Seal virtual optimization for enhanced sustainability

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SAMBA is an advanced simulation platform coupling a commercial FEM solver with proprietary analytical equations to predict the behavior of sealing systems in terms of transient dynamics, friction and thermal performance. The modelling method combines viscoelastic material behavior, the heat generated by the seal friction and the heat dissipated inside and outside the sealing system. The equations implemented consider the influence of the tribological, lubrication and heat transfer phenomena, including the temperature dependencies of each variable. The model predictions obtained show very good agreement with experimental test results in terms of temperature, and friction torque. In practice, a real case example shows how the SAMBA prediction capabilities are actively supporting the journey towards cleaner and more sustainable sealing solutions.

1 Introduction

The seal is a major contributor to the friction in rotating equipment; up to 60% of the total friction torque in some applications. Lowering the seal friction torque is thus one of the main customer requirements to improve the system efficiency, reduce energy consumption and overall carbon emissions. With stricter CO_2 regulations, an increasing challenge in seal product development and engineering remains the design of an optimal sealing solution balancing low friction with maintained sealability. Therefore, accurately predicting the seal transient dynamics and seal friction, with the aid of simulation tools, is paramount to accelerate the product development phase and reach the friction target set by the customer in the shortest amount of time possible.

This paper presents some of the latest modelling techniques enhancement on seal frictional heat and thermal dissipation, implemented in our internal simulation platform SAMBA, to cope with disruptive market demands targeting more sustainable sealing systems. For the prediction of the seal friction torque and temperature, a commercial FEM solver is coupled with proprietary analitycal equations considering the temperature dependencies of each variable included in the seal frictional heat generation and dissipation models. Obtained results are then coupled with a proprietary CO2 emissions estimator to demonstrate how more sustainable sealing solutions can be enabled with the aid of advanced simulation platform.

2 SAMBA performance prediction

The seal friction and temperature performance prediction require a combination of tribological, lubrication and heat dissipation models. The temperature needs to be accurately predicted as most of the variables used in the model are temperature dependent. The analytical equations describing the frictional heat generation and heat dissipation need to be adapted for use in numerical FEA software. Such modelling approach is non-standard and cannot be implemented directly via common FEA software interfaces. The implementation of the analytical equations is only possible by combining multiple external subroutines. The subroutines give to the user access to more advanced capabilities such as customized friction coefficient, heat generation and dissipation.

2.1 Modelling approach

The transient evolution of the temperature in a sealing system stabilizes when there is an equilibrium between the amount of heat generated by the seal frictional torque and the amount of heat dissipated to the outside of the sealing system. Thus, it is crucial to consider both the frictional heat generation and the thermal transfer together to insure a realistic temperature prediction. Many variables involved in the seal torque prediction are temperature dependent, which makes the predictive modelling even more complex. The integration of the SAMBA modelling equations into an FEA package allows for an update of all the interdependent variables at each increment of time of the simulation, thereby taking full advantage of the coupling between the proprietary analytical models and the FEM numerical solver.

2.1.1 Seal friction torque and heat generation

The heat generated by the seal frictional loss [1,2] is considered as a heat source in the model (see Figure 1).

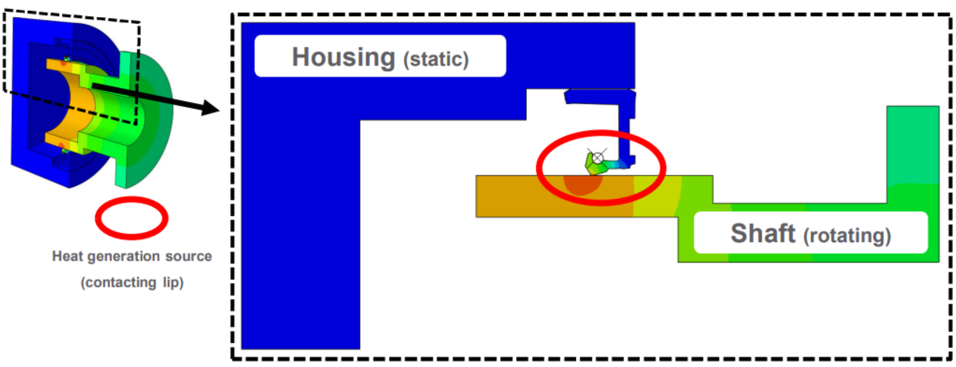

Figure 1 - Example of contacting lip generating heat via frictional loss.

The heat energy is derived from the overall friction force as per equation (1)

$$P_{Loss} = F_{Torque} \,.\, u \quad (1)$$

Where the overall seal friction force (2) for a lubricated lip is the combination of the viscous shearing force from the lubricant (3) and the rubber material friction force (4)

$$F_{Torque} = \left(F_{Lub} + F_{material}\right) \quad (2)$$

The lubricant viscous shearing force is defined in equation (3)

$$F_{Lub} = \frac{\eta u}{h_e} S_{contact} \quad (3)$$

The rubber material friction contribution is described by equation (4).

$$F_{material} = k_2 \left(\mu_0 + \mu \, k_3 \, e^{-b\left(\frac{2h_e}{Ra_{shaft}}\right)^{\varepsilon}} \right) F_{seal} \quad (4)$$

The lubricant film thickness, h_e, is then calculated as follows:

$$h_e = k_1 \frac{(\eta u)^{\delta}}{F_{line-contact}{}^{\gamma} E^{\alpha}} \quad (5)$$

2.1.2 Heat dissipation models.

The SAMBA thermal model assumes that the convection and conduction are the main heat transfer mechanisms and the effect of radiation is not considered.

The energy dissipated by convection between solid and fluid within the sealing system is modelled by the following formula (6):

$$q = H\,(\theta + \theta_{sink}) \quad (6)$$

Where, q, the heat flux at the surface is based on multiple studies performed at the university of IMA-Stuttgart, which focusses on temperature rise of contact area of radial lip seals [3], and a general dissipation model for cylindrical objects proposed by Holman [4]. The rotating aspect of the sealing application under study requires a specific coefficient of dissipation H.Depending on the operating conditions; a surface can be either standing still (static) or rotating (dynamic) in application. Similarly, a surface can be in contact with either the air or with the oil in the lubrication sump.

This results in four different combinations of operating conditions and, consequently, in four different descriptions of the required coefficient of dissipation H, as illustrated in Figure 2.

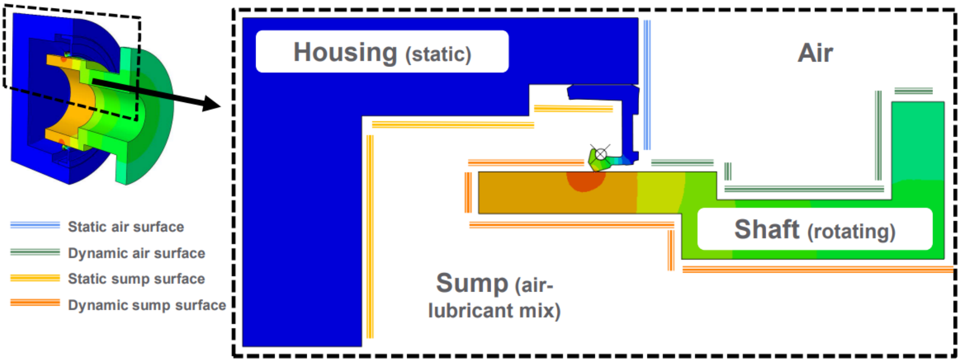

Figure 2 - Example of dissipation surfaces on a single lip seal application

As described in equation (6), the sink temperature θ_{sink} has a direct impact on the amount of heat dissipated via convection. For the surfaces in contact with the air, we assume the sink temperature to be a constant equal to the ambient temperature, where the ambient temperature is defined by the application. For the temperature of the lubricant present in the sump, two options are implemented:

- The sump is being controlled by a heater or a thermal resistance. In this case, the temperature of the sump is defined by the user as an input parameter.
- The sump temperature is free or uncontrolled. In this case, the heat transferred by the surface in contact with the sump will regulate the temperature of the lubricant in the sump according to the following equation (7):

$$\Delta\theta_{sink} = \frac{(Q_{static,sump} + Q_{dynamic,sump})}{C_{p,oil} * \rho_{oil} * V_{oil}} \quad (7)$$

The heat generation and the heat convection, presented previously, describe the heat exchange phenomena happening at the surface of a part. The heat exchange via conduction within the solid part itself (e.g., the seal) is handled by the FEM thermal solver directly. The heat flux at the element level in an FEA simulation is governed by the thermal material properties, namely the specific heat capacity and the thermal conductivity, and are provided from our proprietary sealing material' database.

2.2 Experimental validation

2.2.1 Test details

The validation test campaign uses industrial oil seals and is run on two similar test rigs (Figure 3)

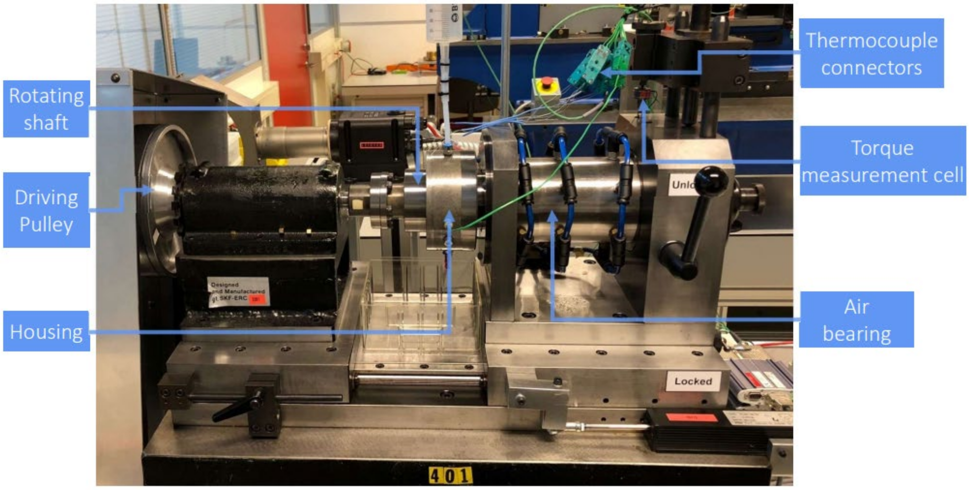

Figure 3 - Performance test rig used for SAMBA validation

For the validation test, the shaft is rotating and the seal is mounted in a static housing. The housing is clamped into an air bearing, whose negligible friction torque allows for only measuring the friction torque being transmitted by the shaft to the seal. Multiple thermocouples are placed on the seal to measure the temperature. The thermocouples are positioned at various locations within the sealing system to ensure proper thermal mapping, and three are positioned as close as possible to the contacting lip where the heat is generated, as depicted in Figure 4

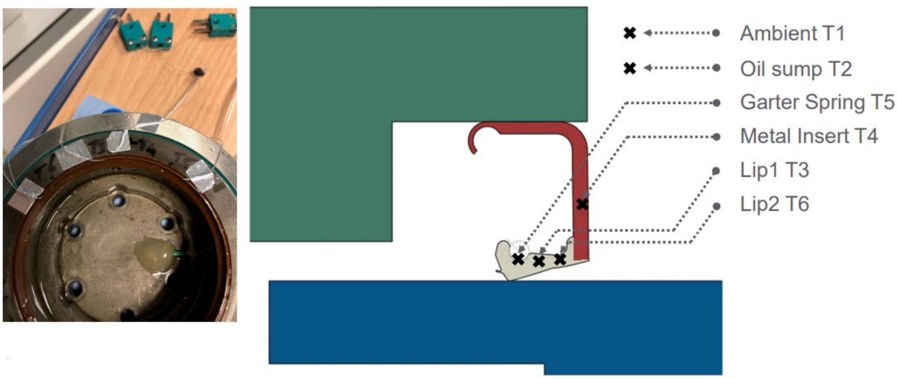

Figure 4 - Thermocouples positioning on seal sample

Four industrial oil seals have been used in the validation tests:

- Seal 1: made of FKM A material and designed for a 3 Inch shaft
- Seal 2: made of NBR A material and designed fora 3 Inch shaft
- Seal 3: made of FKM A material and designed fora 5.5 Inch shaft
- Seal 4: made of NBR A material and designed fora 5.5 Inch shaft

The two 3 Inch rotating shaft seals share the same geometry and only differ in rubber material and the same applies for the 5.5 Inch seals.
Additionaly, five parameters were varied in the validation tests:

- the rotational speed (defined in the speed cycle)
- the shaft diameter size (3 Inch & 5.5 Inch)
- the seal material (FKM A & NBR A)
- the oils used (Lubricant A & Lubricant B)
- the relative lubricant level (0%, 25%, 50% and 75%),

A full factorial Design Of Experiment (DOE) is performed based on the variables described above and each individual experiment within the DOE is performed using the same speed cycle. Combining all levels for each variable in the DOE results in a total of 32 experiments, carried out to ensure validity of our modelling approach

2.2.2 Model and experimental results comparison

The SAMBA platform is used to virtually reproduce the experimental test rig. An example of results for both the experimental test and the simulated predictions, are displayed in Figure 5 and 6. These illustrate satisfactory torque and temperature predictions, the simulation results showing good agreement with the experimental results. Additionally, the transient effects of the torque and temperature are also captured when changing speed for both ramping up and ramping down phases of the used speed cycle

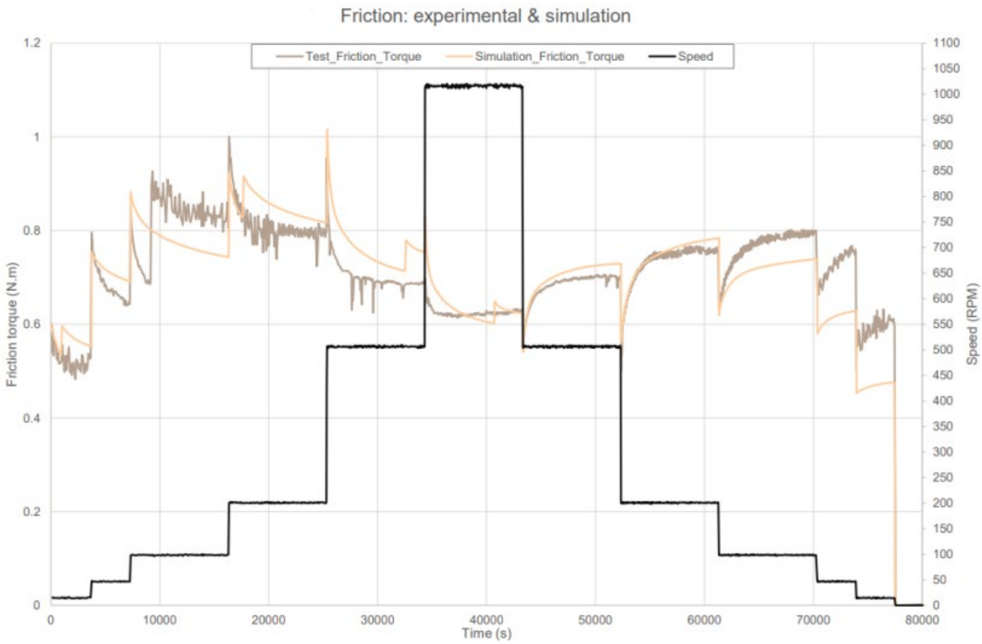

Figure 5- Friction torque: results comparison

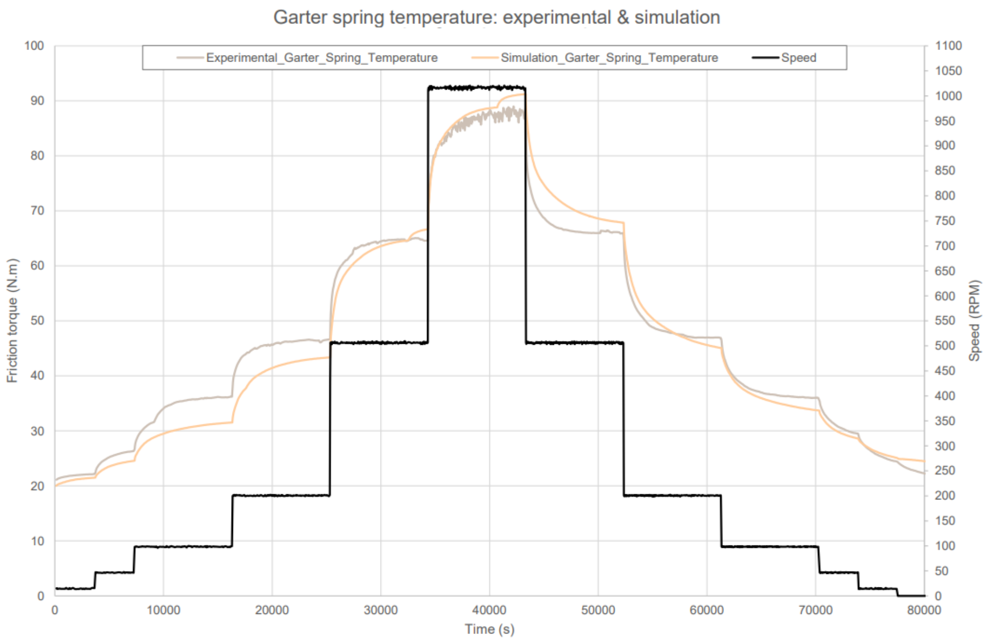

Figure 6 - Garter spring temperature: results comparison

3 Seal optimization for sustainability

As described previously, the SAMBA platform can predict accurately the amount of friction of a sealing system. This friction level can then be converted into a level of CO_2 emissions to allow for a virtual method of selecting the best-in-class seal candidate based on a tangible sustainability criterion. The emissions due to frictional losses are then calculated based on the regional amount of CO_2 emissions per kWh of energy for the chosen geographical location.

3.1 SAMBA approach on a real application case

The SAMBA torque and temperature prediction capabilities have been released internally to our seal product development community. The following illustrates a typical usage example of this advanced platform on a Hub Bearing Unit (HBU) cassette seal application for car wheel end.

In this example, a car manufacturer requests a reduction of friction torque of 20% on the next generation Hub Bearing Unit (HBU). Internal discussions between bearing, lubrication and sealing departments lead to the development of a new low friction grease (grease B) in order to reach the low friction target set by the customer.

The customer requirements for validation of HBU seals friction are based on a rather constant speed condition preventing typical starvation phenomena usually occurring in case of grease lubricated seals used in more dynamic speed cycles. The SAMBA prediction capabilities can then be used for this greased seal friction torque prediction with the current oil lubricated model implemented, provided some adjustments are made to cope with some minor aspects of the grease lubrication behaviour.

The seal development team then decides to use the SAMBA platform to predict the seal friction torque with the newly designed solution using the new low friction grease. The current state of the art design is modelled using SAMBA to predict the friction torque and temperature with the original grease (grease A), to establish a baseline. The baseline design will serve as a reference during the development phase to evaluate the friction reduction improvements between both greases. In practice, as the seal geometry remains unchanged, the evaluation of the frictional potential improvements is operated uniquely via the SAMBA user interface (Figure 7).

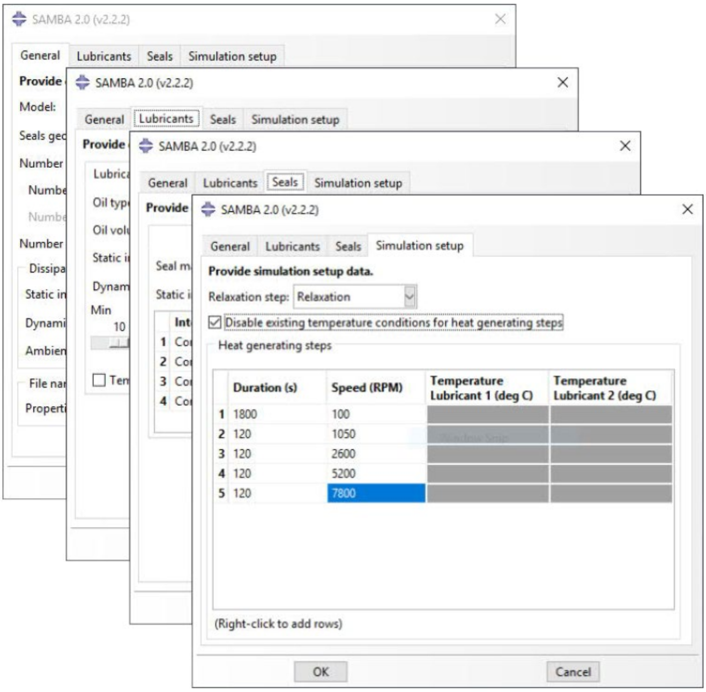

Figure 7 - SAMBA user interface – Courtesy of Abaqus/Dassault Systemes

The user provides specific parameters associated with the HBU seal application such as:

- Rubber properties (from proprietary material database)
- Number of seals, contacting lips
- Lubricant's properties (from proprietary lubricant database)
- Dissipation interfaces
- Ambient temperature
- Lubricant temperature
- Speed cycle

Once the user has defined all the inputs in each of the four tabs of the SAMBA user interface, a script performs all the necessary operations in the background to link the FEM solver to the SAMBA analytical equations described previously in section 2.1.

Comparing the simulation prediction results, the stabilized friction torque values show a 28% friction improvement with the newly developed grease B:

- **0.33 Nm** for the solution using the original grease (grease A)
- **0.24 Nm** for the solution using the new low friction grease (grease B)

This improvement shows a friction reduction of 28% which is better than the 20% reduction target set by the customer. The experimental results coming from the product validation tests in comparison with the SAMBA modelling results also display a very satisfactory accuracy of the SAMBA predictions as illustrated in Figure 8.

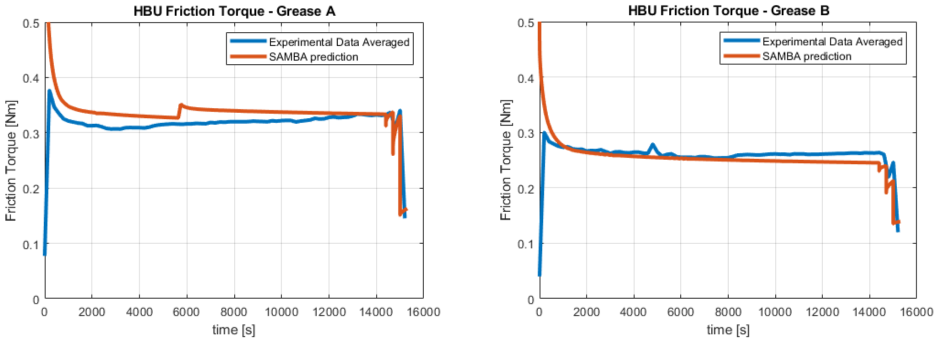

Figure 8 - HBU friction torque results: comparison for both grease scenarios

3.2 Sustainable development scenarios

The undeniable urgency to act on climate change is driving an increasing focus on sustainability It is therefore paramount to discuss and raise awareness for all involved parties across the complete value chain, such as suppliers, manufacturers, and customers, on the environmental impact of our products.

As part of strengthening our engagement on sustainability, our company works on estimating the impact of our products such as the level of CO_2 emissions. Part of this effort translates in creating web-based calculation tools such as the following Sustainability tool – CO_2 emissions estimator.

Using the Hub Bearing Unit seal friction predictions and this emission estimator, one can look at the effect of the performance improvements of our new HBU solution on the scope 3 downstream emissions. The proprietary sustainability tools translating the seal friction energy losses into CO_2 emissions, the impact of grease change described in section 3.1 on HBU cassette seals for a car wheel end application is illustrated in Figure 9.

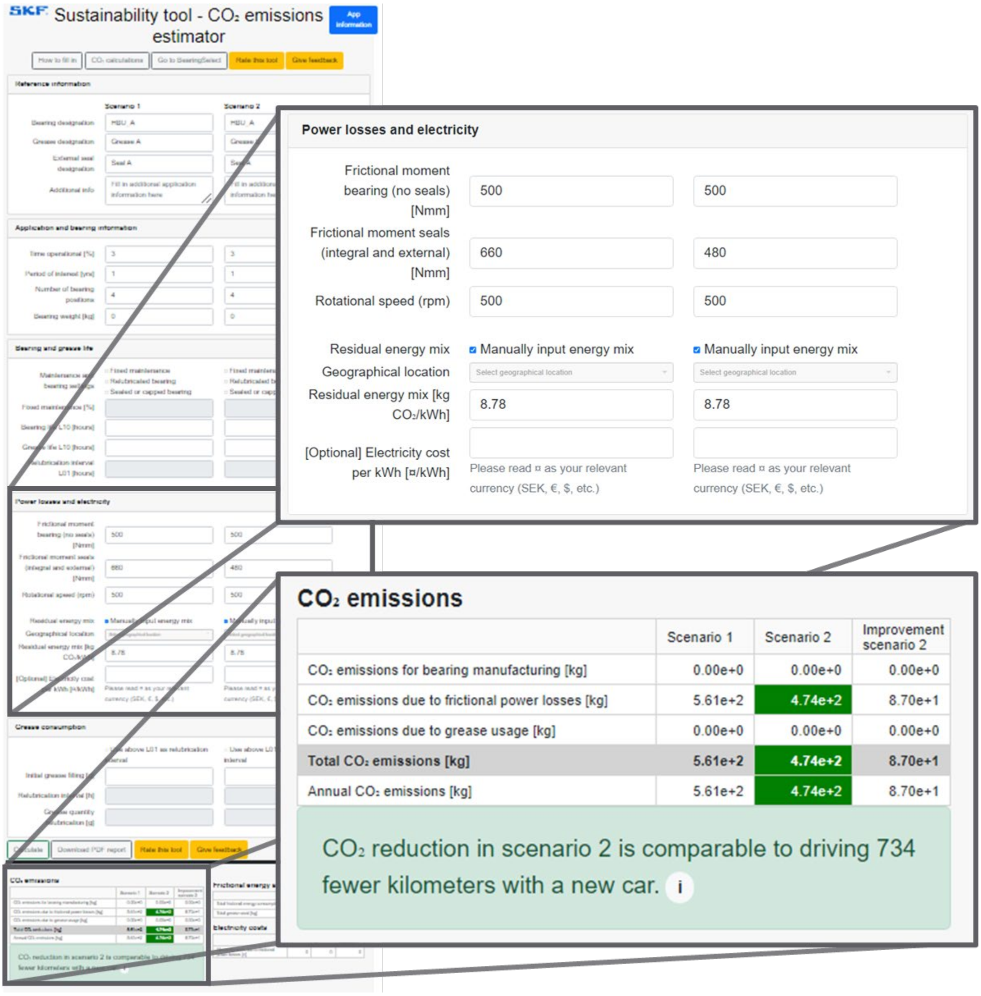

Figure 9 - SKF sustainability tool interface and CO2 emissions estimations

The parameters are based on the previous results from SAMBA predictions to reflect the influence of the existing Hub Bearing Unit sealing solution and the newly designed sealing solution using the new low friction grease.

The two scenarios are described below:

- Scenario 1:
    - Original grease (grease A) solution with 0.33 Nm. stabilized friction
    - Each Hub Bearing Unit is equipped with two seals (Inboard and Outboard) for a combined friction torque of 0.66 Nm. (2*0.33)
    - Car is equipped with 4 bearing units
    - Car is driving 10.000km during a year with an average speed of 50km/h

- Scenario 2:
  - New low friction grease (grease B) solution with 0.24 Nm. stabilized friction
  - Each Hub Bearing Unit is equipped with two seals (Inboard and Outboard) for a combined friction of 0.48 Nm. (2*0.24)
  - Car is equipped with 4 bearing units
  - Car is driving 10.000km during a year with an average speed of 50km/h

The distance travelled and average speed are representative of regular car usage. The average speed used in the estimator matches the speed used during the SAMBA predictions and the experimental validation tests to minimize the potential error due to speed effect on the grease-lubricated friction.

Considering these conditions, the new solution reduces the emissions of a single car by 87kg of CO_2 per year. This is equivalent to a reduction of 8.7 g/km of CO_2 combined for the 4 HBU only considering the improvements made on the cassette seal alone. The Euro 6 emissions standard sets a legal requirement for a car manufacturer to average CO_2 emissions below 98g/km. The implementation of this newly developed solution would provide reduction of ~9% of the Euro 6 $C0_2$ emissions threshold.

4 Summary and conclusion

The SAMBA platform integrates an advanced modelling approach and provides virtual predictive capabilities to our product development engineers. The simulation tool allows for better understanding of seal performance and faster assesment of parameters variations. The SAMBA platform is available within an FEA package and predicts friction and thermal behaviour of a sealing system. The comparison between simulation and experimental results shows that the SAMBA platform predicts well the sealing response for all the parameter combinations considered with their interdependencies.

The thermal prediction is an important milestone required for the next development phase of the SAMBA platform with future implementation of currently-maturing capabilities such as seal ageing and wear life.

In combination with the CO_2 emissions calculator, the SAMBA platform gives an insight to the customer, prior to prototyping or manufacturing, on the potential environmentally friendly improvements of a new sealing solution. In this example, the performance improvement, of the seals equipped in the HBU for light passenger vehicles, showcases the direct benefits using the same criterion used for automotive market regulations. This capability brings us even closer to our customers in the journey toward a more sustainable future.

5 Acknowledgements

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6 Nomenclature

Variable	***Description***	***Unit***
P_{Loss}	Frictional power loss	[W]
F_{Torque}	Total friction force	[N]
u	Circumferential speed	[m/s]
F_{Lub}	Lubricant shearing friction force	[N]
$F_{material}$	Material contribution friction force	[N]
η	Lubricant dynamic viscosity	[Pa.s]
S_{contact}	Lip contacting surface area	[m^2]
h_e	Lubricant film thickness	[m]
k_i	Geometrical factors	[*]
μ_0	Minimum friction parameter	[-]
μ	Material friction parameter	[-]
Ra_{shaft}	Counter surface roughness	[m]
F_{seal}	Total seal load	[N]
$F_{line-contact}$	Linear contact load	[N/m]
E	Local Young modulus	[Pa]
q	Heat flux	[W/m^2]
Q	Heat energy	[W]
H	Film coefficient	[W/ (m^2.C)]
θ	temperature	[C]
E	Local Young modulus	[Pa]
Cp	Specific heat capacity	[J/(kg.C)]
ρ	Lubricant density	[kg/m^3]
V	Lubricant volume	[m^3]

7 References

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