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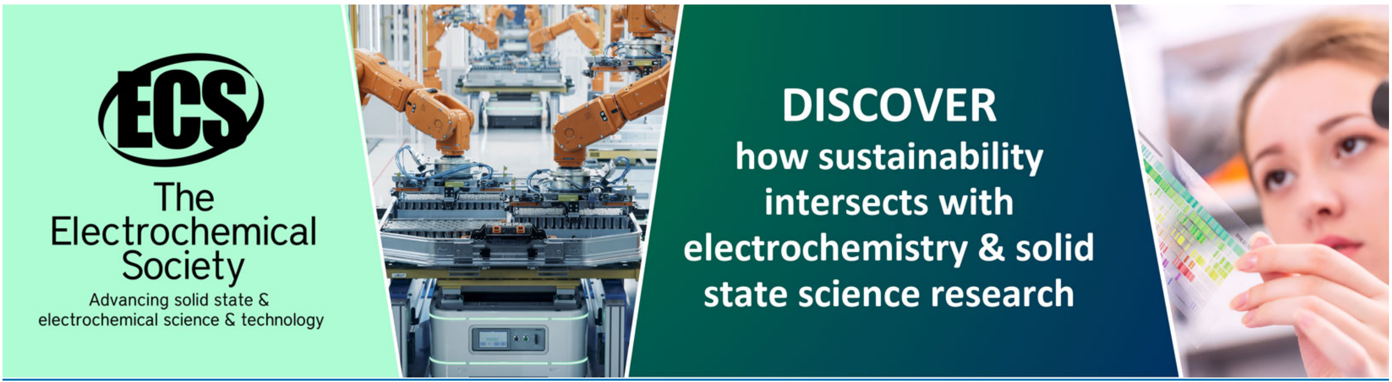

Preliminary experimental data analysis for Digital Twin development of a large bore Dual-Fuel engine

Federico Del Mondo[1*], Davide Pivetta[1], Simone Fratti[2], Lucia Parussini[1], Elio Padoano[1], Paolo Gallina[1], Rodolfo Taccani[1]

[1]Department of Engineering and Architecture, University of Trieste, 34127 Trieste, Italy;
[2] Wärtsilä SpA, 34018 San Dorligo della Valle – Trieste, Italy;

E-mail: davide.pivetta@phd.units.it (D.P.); simone.fratti@wartsila.com (S.F.), lparussini@units.it (L.P.); padoano@units.it (E.P.); pgallina@units.it (P.G.); taccani@units.it (R.T.)

Abstract

In recent years, digital models, and in particular Digital Twins (DTs), have seen a growing interest due to their ability to provide support in the development of more efficient systems and processes. This study presents the preliminary steps taken to develop a DT model for a marine Large Bore Dual-Fuel engine manufactured by Wärtsilä. The correlation between dependend and independent data set variables is presented in order to map the engine behaviour and validate the DT model before becoming operational. The analyses are conducted using the engine in gas mode, operating at 85% of Load (at the nominal speed of 600rpm). This operating point represents the typical target design for constant speed applications. The engine efficiency, emissions and combustion chamber parameters are investigated by varying the air-fuel mixture pressure, timing and duration parameters. Sensitivity analysis presents a tight relation between Nitrogen Oxides and Hydrocarbons (HC) emissions by varying the Scavenging Air Pressure. The HC emission function around the nominal value of the Pilot Fuel Injection Duration reverse its trend, while In Cylinder-Pressure and Combustion Duration functions presents opposite gradients. By advancing the Pilot Fuel Injection timing is shown an increase in Engine Efficiency respect to others input parameters.

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[*] Correspondence: federico.delmondo@dia.units.it (F.D.M.);

1. Introduction

Digital Twins (DTs) are virtual representations of physical systems that allow engineers and operators to monitor and control the assets in a digital environment. With reduced testing costs and shorter test times, DTs are powerful tools for testing and assessing the performance of a system or process in a controlled environment before its actual implementation [1].

The model should ideally be an exact digital copy of the real system, implemented by a data-based approach and updated step by step with the physical system through a direct and reverse exchange of feedback [2–4].

In the maritime industry, DT could be used for instance to predict the behavior of a vessel under different operating conditions, to optimize ship designs, and/or to improve engine performance, efficiency and emissions. The utilization of DT technology within the maritime industry has the potential, among others, to enhance the creation of predictive maintenance strategies, allowing for real-time monitoring of vessel conditions and aiding in decision-making processes to maximize operational efficiency [5].

DT applications to Large Bore combustion engines could be significantly relevant, primarily due to the expensive nature of the testing. Collecting large amounts of engine performance data can be a costly and time-consuming process; the employment of DTs allows simulating and analyzing engine performance in a wide range of conditions, reducing the need for physical testing [6–8].

Differently from others digital models, DTs perform reciprocal data exchange with the physical system, keeping the model up to date, and making it increasingly adherent to the physical system it replicates [9]. Extensive and robust DT models can be used to directly control the behavior of a physical system, e.g. during navigation to maintain the same performance levels when environmental conditions change [10].

IMO regulations [11], port decarbonization [12] and increase of efficiency in sea transport [13], placed a growing interest on DTs development and their critical role that can have in maritime transport.

The final objective of the project, not presented in this paper, is the development of a large bore Dual-Fuel (DF) engine DT, starting from the engine data collected during test bench operations. Subsequent steps include integration with engine automation and subsequent enlargements of the model dataset.

The engine is manufactured by Wärtsilä, a Finnish multinational corporation that provides advanced technologies and lifecycle solutions for marine and energy markets [14].

The purpose of this study is to identify the preliminary stages that lead to the creation of a DT, starting from the generation of the data set to the model input-output sensitivity analysis.

The objective is to describe the behaviour of the engine as a function of parameters that influence substantially the combustion process and use these results to validate the DT model once realised.

2. Brief literature review on Digital Twins

The use of numerical models, machine learning algorithms and, in recent times, DT for predicting the behaviour of large combustion engines is a topic of growing interest in the literature. This section introduces some studies highlighting the stages for a DT development, and some studies proposing DT deployment in marine sector.

The implementation process of a DT model is composed by different project stages. Ariansyaha et al. [15], propose a step by step guideline for the model development. The main stages consist in DT model requirements definition, model implementation, development of system–model communication network and validation.

The study proposed by Wael et al. [16] found three main aspects required by DTs: modeling, interfacing and information exchange. They also pointed out that one of the main attributes of the DT model is the scalability, i.e. the possibility of adding several perspectives to a DT in order to increase its capabilities.

The DT development process is also discussed in [17], starting from the parameters for planning the digital model to the verification and implementation of the model-system control loop. The analysis highlights the need to define each system according to its specific characteristics and parameters, and to focus model development on end-use.

DTs have seen also a growing interest in the field of engine design and management. For example, Bondarenko and Tetsugo [18] developed a DT of a diesel-fuelled engine to predict propulsion system dynamics by improving the cycle-mean value modeling approach for evaluating engine performance and efficiency. DTs are also useful for anomaly detection, failure mode management, tracking of thermal efficiency, emissions prediction, and evaluation of transient response.

For instance, in [19], different mathematical models of reciprocating internal combustion engines are presented and their possible application for DT development is discussed.

A study of Rogers and Ebrahimi [20] investigates a model-based monitoring system for in-cylinder pressure measuring chains in engine control systems. It suggests using a DT concept to observe real-time data from the physical system, compare it with predicted data of the model, and identify faults by early warning and continuous prediction of failure.

A zero-dimensional multi-stage scavenging model is proposed in [21] to simulate the uniflow scavenging process in two-stroke marine engines, which accurately predicts the mass flow rate, temperature, and pressure of air and of residual gases in the different stages by means of a series of thermodynamic equations.

The development of an integrated model for the simulation of the performance of a marine DF four-stroke engine and its control system is proposed by S. Stoumpos et al. [22]. The study focuses on investigating the engine response and identifying its operational limitations during transient operation with fuel switching and load changes. The developed model is able to predict the engine parameters response with sufficient accuracy during the investigated operating cases.

3. Investigated engine description

The engine under investigation is manufactured by Wärtsilä and named “Wärtsilä W8L46DF”. It is a dual-fuel, medium-speed, 8 in-line cylinders engine used in marine propulsion applications with a bore of 460 mm and a stroke of 580 mm that leads to a maximum continuous power output of 9160 kW at 600 rpm. The analysed engine is part of the 46DF engines manufactured by Wärtsilä that are typically employed for the purpose of dual fuel operation, i.e. engines that could be fuelled by natural gas or Diesel [23]. In this analysis the gas mode will take into account.

The engine is even more efficient in gas mode (i.e. when fuelled by natural gas), and its Nitrogen Oxides (NOx) emissions are already at a level that will enable it to meet the upcoming standards posed by maritime sector [24].

It is feasible to switch between operating modes while the engine is in operation without disrupting power generation. If gas supply is cut off, engine switch automatically to Diesel mode operation, i.e. fuelled, in this case, by Marine Diesel Fuel (MDF).

The fuel gas is combined with the incoming air before it enters the cylinder through the inlet valve, and the ratio of air to fuel is regulated using an electronically controlled exhaust waste gate that diverts a portion of the exhaust gases around the turbocharger turbine. The combustion process in the Wärtsilä 46DF engine is controlled by the use of a common rail fuel injection system, which allows for precise control over the amount and timing of fuel injection. The process of combustion begins with a small quantity of pilot fuel oil that is injected into the cylinder through a smaller nozzle of the injector. The amount of pilot fuel that is injected depends on the operating mode and the load of the engine.

In this study, the examined engine was considered as a part of a generator set operating at a constant speed of 600 rpm. Table 1 presents the main engine characteristics and Figure 1 illustrates a simplified scheme of the engine layout test bench and components. The internal cylinder sensor (one for each cylinder) is used to measure the cylinder pressure from which can be derived the amount of heat release. Further details about the engine are available in the manufacturer product guide [23].

Table 1: Main Engine characteristics.

Characteristic	Unit	Value
N° of cylinders	-	8
Cylinder output	kW	1145
N° of valves	-	2 inlet – 2 outlet
Mean Effective Pressure	MPa	2.38
Turbocharger units	-	1

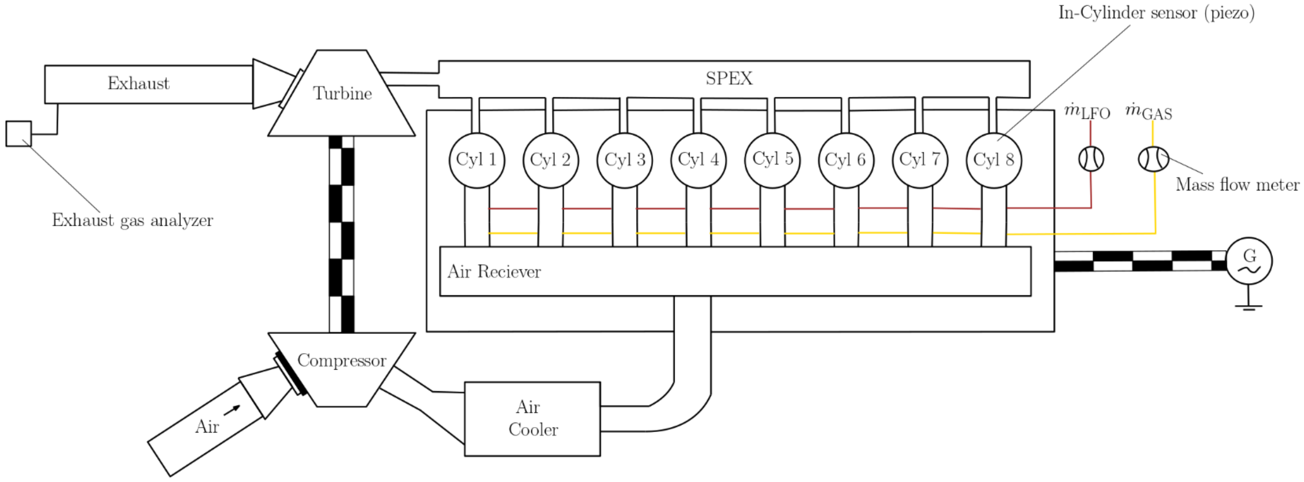

Figure 1: Wärtsilä W8L46DF engine scheme.

4. Experimental data set acquisition

Engine testing is a crucial step in the development of engines. Internal combustion engines are complex machines that require many auxiliary systems and support devices in order to meet the required performance. Advanced control and a data collecting system is necessary for an engine testing facility to carry out the test procedures.

The Wärtsilä UNIC (Unified Controls) system is an embedded control system for Wärtsilä 4-stroke engines that enables real-time data collection from a variety of on board vessel sensors. It consists of a management system that control the start/stop phases, engine safety, fuel management system and speed/load control system as well as charge air, cooling and combustion [25].

Testing provides valuable information about the performance and efficiency of an engine under various operating conditions.

Wärtsilä's engines are tested in engine test rooms under controlled environmental conditions varying, among others, operating parameters such Scavenging air pressure, Pilot Injection Timing, Pilot Injection Duration, and Load to evaluate engine behaviour characteristics. The test typically takes about 10 minutes and the data collection frequency relies on the variation over time of the acquired quantity. Failures of the data acquisition system and relative components can introduce errors during data collection operations. This aspect will be taken into account by introducing a screening process in order to avoid the presence of errors points during the data set generation.

5. Data set description

Generating an accurate and reliable data set is critical for the development of any engine model. As mentioned before, the input variables of the model are related to the parameters that control the ignition process (e.g. Pilot Injection Timing) and others that influence the combustion process (e.g. Ambient Pressure). Conversely the output variables of the model includes: engine emissions, engine efficiency, combustion duration, and turbocharger operating data. It is worth noting that a limited number of variables were chosen the first model release, even knowing that additional variables could be included to improve the accuracy of the model.

The collected quantities are necessary to describe the engine's behavior, although some may have a lower impact and may be correlated with other quantities, while others are of fundamental importance.

The independent and dependent variables are extracted from the files containing the quantities collected during engine testing and a screening methodology was used to check for the presence of outliers points in the collected data. The data, collected at constant speed, are provided for different engine loads, here the nominal operating condition of Wärtsilä 46DF engine (85 % Load), have been analyzed.

The reported study presents the analysis of some dependent and independent variables considered for the model implementation. The analyzed input variables are the Pilot Fuel Injection Timing, Scavenging Air Pressure and Pilot Fuel Injection Duration; the target variables are: NOx and Hydrocarbons (HC) emissions, Engine Efficiency, In-Cylinder Pressure and Combustion Duration.

Pilot injection timing is a term used in Diesel and DF engines to describe the timing at which a small amount of fuel is injected into the combustion chamber before the main injection event [26].

Pilot Fuel Injection Timing is typically specified as Crank Angle degrees before Top Dead Center (°CA bTDC), which refers to the position of the piston in the cylinder before it reaches the top of its stroke.

The timing of the Pilot Injection is crucial in achieving optimal combustion and engine performance. If the Pilot Injection is too early fuel air mixture encounter low pressures and temperatures, which leads to poor fuel evaporation and wall wetting problems, resulting in incomplete combustion and increased emissions. On the other hand, if the Pilot Injection is too retarted, there may not be enough time for the fuel to ignite and for the flame front to propagate, resulting in a less efficient combustion process [27].

When the diesel fuel injection is significantly advanced, the ignition delay time is increased, which helps to create a more homogeneous mixture, leading to a faster combustion and higher cylinder pressure peaks occurring closer to the top dead center (TDC). Advancing the Pilot Injection Timing, the ignition delay can be extended, the gas-air mixture can mix with the pilot fuel more homogeneously, resulting in more fire points and an increase of engine efficiency [28,29].

In this study, the Engine Efficiency is described as the inverse of the Break Specific Energy Consumption (BSEC) kJ/kWh that is a measure of a engine’s fuel efficiency that generates rotational or shaft power by burning fuel [30].

$$\eta = \frac{1}{BSEC} \; [\%] \tag{1}$$

The air receiver is the air that the compressor of the turbocharger draws from the engine room, through an air filter and its also called scavenging air. From the turbochargers, the air is led via the charging air pipe, through air coolers and scavenge air receiver to ports of the cylinder liners [31].

The scavenging process is responsible for delivering fresh air to the combustion chamber and removing combustion gases in the cylinder [32].

The scavenging process affects the air pollution and its operation is strictly controlled and regulated [33]; it improves the combustion efficiency due to a better air/gas exchange [34].

Excessive and low Scavenging Air Pressure can lead to reduced engine performance, increased emissions and engine damage.

NOx are formed in the combustion chamber, due to the combustion reaction of nitrogen and oxygen in high pressure and high temperature conditions. One of the most used methods to reduce NOx emission consists in reducing the peak combustion temperature and combustion duration [35].

In contrast to NOx emissions, higher pressure causes more unburned HC to escape from the exhaust valve, resulting in higher hydrocarbon emissions. During the valve overlap period, as the scavenging of the combustion chamber takes place, part of the fresh mixture could directly flow from the intake to the exhaust valve, so that the embedded unburned fuel is emitted [36]. In some cases, due to the cooling effect that engine walls have on combustion process, the heat transfer to the walls can be significant enough to extinguish the flame, preventing it from completing its combustion process [37]. These are the main phenomena that most influence the increase in HC emissions.

When the Pilot Injection Duration is increased, it can improve combustion stability and reduce the ignition delay of the main injection. This is because the pilot injection serves to initiate the combustion process, allowing the fuel to start burning earlier and reducing the overall CD [38].

The CD can be calculate from other quantities like the Heat Release (HR) °CA with the following correlation:

$$CD = HR_{90\%} - HR_{5\%} \quad [°CA] \tag{2}$$

HR in a combustion engine refers to the energy released during the combustion process; the HR evaluation takes into account the chemical energy of the fuel, the work of the piston, the heat transferred to the walls of the combustion chamber and the flow across the system boundaries [39].
HR 90% is a measure of the combustion process in an internal combustion engine. It refers to the crank angle at which 90% of the fuel's heat energy is released during the combustion process [40].
However, the effect of Pilot Injection Duration on CD can depend on several factors, such as engine load, fuel properties, and combustion chamber design.

6. Methodology

In this work a local sensitivity analysis, based on data set points, is carried out to evaluate the effects of small variations in engine dependent parameters over independents ones.
A limited set of variables is presented here in the analysis; however, additional variables will be included for the model development.
By conducting local sensitivity analysis, analysts can identify critical variables and prioritize resources for further investigation or control. The analysis determines how target variables are affected based on changes in other variables known as input variables, and is a valuable tool for assessing the stability and realibility of a model [41].
By analyzing the sensitivity of the engine to these variations, a deeper understanding of the system's dynamics is reached and this helps in a better evaluation of the DT model once is realised.
In particular three sensitivity indeces are defined:

$$\boldsymbol{SI = \frac{f(X_{max}) - f(X_{min})}{X_{max} - X_{min}}} \tag{3}$$

$$\boldsymbol{SI_{left} = \frac{f(X_{nom}) - f(X_{min})}{X_{max} - X_{nom}}} \tag{4}$$

$$\boldsymbol{SI_{right} = \frac{f(X_{max}) - f(X_{nom})}{X_{max} - X_{nom}}} \tag{5}$$

where X_{min}, X_{nom} and X_{max} are respectively the minimum, the nominal (standard) and the maximum values of the input parameter X under analysis, and $f(X_{min})$, $f(X_{nom})$ and $f(X_{max})$ are the values of target variable $f(X)$ in those points. Here X is normalised with respect to X_{nom} and $f(X)$ are normalised with respect to $f(X_{nom})$. SI will give us the sensitivity of $f(X)$ respect to X in the interval around the nominal value of the input parameter. SI_{left} is an approximation of left derivative, giving the trend of output variable when the input variable decrease with respect to the nominal value. SI_{right} is an approximation of right derivative, giving the trend of output variable when the input variable increase with respect to the nominal value. The sensitivity analysis will be reassessed in the validation phase of the DT model to verify if the engine predicted behavior, in the proximity of the considered operating points, reflects the trend measured by installed sensors.

7. Results

A sensitivity analysis is conducted close to the nominal point (standard engine settings) in order to carry out a subsequent assessment of the DT results. The analyses are conducted reffering to data with the engine in gas mode, operating at 85% of Load (at the nominal speed of 600rpm). This operating point represents the typical target design for constant speed applications. The following figures presents some of the normalised data available for the analysis, not all the variablesf the model are presented. In particular, Figure 2 and 3 shows, respectively, the effects of Pilot Fuel Injection Timing over Engine Efficiency and In-cylinder pressure. Figure 4 and 5 express NOx and HC emissions as functions of Scavenging Air Pressure.

Figure 6 shows the effects of Pilot Fuel Injection Duration over the Combustion Duration.

The data analysis shown that advancing the Pilot Injection Timing can result in an improvement in combustion and aincrease Internal Cylinder Pressure, leading to higher Engine Efficiency.

This happens because as fuel injection advances, there is a better air-fuel mixture and higher in-cylinder pressure, which leads to a better ignition of the fuel, thus increasing engine efficiency.

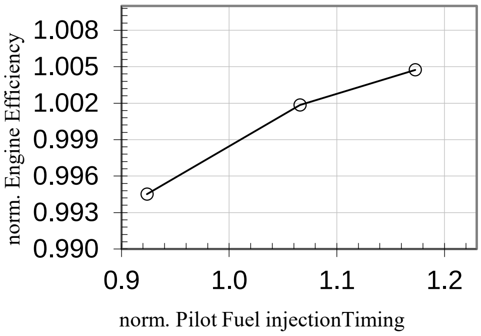

Figure 2: Normalised Engine Efficiency over normalised Pilot Fuel Injection Timing.

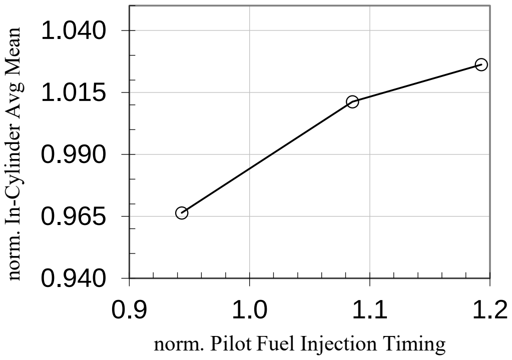

Figure 3: Normalised In-cylinder pressure over normalised Pilot Fuel Injection Timing.

Additionally, the pressure in the receiver was found to be a critical parameter related to the air fuel equivalence ratio, and an increase in the Scavenging Air Pressure can result in a significant reduction of NOx emissions due to leaner combustion, as well as an increase in HC emissions.

The optimal Scavenging Air Pressure depends on the given engine Load, and is determined by factors such as the engine's stroke-to-bore ratio, piston speed, and combustion chamber geometry.

These factors influence the scavenging air flow rate and velocity, which can affect the engine's thermal efficiency, power output, and emissions.

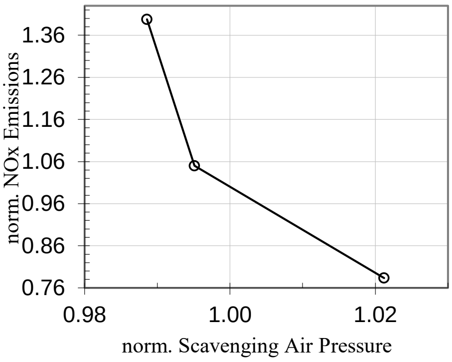

Figure 4: Normalised NOx emissions over normalised Scavenging Air Pressure.

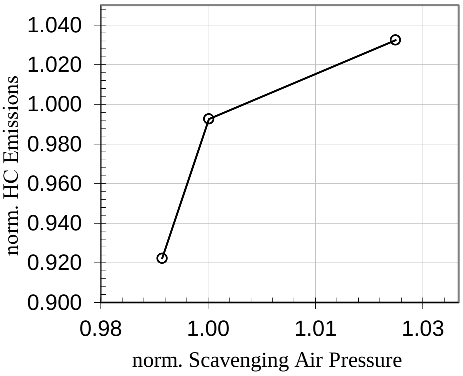

Figure 5: Normalised HC emissions over normalised Scavenging Air Pressure.

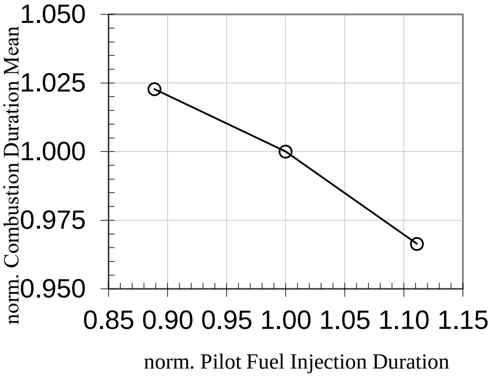

Figure 6: Normalised Combustion Duration over normalised Pilot Fuel Injection Duration.

Increasing the Pilot Injection Duration by 25% reduces combustion duration by about 6%, which is due to a reduced ignition delay that leads to a faster combustion.

Table 2 shows the relative variation of the dependent variables aroud the nominal value, computed as $(\mathbf{max}\ \boldsymbol{f}(\boldsymbol{x}) - \mathbf{min}\ \boldsymbol{f}(\boldsymbol{x}))/\boldsymbol{f}(\boldsymbol{x}_{\boldsymbol{nom}})$, where *x* and *f(x)* are dimensional variables.

Table 2: Relative variation of output parameters around the nominal value.

Output	Variation %
Comb. Duration mean	16.11
Engine Efficiency	0.02
Hydrocarbons Emissions	11.75
NOx Emissions	61.43
In-Cylinder Pressure mean	8.07

Table 2 hilights that the target variable with the higher variation is NOx emissions. It is relevant to assess which input variables most influence this parameter.

Table 3 presents the value of *SI*, defined in equation (3), which identify how much the input variables affect the output variables. Table 4 and Table 5 give the values of SI_{left} and SI_{right} presented in equation (4) and (5), respectively. The statement n.a refers to “not available” data.

Table 3: *SI* index.

Input/Output	Pilot Fuel Injection Timing	Pilot Fuel Injection Duration	Scavenging Air Pressure
Comb. Duration mean	n.a.	-0.37	0.66
Engine Efficiency	0.35	0.27	-0.39
Hydrocarbons emissions	-0.60	0.25	0.97
NOx emissions	n.a.	0.40	-1
In-Cylinder Pressure mean	0.75	0.57	-0.68

In Table 3, *SI* index is equal to -1 for NOx emissions and 0.97 for HC emissions varying the Scavenging Air Pressure. Lowering HC means increasing NOx and vice versa, therefore finding a compromise between this two opposite targets is crucial to ensure compliance with emission regulations and minimize the environmental impact of marine vessels.

Table 4: SI_{left} index.

Input/Output	Pilot Fuel Injection Timing	Pilot Fuel Injection Duration	Scavenging Air Pressure
Comb. Duration mean	n.a.	-0.15	0.48
Engine Efficiency	0.19	0.22	-0.29
Hydrocarbons emissions	-0.24	-0.06	0.68
NOx emissions	n.a.	0.27	-0.65
In-Cylinder Pressure mean	0.42	0.35	-0.45

Table 5: $\mathrm{SI}_{\mathrm{right}}$ index.

Input/Output	Pilot Fuel Injection Timing	Pilot Fuel Injection Duration	Scavenging Air Pressure
Comb. Duration mean	n.a.	-0.22	0.17
Engine Efficiency	0.16	0.05	-0.09
Hydrocarbons emissions	-0.36	0.32	0.28
NOx emissions	n.a.	0.13	-0.35
In-Cylinder Pressure mean	0.33	0.22	-0.23

In particular Table 4 and 5 identifies a decreasing correlation between this two parameters. By reducing the Scavenging Air Pressure with respect to *Xnom* there is an increase in NOx emissions, at the other side, there's a decrease being $|SI_{right}|<|SI_{left}|$.
The HC emissions evaluation around the nominal point of the Pilot Fuel Injection Duration in Table 4 and 5, underline a change in the function trend with a reduction in emissions before the nominal value and an increase afterwards.
All the three considered input values, have similar quantitative influence over the In-Cylinder Pressure with a slightly more influence of the Pilot Injection Timing like introduced before in the text.
Around the nominal value of Pilot Fuel Injection Duration and Scavenging Air Pressure, Tables 4 and 5 show a change in the slope of the function over the Engine Efficiency.

8. Conclusions

The operation of an engine is influenced by multiple parameters and therefore the analysis of operations at different conditions can be complex. Moreover, by varying a parameter, this can influence several operating characteristics and may be necessary evaluate the change of other settings (e.g. the influence of Load over Scavenging Air Pressure).
In the case discussed here, the W8L46DF engine behaviour is strongly influenced by the environmental conditions and the trends shown here are the results of tests performed in the same day by investigating operating condition correspondent to 85% of Load and the engine running in gas mode.
With the same engine parameters, evaluating tests on different days, which are influenced by slight variations in environmental conditions, lead to a high difference in sensitivity analysis with a greater difficulty in identifying the expected behaviour.
A data-driven Digital Twin (DT) model can be more effective in capturing these variations and replicating the engine behaviour when subjected to small conditions variations.
These findings will support the development of the DT model and enable post-processing analysis of the model's operation. The experimental data suggests that some relations between engine settings and performance outputs are dependent on the engine operating point, indicating a non-linear correlation between independent and dependent variables.
To address this non-linear correlation, algorithms can be effectively employed to reduce uncertainties in the assessment of engine performance indicators by exploiting large data sets. Therefore, the use of Machine Learning algorithms in future studies could provide valuable insights into the complex interactions between engine variables and performance outputs, leading to more efficient and environmental-friendly engine design, testing and validation.

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