PU), High-density polyethylene (HDPE) and polyethylene (PE). For the composite archetypes, GF and CF stands for glass fiber and carbon fiber respectively. The full names for the abbreviated metals are aluminum bronze alloy and cobalt chrome alloy.

et al., 2009). Such analyses are outside the scope of this study, but would come to similar conclusions regarding what bearings are better for what applications.

5. Discussion

In this work a method is proposed that allows bearing designers to make initial decisions concerning the sustainability of their design

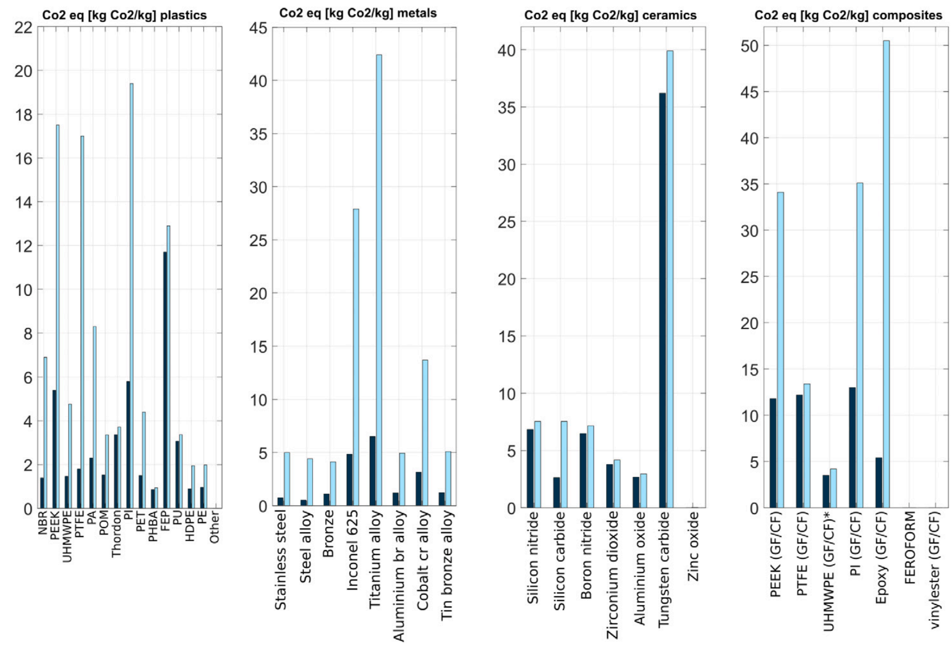

Fig. 8. CO_2 equivalent for all materials presented in this work, obtained from CES Edupack (Cebon et al., 2009) and ecoinvent 3.6 (Wernet et al., 2016). The dark and light bars are the worst and best case scenarios in terms of recycling. The CO_2 equivalents for materials FEROFORM and fiber filled vinylester were not found in literature and therefore not determined.

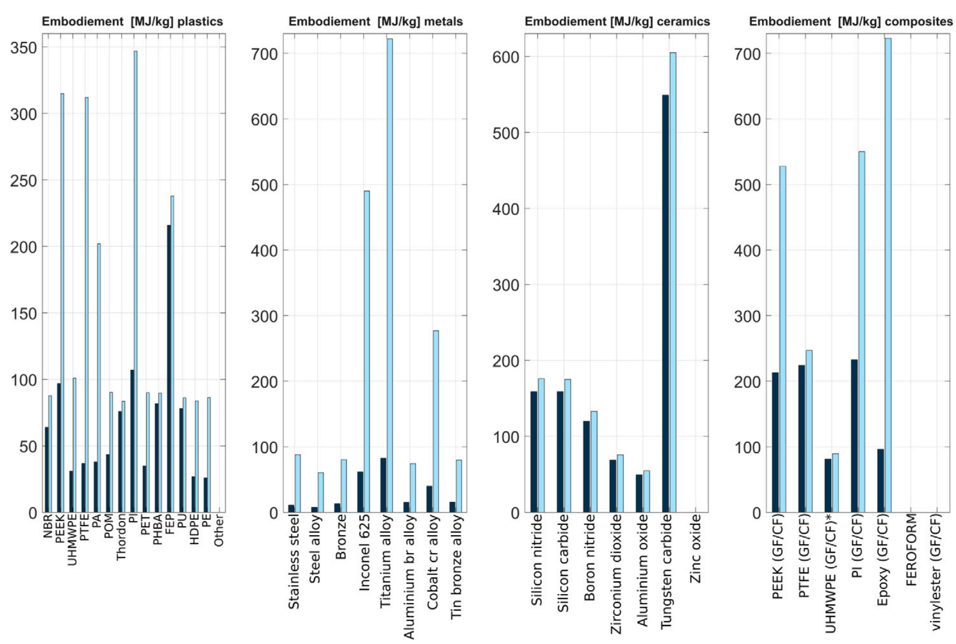

Fig. 9. Primary energy for all materials found in this work, obtained from CES Edupack (Cebon et al., 2009) and ecoinvent 3.6 (Wernet et al., 2016). The dark and light bars are the worst and best case scenarios in terms of recycling. The CO_2 equivalents for materials FEROFORM and fiber filled vinylester were not observed in literature and therefore not determined.

Table 4
Data for anticipatory sustainability analysis using framework presented in this article.

Sleeve material	M_{total} [kg]	V_0 [L]	Production 1	Production 2	Lubricant
UHMWPE	22.065	1.1	Polymer molding	Polymer fine machining	water
PEEK	30.81	1.1	Polymer molding	Polymer fine machining	water
Steel	184.86	0.6	Metal forging	Metal fine machining	oil
Bronze	208.56	0.6	Metal casting	Metal fine machining	oil
UHMWPE	22.065	1.1	Polymer molding	Metal fine machining	oil

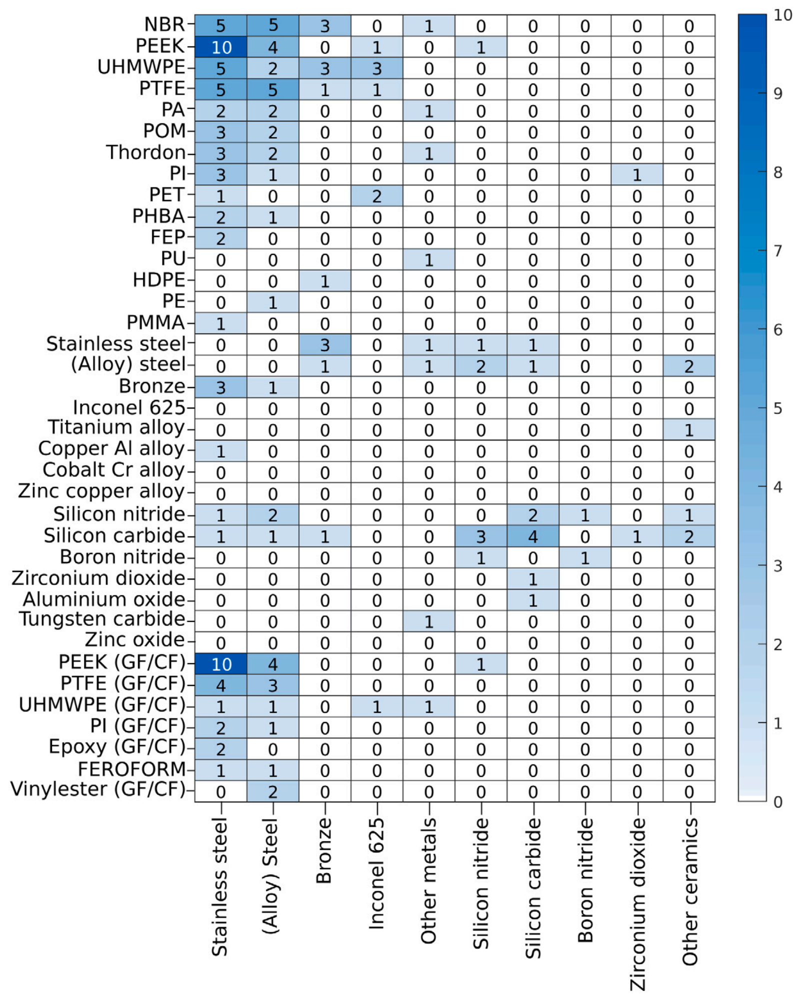

Fig. 10. Overview of material combinations found in literature. The number is a representation of the material combination occurrence in literature, meaning how often the material combination was found in the articles investigated in this work.

concepts. The focus is to propose an analytical approach, minimizing uncertainty, while a secondary focus is to provide all data necessary to perform the analysis for water lubricated bearings. The model uses anticipatory LCA, with the analytical equations fed by data from literature to enable environmental impact analysis. Details on these three parts of the results follow.

5.1. Eco-impact metric based on anticipatory LCA

The proposed model has two dominant choices that greatly influence the performance: The bearing system and bearing load case, both of which will be discussed.

First is the choice of bearing system, defined in Fig. 4. This means the proposed method is not suitable for some cases to define the eco-impact of the bearing system. For example, the effect of water leakage of bearings in water pumps, where the hydraulic liquid is simultaneously also used as lubricant, can be neglected for a closed system. Rather it should be used as a tool in design cases where the choice between water or oil-based alternatives can be made. Pumps and motors of various sizes as well as the previously presented ship's propeller shafts are examples of these. Because of the intended generality of the approach and the list of assumptions for the bearing system, the modeling approach already contains several simplifications. However, because of this generality, not many assumptions need to be made for bearing designers to implement the analysis, allowing for fast initial sustainability statements. As with other anticipatory LCA methods, it should be used to make comparisons and identify the largest impacts, to support decision making and prioritization. The case study shows, using the supplementary calculator, how this analysis can be performed.

Secondly the load case can greatly change depending on the type of lubricant used and the subsequent change in bearing geometry and performance characteristics. This effect is neglected in the proposed model, in favor of consistency between all combinations, thus limiting uncertainty. More specifically, since these types of data are in general not available for engineers in initial design stages, this type of uniform comparison often results in a more reliable comparison. The alternative would be to test several materials for the given load case of the proposed application, an action which is labor intensive, as well as requiring potentially significant initial investment.

5.2. Data from literature

To enable the impact calculation, much data has been gathered from literature. The analysis showed that a wide variety of material combinations has been used for water lubricated bearing applications, but only a few have been reported in high numbers. Within this range of materials, there is however a significant difference in eco-impact, and it thus worthwhile for bearing designers to investigate the scope of possibilities. As is often expected in LCA types of analyses, the impact of the primary material plays a dominant role in the eco-impact of the system.

What is most interesting to note for the identified bearing geometries is the relative lack of innovation when it comes to the development

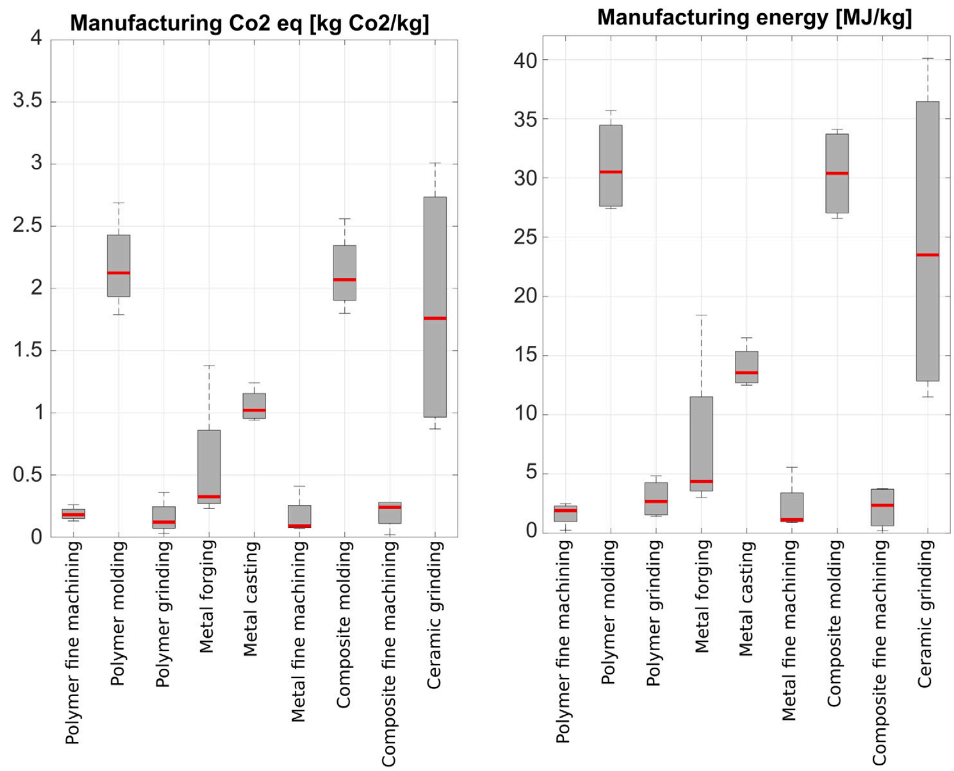

Fig. 11. Overview of the primary energy and CO_2 equivalent of several manufacturing processes for the different material archetypes. The data set is obtained through the use of CES edupack (Cebon et al., 2009).

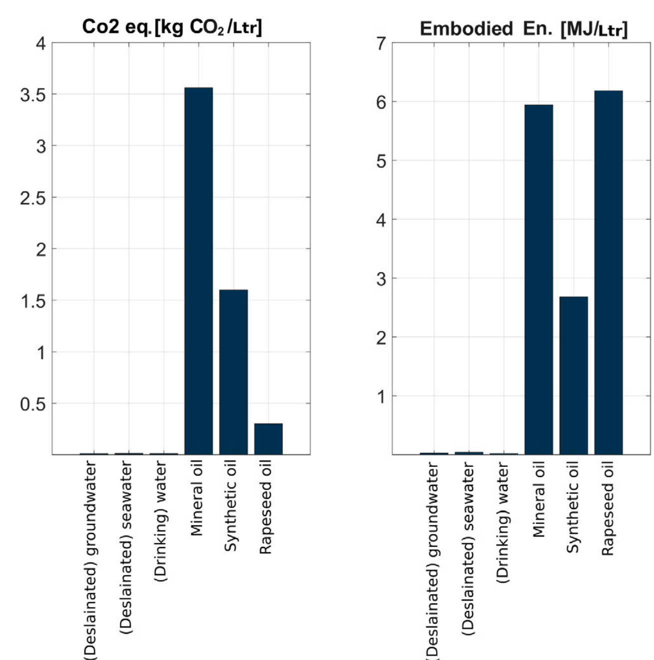

Fig. 12. CO_2 equivalent and Embodiment energy of several lubricants. Note that for desalinated groundwater at 0.0016 [kg/CO_2/ltr] & 0.027 [MJ/ltr], desalinated seawater at 0.0025 water [kg/CO_2/ltr] & 0.042 [MJ/ltr] and recycled drinking water at 0.0011 [kg/CO_2/ltr] & 0.018[MJ/ltr] is significantly lower than any oil alternative.

of novel geometries. The largest body of work is still being performed on bearing geometries that have been around for many decades. It is interesting to note that the conventional lay-out of the journal bearing (A.0), a bearing geometry over 100 years old, is still one of the main focus points when it comes to bearing design. A similar trend also occurs in the materials, where mostly PEEK or its composite forms have been analyzed extensively by multiple researchers over the past two decades.

5.3. Impact analysis

The modeling equations show that the highest impact comes from the material combination, and its wear rate, as well as the lubricant leakage. The example case shows the significant effect of the lubricant in particular, showing that a material combination which is superior in lifetime can still be a far inferior choice when it comes to sustainable design. An interesting observation to note in the case study is that water lubricated PEEK proves to be a superior choice to oil-lubricated PEEK when looking at CO_2, but can be inferior when analyzing the primary energy values.

The case study shows that in some cases the replacement of an inferior material combination would be preferable because of the lubricant use. This is counter intuitive for many design cases, where often the system with the highest lifetime is chosen because of its superior performance. There are however situations where the most sustainable option is one of increased replacement, especially when the time-to-maintenance is dominated by other components in the mechanical system. The proposed method allows for this metric to be taken into account similar to mechanical performance and cost during decision making. This approach of course only partially allows for the engineer to makes these conclusions based on solely two parameters, and as such has its limitations.

Engineers may choose to use more comprehensive LCA metrics that measure many impact categories such as ReCiPe (Goedkoop et al., 2009). However, even the basic quantification of environmental impacts presented in this work clearly shows the importance of lubricant loss on the bearing system's sustainability.

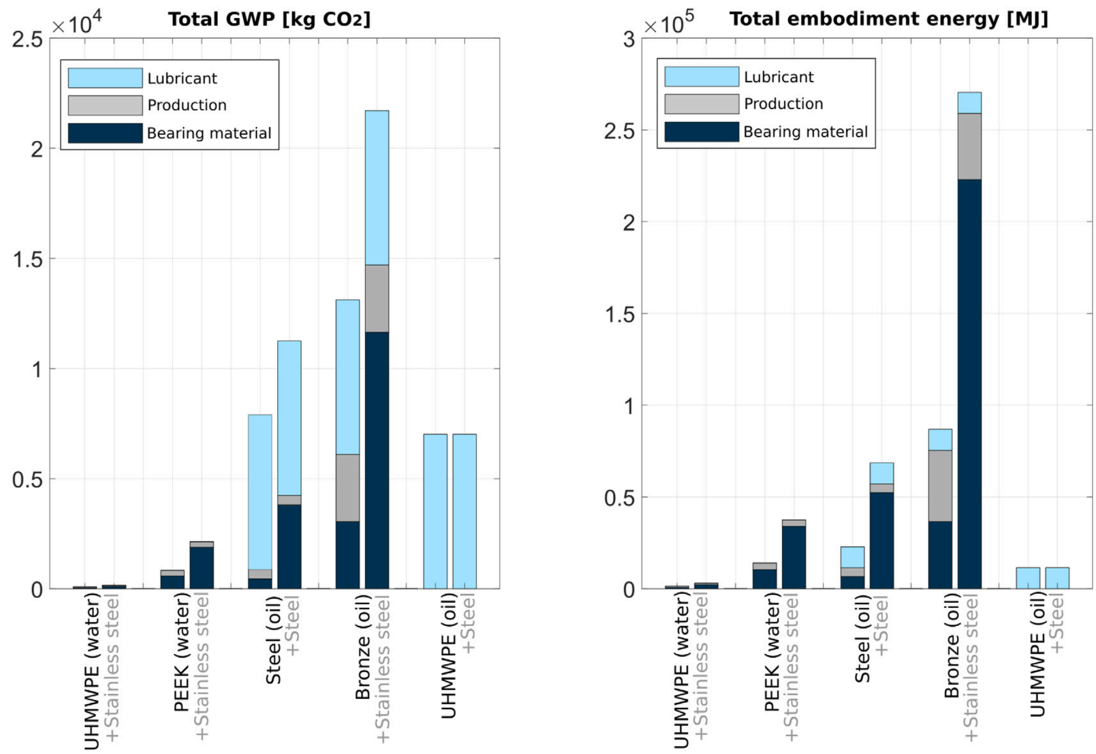

Fig. 13. Total GWP and embodiment energy for the 5 material/lubricant combinations analyzed in the case study. In all cases, both the worst and best case material scenario's (recycled or virgin) have been presented. Lubricated UHMWPE-stainless steel is 191.44 and 360.72 kg CO_2, and the total embodiment energy equals 3335.72 and 6920.33 MJ respectively.

6. Limitations & future work

Based on the previous discussion of the results, a number of model limitations has been identified. Anticipatory LCA in literature (Wender et al., 2014b) has been defined as a systematic tool that prioritizes contributions with the greatest potential for environmental improvement, by redirecting a technology's pathway. This thus attempts to move the use of LCA away from being a product itself and towards its being a process. This is also the objective of this work, by the introduction of the LCA concept design tool. Anticipatory LCA is however not without its limitations, and these limitations should be understood before the presented method is implemented. Because the presented anticipatory LCA method is a concept design tool for non-developed bearing systems, its validation process is difficult to identify (Wender et al., 2014a). The validity of the method can primarily be enforced by using it during concept design, fully developing the system and its alternatives and performing a conventional LCA afterwards. This is a very extensive analysis which falls outside the scope of this work, but eventually needs to be performed to reinforce the promise of the proposed method. The second way the presented method is limited, is its dependency on externally gathered data. Though Table 3 does provide several of the primary material combinations seen in Fig. 10, not all material combinations could be defined. Primarily, data for ceramic material combinations is lacking. The way this data is collected is generally for different sets of load conditions, again important for making balanced comparison decisions. The creation of reliable test data that the model requires for all material combination is a serious undertaking, and load case operations significantly effect the efficacy of certain materials. This statement can also be extended to the use of lubricants. Different types of water, such as seawater, groundwater and water contaminated with sand all influence the lifetime factor. The model now only takes into account the lubricant based on the external material database, which does not accurately account for such subtle lubricant differences, and through the base impact of the lubricant. This further reinforces that the presented method should not be used to accurately determine environmental impact, but use the relative impacts to compare in a design process. The benefit of this approach though is the absence of weight factors, which introduce subjectivity into the process. Thirdly, the model lacks to incorporate the effect of the encompassing mechanical system, of which the bearing system is a part of. This is a fundamental limitation of the presented model, given the defined bearing system boundary. There are systems where the impact of the bearing could be small compared to other components, although the bearing usually has an important indicator for the lifetime of the entire system. There are thus systems that do implement bearings, but where the presented method in this work would only have limited value for the decision process. A number of steps have thus been identified for future work. The first is the further validation of the proposed method. Initial validation steps have been made through the presented case study and the different environmental impact factors that were found based on the materials and lubricant. The next step would be to implement the presented method during concept development of a new case, work through the detail design and production steps of the different design alternatives and performing a conventional LCA. The results can then be used to determine both the process implication the anticipatory LCA has provided and give some indication of the accuracy of the proposed method. It also can be used to identify what is impact is of simplifications that are made in the presented method. A second important step is to increase the size of the data library, through experiments of different material combinations under equal load conditions. The most logical step would be a large study of materials under equal load condition using pin-on-disc setups. An important note to make for this step, is that simplifications of the model will still limit the increased accuracy this extended data set will generate. The model spreadsheet provided in the supplementary material can be extended to incorporate this increase of data.

7. Conclusion

The presented method allows designers of water lubricated bearings to calculate the environmental impact of their designs during concept design stages through the use of the anticipatory LCA based approach. The work provides a extensive data-set for water lubricated bearings in particular, where the past 20 year state of the art has been identified and collected in a dataset. Several of these material combinations possess impressive performance characteristics even in comparison with some oil-lubricated alternatives. The presented case study shows how this anticipatory LCA base approach can be used to give initial indications on sustainability of bearing designs considering certain materials and combinations. The provided supplementary material accompanying this paper can be used to perform this calculation. It indicates the crucial effect the lubricant has on statements concerning sustainability, even when bearing embodiment is an order of magnitude better in terms of wear, as can be seen between water-lubricated UHMWPE on steel and oil-lubricated UHMWPE on steel. As long as uncertainty and possible ranges of different values are accounted for in different scenarios, anticipatory LCAs can greatly aid in decision making.

Thus, the statement often seen in literature that water lubricated bearings are a green alternative to oil-lubricated bearings, depends heavily on the design case. Especially when a closed system is used, it might be a significantly more sustainable option to take the more conventional oil-lubricated bearing. This way, sustainability can be used as a design criteria, similar to the way costs and performance are used currently for decision making in these types of systems.

CRediT authorship contribution statement

J.P.A. Nijssen: Conceptualization, Methodology, Software, Formal analysis, Data curation, Investigation, Writing - original draft, Writing - review & editing, Visualization. **J. Faludi:** Methodology, Software, Formal analysis, Writing - original draft. **R.A.J. van Ostayen:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128874.

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