ABSTRACT

To achieve a green transition in construction, all parts of the building lifecycle should be examined for potential emission reductions. Historically, much effort has been placed on operational energy of facilities. Recently, the focus has been supplemented with an embodied energy focus, looking at the production of materials and the circular economy aspect of reuse and recycling. However, the construction process itself has, until now, attained little focus in the green transition. At the same time, construction is inefficient and wasteful, as research shows that only 33% of working time is value-adding, resulting in longer construction duration. Longer duration requires more operation of machines, transportation, and daily running of construction sites. These non-value-adding operations require energy and emit unnecessary emissions. Consequently, today’s tacit acceptance of time and cost overruns is effectively the same as an industry’s acceptance of unnecessarily large emissions. To reduce construction emissions from equipment-related operations, a closer to real-time monitoring of construction equipment’s efficiency and their emissions is needed. This research’s vision aims to minimize emissions by optimizing the site layout and improving planning, hence reducing construction machine working hours. Our method incorporates real-time sensory data (mainly position, NOx, and particle emissions from internal combustion engines) and information modeling to achieve this novel agenda. This paper presents a small-scale sensor technology called SEMS (Simplified Emissions Measurement System) capable of rapidly measuring such emission data. Preliminary findings from experimental testing identify potentials and future methodological considerations how such data can be applied in information management and decision making.

INTRODUCTION

The energy consumption for establishing, maintaining, and operating buildings accounts for approximately 39% of the world’s total carbon dioxide (CO₂) emissions (Abergel et al., 2017). The construction industry is also responsible for a significant amount of greenhouse gas (GHG) like carbon monoxide, nitrogen oxide, and criteria air pollutants (CAP) like particle emissions. To achieve a full green transition in construction, all phases of the building lifecycle should be examined for possible emission reductions. Life cycle energy consumption of the built environment can be divided in (a) Operational Energy (OE) – energy used for the occupation/operation of buildings (including heating/cooling, ventilation, hot water, etc.); (b) Embodied Energy (EE) - the energy used for the construction, maintenance, renovation, and demolition of the built environment (Cabeza et al., 2014). Historically, the OE accounts for about 80% of the total energy use (Sartori and Hestnes, 2007). Therefore, the analysis of the OE and its related carbon emission has dominated energy research for many years. However, recently the
emissions due to Embodied Energy (EE), i.e., the energy used for extraction of raw materials, the processing into building materials, and on-site construction have gained attention. Currently, the built environment continues to grow in size, energy use, and emission.

To achieve net-zero carbon building stock by 2050, the International Energy Agency (IEA) estimates that building CO\textsubscript{2} emissions need, by 2030, to fall by 50%. This equates to building sector emissions falling by around 6 per cent per year until 2030, which is close to the 7 per cent decrease in 2020 global energy sector CO\textsubscript{2} emissions due to the pandemic. Worryingly, the rate of annual improvement is decreasing. It, in fact, halved between 2016 and 2019. To get the construction sector back on track to achieving net-zero carbon by 2050, all actors across the building value chain need to increase decarbonization actions and their impact by a factor of five.

Several technologies for energy and emissions reduction are ‘off the shelf’ solutions in other industries and sectors, however still not widespread in construction, and particularly not on construction sites. One example is electrification of large construction machinery, also called non-road mobile machinery (NRMM). While the worldwide penetration of electric vehicles for on-road use (i.e., cars and busses) has increased from 0.7 million in 2015 to 4.8 million in 2019 (IEA, 2020), the same trend is not seen on construction sites for NRMM. Today, almost all construction machinery runs on diesel or petrol fuel. Uses of electric powered NRMM are limited and too expensive today (Lajunen et al., 2018) as shown in the Bellona database of emission-free construction equipment that contains less than 100 registered electric NRMM (Bellona 2021). In fact, the term “emission-free” is wrong, as the source of emissions from electric-powered vehicles is just shifted to a power plant that replaces the fuel type. Nonetheless, so called “emissions-free construction sites” do exist and a Norwegian study reports a construction site running 100% on electric-powered equipment. This saved an approximate 35,000 liters of diesel, equivalent to 92,500 kilograms of carbon emissions (DNV, 2019).

Today, around 10% of the total emission in construction originates from construction sites (Yokoo and Yokoyama, 2016), i.e., fuel for large construction equipment and electricity for hand-powered tools, lighting, heating, dehumidifying, and sheds. According to Huang et al. (2018), around 50% of all energy in the built environment uses Diesel. Particular heavy construction equipment and generators for heating and dehumidification consume large amount of fossil fuel (DB, 2020).

The Danish Government has an ambitious plan for its green transition of the built environment and construction. An expert group with stakeholders from all parts of the construction value chain came up with 27 suggestions to meet the 2050 goals of becoming carbon neutral (DB, 2020). The potential of CO\textsubscript{2} reductions from construction sites was estimated to 850,000 tons CO\textsubscript{2} per year for Denmark. Six main initiatives were proposed to combat this (Table 1), of which (a) small construction machines (<75 kW) may only be powered by electricity/battery from 2025 and (b) large machines (>75 kW) may only be powered by electricity, batteries or fossil-free fuel, such as hydrogen, by 2030 at the latest. For a transitional period leading up to 2030, a strategy focuses on removing barriers for implementation (e.g., price and tax for CO\textsubscript{2} neutral fuel type).

<table>
<thead>
<tr>
<th>Initiative</th>
<th>Yearly CO\textsubscript{2} saving potential in DK</th>
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<tbody>
<tr>
<td>Electric and district heating of the site</td>
<td>35,000 tons per year</td>
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<tr>
<td>CO\textsubscript{2} free dehumidification and heating</td>
<td>75,000 tons per year</td>
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<tr>
<td>Fossil-free production equipment at the site</td>
<td>275,000 tons per year</td>
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<tr>
<td>CO\textsubscript{2} accounts (as new volunteer sustainability class)</td>
<td>35,000 tons per year</td>
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<tr>
<td>Less construction waste</td>
<td>330,000 tons per year</td>
</tr>
<tr>
<td>Optimized planning and layout</td>
<td>100,000 tons per year</td>
</tr>
</tbody>
</table>
BACKGROUND

Emission regulations for heavy construction equipment. Emissions from NRMM are regulated in the European Union (EU) via directives that include emission standards. The EU standards contain threshold values of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) (of which this research focuses on PM and NOx, as the two dominant concerns relating to heavy construction equipment). The standards are harmonized in Europe, thus its member states have to implement but cannot further tighten the set limits. During the last 25 years, the emission thresholds for NRMM have been tightened several times, reflected in Stages I to V. Each stage has a year of approval and the “birth year” of a machine’s engine relates to the stage that must be confirmed. The development is depicted in Figure 1.

Emission measurement in laboratory and field applications. The EU threshold values are based on laboratory test where the engine is stripped from the machine and tested in a controlled environment. The test procedure is governed by ISO Standard No. 8178 (ISO, 2021). Threshold values are based on a weighted average of up to 11 laboratory tests (NRSC - non road steady cycle). Individual load points may exceed the emission threshold as long as the weighted average stays below the threshold stated in the EU regulation 2016/1628 (EU, 2016). The weighing factors to calculate the weighted averages depend on the machine type, as stated in ISO 8178. One would expect, for example, in compliance testing outside of a laboratory, the values to range, as the engine is built in the machine, and furthermore, age, wear, and tear may impact its performance over time.

![Figure 1. EU NRMM emission thresholds for 18-560 kW diesel engines. Stage V includes engines sizes above 560 kW and below 56 kW (not depicted) (modified, Dieselnet, 2021).](image)

Construction equipment stock and related emissions in Denmark. Denmark’s stock of NRMM in construction is based on registration numbers. Figure 2 shows a slight increase in total numbers since 1985. Machines are categorized by their stage according to EU 2016/1628. Until today, a few NRMM are regulated on Stage I as the machines were registered before 1999. However, only 7.5% of all Danish NRMM are on Stage V and 54% are still on Stage III (Nielsen et al., 2019).

Related research and development. Surprisingly few studies exist that focus specifically on construction equipment emissions. In their study on concrete delivery trucks, for example, Artenian et al. (2010) explain that combustion of fossil fuels for its transportation and industrial production processes in construction significantly contributes to global climate change. However, while the focus was on optimizing delivery routes from concrete batch plants to construction sites
by avoiding congested roads in a large Canadian metropolitan area, simulation rather than real-life monitoring was the method used for raising such argumentation. Similarly, Ahn et al. (2010) focused on discrete-event simulation based on engine data from manufacturers to model emissions in earthwork construction operations. The limitations of existing simulation models to quantify construction emissions is that they are highly dependent on the emission factors of construction machinery. As such is the most significant contributing source to emissions the type of engine (e.g., kW, production year) that is built into the machine. The reliability of estimates largely depends on the accuracy of the predicted productivity and utilization rates of the equipment in its operation. These models are quite theoretical and do not provide any real-life construction emission data as they apply predetermined emission factors determined in laboratory tests.

![Stock of NRMM in Denmark per stage (Nielsen et al 2019)](image)

Figure 2: Stock of NRMM in Denmark per stage (Nielsen et al 2019).

Therefore, a more recent study on on-road light duty diesel vehicle emissions in London tested significant differences between real-world NOx emissions compared with results from laboratory based regulatory tests. Desouza et al. (2020) show a quantification of the real-world tail-pipe NOx, CO₂, and particle matter emissions, for 30 of the most commonly used construction machines under normal working conditions. A portable emissions measurement system (PEMS), UN-ECE R-49 compliant, was used. Since then, Guo et al. (2020) raise concerns that pollutant emissions from non-road mobile construction machinery would contribute from 29% (now) to somewhere between 34-61% in 2025. This is a reason why research like Bemer and Subra (2017) developed new methods to measure particulate emission in terms of particle number and particle mass. The methods were investigated in different configurations: with and without removal of volatile compounds by thermo-dilution, with and without diesel particulate filters. Their work shows the reduction of emissions of soot particles contained in the exhaust gases of NRMM diesel engines.

For the past decade, numerous suppliers in the automotive sector explored the more widespread use of emission measurement systems. Some products failed appearing in the market because laws do not demand it. Others lacked understanding the usefulness of applications of thereof. For example, while passenger cars will in the coming years be subject to a corresponding Real Driving Emissions (RDE) requirement, construction machinery, and especially older versions, may not be targeted. Winther (2020) makes therefore an important observation that the periodic inspection of construction machines has not been introduced by EU law yet (only for vehicles participating in public traffic). Shao and Dallmann (2016) explain that newly manufactured construction machines...
have to reach the Stage V standards, adopted by the EU Parliament in July 2016 and published in the Official Journal of the EU as Regulation (EU) 2016/1628 in September. This regulation tightens older restrictions on non-road engines and equipment and sets stricter limits on emissions of particulate matter (PM). These changes, along with newly proposed particle number (PN) limits forced manufacturers to equip non-road engines of between 19 kW and 560 kW with diesel particulate filters. Other developments are underway to electrify smaller construction machinery.

OBJECTIVE AND METHOD OF TESTING SEMS

As a result of a number of revelations of errors and omissions regarding laboratory measurements of car emissions, the past few years have seen an increased international focus on measuring real emissions from vehicles. Trucks and buses, for example, are already subject to a so-called PEMS requirement for measuring emissions under realistic conditions (Portable Emission Measurement System). PEMS measurement comes at the cost of a single measurement unit of about 300,000 €. PEMS is quite large in size, requiring experts to install it, for example technology in the size of 100x50x40 cm exterior to the vehicle. PEMS creates highly accurate integrated advanced gas analyzers, exhaust mass flow meters, weather station, Global Navigation Satellite System (GNSS), controller area network (CAN) connection to other vehicle data, HC, CO, CO₂, NOₓ [or NO + NO₂], and PM (particulate matter).

Compared to PEMS, SEMS is a compact, inexpensive (a few thousand €), portable emission meter that can be used by a wide range of vehicles, incl. NRMM in construction. For a temporary measurement it can be installed in less than 20 minutes with safe access to the exhaust pipe of the machine (Figure 3). Various sensors inside SEMS measure timestamped data of emissions and other information, incl. O₂, NOₓ, Particulate Matter (PM) or Particulate Number (PN), pressure, temperature, position using centimeter GNSS, velocity, and the total amount of fuel consumption. CO₂ is calculated based on the O₂ measurement: CO₂=13.54−0.6463*O₂. SEMS streams all of the data run-time into a cloud storage where, for now, processing happens after data gathering.

The objectives of this research are: (a) to test if SEMS offers a robust, economical and user-friendly (portable and quick to install/remove) emission data transmitter for Stage IV and lower, (b) convert raw sensor data into meaningful information that helps understand if the investigated construction machine meets or exceeds the requirements, and (c) outline in form of a visionary concept how it can assist making construction equipment operations greener.

The next information presented in this paper is limited to a very small data sample (a few hours) that was recorded with SEMS technology from Techno-Matic A/S, Denmark in a construction laydown yard of Aarsleff Røtetechnik in Aarhus, Denmark in May 2021. The test procedure foresaw the SEMS technology that was about to be used in the validation to be first verified. This helped the general understanding that the error of SEMS in measuring NOₓ and PM compared to the more accurate PEMS is not significant. The verification was performed by the assistance of the Danish Technological Institute, however, on non-construction vehicles (e.g., bus, passenger car). For this purpose, Winther (2020) produced a detailed report that this is the case with some exceptions (as explained later in the presentation of the raw data and the discussion of the results). Our work then was able to implement and validate the system for the first time on NRMM in construction.

IMPLEMENTATION AND PRELIMINARY RESULTS

A field test was conducted with a Volvo wheel loader L350F with a mass of 56.3 tons and a 397 kW engine. The machine was manufactured in 2015, however, the engine model was an older
version, thus the authorization is a Stage III EU 2016/1628. The following explains the SEMS implementation in a realistic construction environment. Two samples were drawn from the total data set that was gathered. The objective was to demonstrate if the machine complies with the Stage III requirements. This includes a conversion of the measurement data in order to have identical units as shown by the EU regulation.

Figure 3: (a) Installation of SEMS, (b) wheel loader L350F, (c) equipment trajectory, and (d) velocity [km/h] and NOx [g/kWh] over time [s] (red areas indicate limit exceeded)

Data sample 1 (staying below required limit). The wheel loader is slowly driving with 15 km/h at timestamp: 274s. The exhaust temperature is 106.1°C with a pressure of 7.5 kPa. The emissions are NOx = 292 ppm, PM=0 and the CO₂ concentration is 5.98%. It should be mentioned that PM likely is not zero, but SEMS can only measure PM values above 2 mg/m³. Thus, only the NOx is compared to the Stage III threshold values [g/kWh]. The SEMS measurement for NOx is in ppm and thus requires the following steps to convert the values into units of g/kWh. The NOx content of a diesel engine can be calculated based on Equation 1.
\[ NOx = \frac{C \cdot BSFC}{\rho} \]  

Where: \( NOx \) = NOx content [g/kWh]; \( C \) = NOx concentration in diesel [g/l]; BSFC = Brake-specific fuel consumption of the diesel engine [g/kWh]; and \( \rho \) = the density of diesel [g/l]. The NOx concentration, \( C \), has to be calculated based on the input values NOx [ppm] and \( \text{CO}_2 \) [%] measured in the experiment (Equation 2).

\[ C = \frac{NOx \cdot M_{NOx}}{CO2 \cdot 10,000 \cdot M_{CO2}} \cdot CC \]  

Where: \( C \) = NOx concentration in diesel [g/l]; \( NOx \) = NOx particles measured [ppm]; \( M_{NOx} \) = Molecular weight of NOx [g/mol]; \( \text{CO}_2 \) = \( \text{CO}_2 \) concentration measured [%]; \( M_{CO2} \) = Molecular weight of \( \text{CO}_2 \) [kg/mol]; and \( CC \) = Carbon content of fuel [kg/l]. When \( NOx = 292 \) ppm and \( \text{CO}_2 = 5.98\% \), the NOx concentration in Diesel is calculated based on Equation 2.

\[ C = \frac{292 \text{ ppm} \cdot 4 \frac{g}{mol}}{5.98\% \cdot 10,000 \cdot 0.044 \frac{kg}{mol}} \cdot 2.65 \frac{kg}{g} \cdot l = 13.53 \frac{g}{l} \]

The carbon content of diesel fuel is estimated to \( CC = 2.65 \), which is an average number for Danish ambient conditions (e.g., weather). Then the NOx content can be calculated based on Equation 1.

\[ NOx = \frac{13.53 \frac{g}{l} \cdot 230 \frac{g}{kWh}}{837 \frac{g}{l}} = 3.72 \frac{g}{kWh} \]

The measured NOx content of 3.72 g/kWh can now be compared to the threshold value of a Stage III machine with a 397 kW engine, which equals 3.81 g/kWh. Thus, the measured emission is below the limit in Sample 1.

**Data sample 2 (exceeding required limit).** In another situation, the same wheel loader is driving fast 26.8 km/h at timestamp: 513s. The exhaust temperature is 146.2°C with a pressure of 15.6 kPa. The measured emissions are \( NOx = 410 \) ppm, \( \text{PM}=0 \), and the \( \text{CO}_2 \) concentration is 7.14%. According to Equation 2, the NOx concentration in Diesel (\( CC = 2.65 \)) is 15.91 g/l and subsequently the NOx = 4.37 g/kWh. This value is again compared to the threshold value. Since it is still the same machine, the measured emission is above the limit. As mentioned before, it was expected that the emission can exceed the threshold at certain load points, as this is also accepted by the ISO 8178, and due to the fact that the engine is used and has wear and tear.

**CONCLUSION**

As statistics show, internal combustion engines from non-road mobile machinery in construction contribute in large amounts to emissions (e.g., NOx and particle emissions). However, these values are estimates based on emission factors from engine data that manufacturers provide and thus may not portray the true picture. Choosing a Simplified Emission Measurement System (SEMS) provides real emissions data of construction machinery in live work environments. While its application may vary from short-term inspection to long-term monitoring assignments, once the data SEMS provides is processed and compared against regulations, the information can contribute...
to new, more reliable evidence on the environmental impact of construction machinery. The SEMS and the first research exploration on construction machinery in a realistic construction work environment demonstrate the feasibility of the approach. While SEMS need to be tested over an extended time period to measure its full validity, future work might also be directed towards observing change in work behavior or fuel consumption, for example, measuring the impact of newly gained information once given to machine operator or construction site layout engineers.

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