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Challenges of Micro/Mild Hybridisation for Construction Machinery and Applicability in UK

D.Q. Truong [a,*], J. Marco [a], D. Greenwood [a], L. Harper [b], D.G. Corrochano [b], J.I. Yoon [c]
[a] *Warwick Manufacturing Group (WMG), University of Warwick, Coventry CV4 7AL, UK*
[b] *JCB, Rocester, Straffordshire ST14 5JP, UK*
[c] *Korea Construction Equipment Technology Institute (KOCETI), Gunsan 573-540 Sandan-ro 36, Korea*
[*] *Corresponding author. Tel.: +44 24765 74902. Email address: q.dinh@warwick.ac.uk (D.Q. Truong)*

ABSTRACT

In recent years, micro/mild hybridisation (MMH) is known as a feasible solution for powertrain development with high fuel efficiency, less energy use and emission and, especially, low cost and simple installation. This paper focuses on the challenges of MMH for construction machines and then, pays attention to its applicability to UK construction machinery.

First, hybrid electric configurations are briefly reviewed; and technological challenges towards MMH in construction sector are clearly stated. Second, the current development of construction machinery in UK is analysed to point out the potential for MMH implementation. Thousands of machines manufactured in UK have been sampled for the further study. Third, a methodology for big data capturing, compression and mining is provided for a capable of managing and analysing effectively performances of various construction machine types. By using this method, 96% of data memory can be reduced to store the huge machine data without lacking the necessary information. Forth, an advanced decision tool is built using a fuzzy cognitive map based on the big data mining and knowledge from experts to enables users to define a target machine for MMH utilization. The numerical study with this tool on the sampled machines has been done and finally realized that one class of heavy excavators is the most suitable to apply MMH technology.

Keywords: Hybridisation; micro/mild hybrid; construction machine; data mining; decision tool

Contents

Nomenclature

ASBBS	Advanced string-based bubble sort
BSA	Belted starter alternator
CAN	Controller area network
CAP	Criteria air pollutants
DOH	Degree of hybridisation
DP	Dynamic programming
ECU	Electronic control unit
EM	Electric motor
EMS	Energy management strategy
FCM	Fuzzy cognitive map
GA	Genetic algorithm
GHG	Greenhouse gas
GPS	Global positioning system
HDT	Hydrodynamic transmission
HEM	Hybrid electric machine
HEV	Hybrid electric vehicle
HST	Hydrostatic transmission
ICE	Internal combustion engine
ISA	Integrated starter/alternator
MMH	Micro/mild hybridisation
OEM	Original equipment manufacturer

OPT	Optimisation method
RB	Rule-based method
SOC	Battery state of charge
P_{EM}	Electric motor power
P_{ICE}	Engine power
Fl_{full}^{event}	Total fuel consumed by engine for each event
Fl_{idle}^{event}	Total fuel consumed by engine whilst idling for each event
T_{full}^{event}	Total engine working time for each event
T_{idle}^{event}	Total engine run time whilst idling for each event
n_E^{band}	An engine speed band limit
τ_E^{band}	A engine torque band limit
Fl_{rate}^{band}	Actual fuel consumption rate of engine for a set of engine toque-speed band
Fl_{act}^{band}	Actual total fuel consumed by engine for a set of engine toque-speed band
T_{act}^{band}	Total working time of engine for a set of engine toque-speed band
η_{act}^{band}	Actual engine overall efficiency for a set of engine toque-speed band
E_{rate}^{th}	Theoretical engine rating power
Fl_{rate}^{th}	Theoretical fuel consumption rate of engine
η_{th}^{E}	Theoretical engine overall efficiency
C_i or A_i	FCM concept i^{th}
w_{ij}	FCM weight representing relationship between nodes i^{th} and j^{th}
W	FCM weight matrix
f	FCM activation function
x_i	Value of FCM concept i^{th}
λ	FCM steepness parameter
α_i	MMH cost factor i^{th}

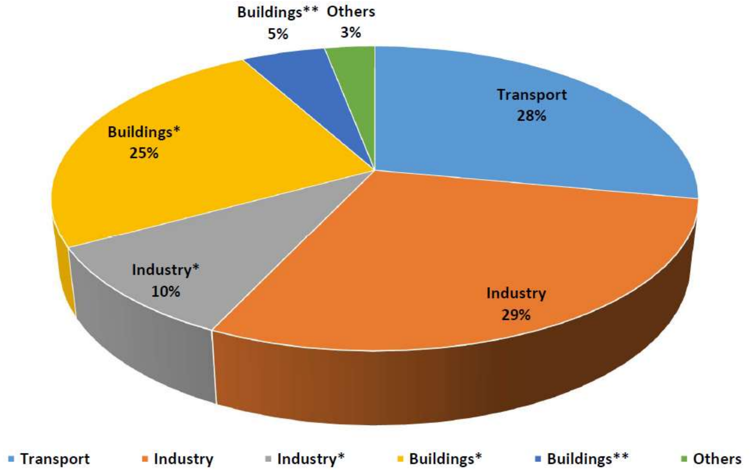
1. Introduction

The continuous deterioration of the world environment has been being a very urgent issue which significantly affects the health of human and other organisms. The reason majorly comes from the uncontrolled emissions of the hazardous and polluting elements to the atmosphere. And burning of fossil fuels in both on-road and off-road sectors is certainly recognized as one of the most significant contributing factors [1]. In addition, the rapid depletion of fossil fuels due to the human activities becomes another crucial issue. These, subsequently, have paved opportunities to the development of hybrid electric vehicles. Similar to automotive industry, construction machinery is also one of the most significant factors causing the GHG and CAP emissions as well as the fuel exhaustion.

It was reported that, the manufacturing and construction sector accounted for an average of 12.6% of the world air pollutions (in 2006, [2]) and 13.8% of the total CO_2 emissions (in 2004, [3]). In 2014, the total fuel consumption share in 2014 is summarized in Fig. 1. Here, among 30%

of fuel consumption burned for buildings [4], only the direct energy burnt for construction equipment activities (including ‘unoccupied’ built environment, such as road, bridges and other infrastructure) already took 5%, contributing 4.1% of the global CO_2 emissions based on the analysis in [5]. In addition, there is a number of other activities using construction equipment, such as in agriculture or in mining and quarrying. However, due to the lack of sufficient data sets, such as sub-contractor fuel used, fuel costs and sales, and emission taxes for specific non-road/off-highway operations, it is difficult to quantify exactly amounts of fuel consumption and emissions from the global construction equipment [6] (the actual global shares in 2014 should higher than 5% and 4.1%, respectively). Hence together with the continuous growth rate of above 2% in the global construction sector [7], the demands for energy saving and green emission of construction machineries, without sacrifice of the working performance, safety and reliability, have been highly increased.

There has been much effort to research on hybrid electric systems in terms of fuel costs and environmental impacts for various applications ranging from personal transport cars to large size passenger buses, to heavy loads and goods transportation vehicles, and to construction equipment. In the construction site, although typical hybrid electric systems could bring to many advantages over traditional configurations, they suffer from comparatively high cost for the implementations, reliability and consumer acceptability. Recently, micro/mild hybridisation is known as a feasible solution for modern vehicles with high fuel efficiency, less energy use and emissions and, especially, low cost and easy installation regardless of drivetrain configurations. However, the applicability of this methodology to construction site is still an open topic.



Notes:

- Industry* represents total energy consumption related to iron, steel and cement manufacturing.
- Buildings* represents: (1) building operational energy and; (2) indirect energy used for providing products and services for construction operations.
- Buildings** represents direct energy used for construction activities (including ‘unoccupied’ built environment).

Fig. 1. Global fuel consumption share in 2014 ([4], *Source: IEA World Energy Statistic and Balances 2016, www.iea.org/statistics*)

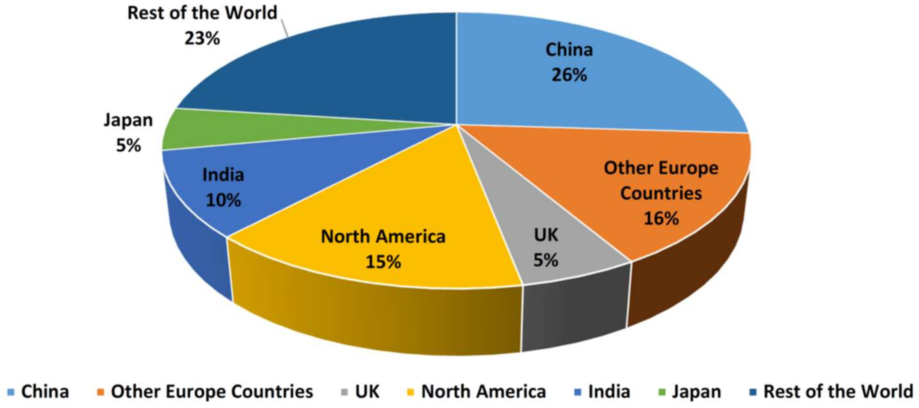


Fig. 2. Global construction market share in 2014 ([8], *Source: Global Market Data*)

Particularly considering manufacturing and construction industries of European countries and UK only, their contributions to the global market can be seen in Fig. 2. From this figure and the above analysis, it can be estimated that CO_2 emissions from the UK construction equipment was about 0.7% of the global CO_2 emissions in 2014. By realizing that emissions remain a major challenge for the off-highway construction equipment market, the UK has tough targets in this respect for the construction machinery and its objective is an overall reduction of CO_2 emissions of 80% by the year 2050, compared to 1990 levels. The Low Carbon Construction Innovation and Growth Team published their report [9] on how the UK construction industry can meet the low carbon agenda. One of the key recommendations from this report is that major construction projects would need to be approved against their sustainability criteria. A number of industry sectors are already providing solutions to improve energy efficiency. This is now built into public sector construction procurement activities, with the UK driving a reduction of 50% over the next decade [10].

Therefore, this research is considered as a generation step for the utilization of MMH in the construction equipment industry, especially paying attention to the UK conditions and EU market. Herein, two main objects are addressed: first, to identify the challenges of MMH technologies in construction sector and, second, to develop an analytic method to decide a target machine in UK for the MMH utilization. The rest of this paper, thus, is organized as follows. Section 2 gives a brief review on hybridisation technologies and points out technological challenges towards MMH in construction sector. Section 3 discusses on the current development of construction machinery in UK as well as MMH applicability. Thousands of sample machines coming from 20 machine variants manufactured by JCB and distributed within Europe have been selected as the case study to represent UK's construction machinery. Next, Section 4 presents a methodology for big data capturing, compression and mining from machines' telematics which is capable of reducing up to

96% of data memory requirement while easily and efficiently managing and analysing performances of any machines. Meanwhile in Section 5, an advanced decision tool is built using fuzzy cognitive map based on the big data mining and knowledge from experts in order to enable users to define a target machine among the different variants for MMH utilization. Concluding remarks are given in Section 6.

2. Technological Review and Challenges Towards MMH in Construction Machinery

2.1 Hybrid electric machines and classification

A hybrid machine is the machine that combines any two power sources. These possible combinations include but are not limited to: gasoline/diesel-electric, gasoline/diesel-flywheel, and fuel cell-battery [11]. The followings of this work pay attention to a specific type – hybrid electric machine of which the propulsion is the combination of electric motor(s) and an internal combustion engine. HEMs can be classified based on configuration or degree of hybridisation.

2.1.1 Gaps between hybrid electric vehicles and hybrid electric machines

Generally, a construction machine comprises five modules: implement, traction, structure, powertrain, control and information [12]. Hence although similar concepts of HEVs can be used to develop HEMs, the hybrid design progress as well as control strategy is different and dependent on particular applications. For a hybrid drive system, the requirement of additional components results in greater initial costs. The additional costs must be compensated by the benefits of the hybrid drive system, including [13]:

- Savings through lower fuel consumption.
- Exhaust reduction through the use of smaller engines.
- Additional functionalities.
- Noise-vibration-harshness reduction.
- Further potential for electrically operated auxiliary units as well as potential indoor operation if all electric modes are implemented.

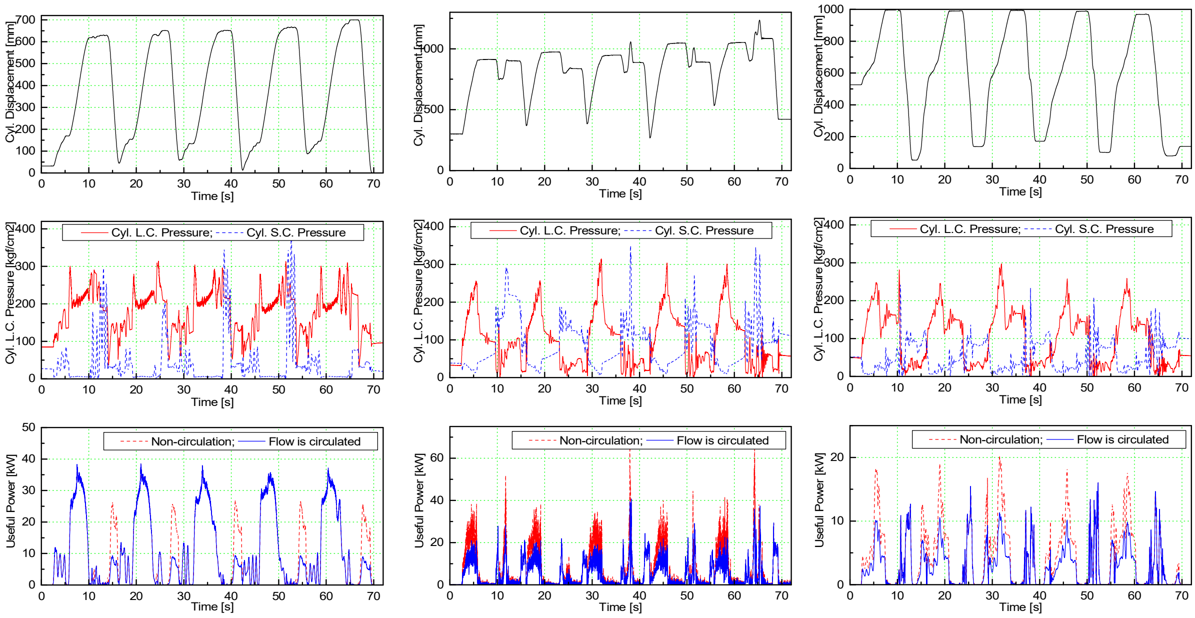
To develop a hybrid drive system, it is necessary to consider gaps between automobiles and construction machines, including system architecture and components, working cycle, energy management strategy and reliability.

Regarding architecture of a generic machine, besides having a powertrain to drive the machine movement as a vehicle, the machine includes multiple hydraulic actuators to perform construction works. Most of engine power of a traditional vehicle is spent for its acceleration. In a hybrid car, the EM can be implemented to, normally, recover energy from braking actions and, re-use this energy to assist the ICE during acceleration. The engine size can be then easily cut down to lessen the fuel consumption using this concept. However in a construction machine, the main power system is to supply power to not only a hydrodynamic transmission (or a hydrostatic transmission) of the powertrain but also a hydrostatic transmission of the actuators. To design an HEM, the EM and ICE should be selected carefully to ensure both the machine drivability and working capacity of the actuators. Additionally, energy recoverability can come from the machine braking actions and/or energy of the actuators which is dissipated as heat in traditional designs. Hence, key components in an HEM design are not limited to only ICE, EM, and power packs. Depending on degree of hybridisation, other key components, such as flywheel, hydraulic accumulator and hydraulic pump/motor, should be considered in the hybrid design to recuperate potential and kinetic energy released from the actuators. Real performances of boom, arm and bucket of a sample 20-ton hydraulic excavator during its typical digging and dumping tasks are demonstrated through Fig. 3. This figure shows that, for example, the useful powers of boom and arm actuators are significantly large and, therefore, there is a high potential for potential energy recuperation [14].

Another outstanding characteristics of construction machines is acknowledged as working cycle. Commonly, a working profile of a machine for a specific task is periodically repeated [15]. The power and torque requirements are continuously and quickly varied in a wide range, from low to high levels, as figured out in Fig. 3. This, therefore, implies that to improve the durability of a machine, the power system needs to be more powerful and, the energy storage devices need to be selected for higher charge-discharge rate, larger number of charge-discharge cycles and lower specific energy compared to their applications to HEVs.

In a hybrid automobile, the motive force is achieved by transmitting the torque produced by the ICE and EM to the wheels with different transmission ratios. To manage this task, an energy management strategy is established on several general rule-of-thumbs, comprising advanced functions such as, performance optimization of both the ICE and EM, minimization of engine dynamics, reduction of idle time, implementation of stop-start for fuel efficiency, and smart range estimation. To design this kind of EMS, it is necessary but easy to assess automobile fuel consumption rate as the fuel consumed per unit of distance travelled. Meanwhile, an EMS design for a construction machine is a difficult problem. The first reason is that the power system needs to drive not only the powertrain but also the hydraulic actuators to perform construction work. Hence, a complex algorithm is needed to manage the performance of ICE, EM and storage devices. The second reason is that it is hard to evaluate the fuel consumption rate over a wide range of working tasks. In addition due to the short and repeatable working cycles of a machine with continuous dynamic changes, it is difficult to reduce the machine idle time as well as to implement the stop-start technology. An EMS for a hybrid machine is required to be designed with three main duties: to ensure a high responsibility of both the power system and work hydraulics; to guarantee a high power transmission efficiency; and to achieve a high performance of energy recuperation.

At last, for the commerciality, a hybrid machine must possess higher adaptability and reliability to various working environments compared to an automobile where is normally designed for normal driving conditions on roads.



(a) Boom (b) Arm (c) Bucket

Fig. 3. Working performance of a typical 20-ton excavator (*Source: KOCETI*)

2.1.2 HEM classification based on configuration

Markers have actively developed various kinds of hybrid machines. Based on the configuration, HEMs can be mainly classified into three categories: series hybrid, parallel hybrid, and compound hybrid [16, 17].

A typical series HEM architecture is depicted in Fig. 4 [17, 18]. Herein, all power generated by an ICE is converted into electric energy using a generator. This energy is converted again into mechanical power using EMs. The number of EMs is depended on each specific machine type. Output power from the EMs are input into hydrodynamic/hydrostatic transmissions to distribute power to both the drivetrain (connecting to wheels or tracks) and hydraulic actuators. Energy from braking or potential/kinetic energy from actuators can be recuperated and stored as kinetic energy in a flywheel [19], and/or hydraulic energy in an accumulator [20], and/or electric energy in a battery (capacitors) [21]. This energy is then reused to accelerate the machine or power the actuators. By using an electronic control unit, the ICE can be operated at a point with higher efficiency regardless of an operating point that is governed by the load, since the engine is mechanically and hydraulically disconnected to the load. However, this series hybrid requires high cost for implementation because the generator should have almost the same capacity as the ICE and the traditional design needs to be severely modified.

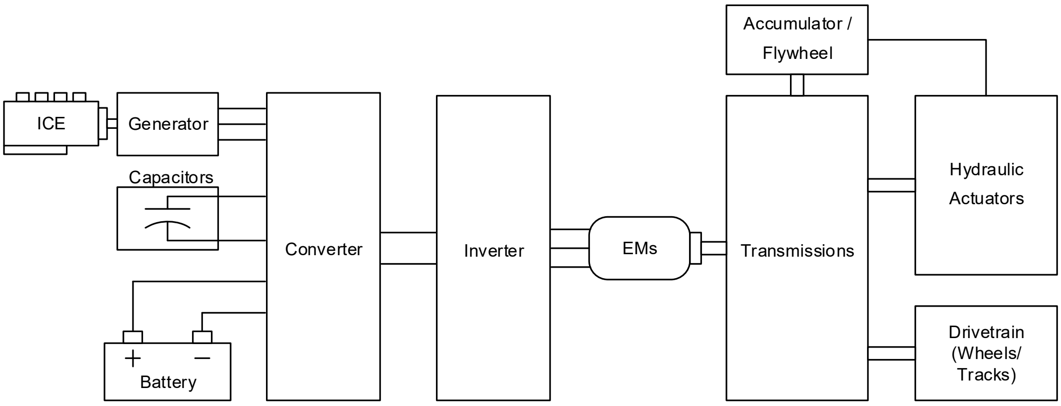


Fig. 4. Typical series hybrid configuration for HEM

A typical parallel HEM architecture is described in Fig. 5 [22, 23]. In this hybrid, the ICE and EMs can be linked together through a differential of which the output shaft is connected to the machine transmissions [24]. Due to this connection, the ECU needs a complex design to control both the ICE and EMs to maximize their efficiencies over various working conditions. However, the energy from power sources is directly transmitted to the transmission and, the generator does not need to have the same capacity as the ICE. It can be designed smaller than that in the series type. Moreover, the implementation cost of this hybrid type is less than that of a series HEM.

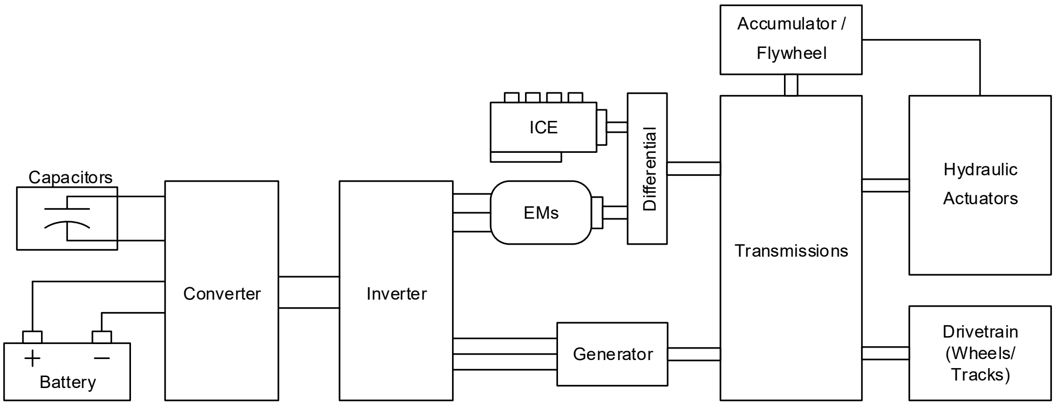
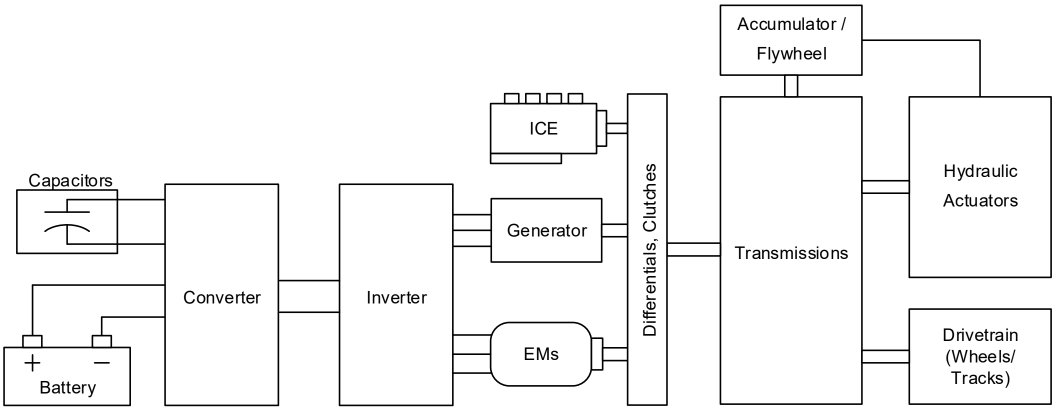
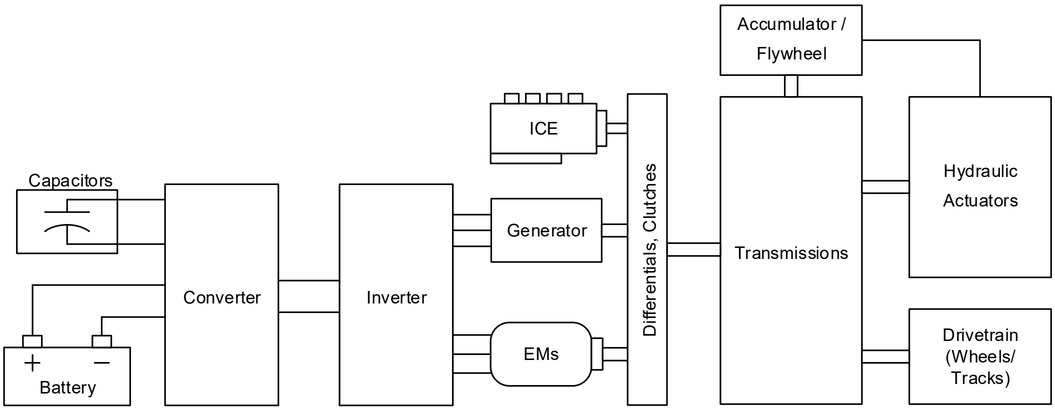


Fig. 5. Typical parallel hybrid configuration for HEM

To incorporate features of both the series and parallel types, compound HEMs are developed. A general form of this hybrid is displayed in Fig. 6 [25]. By using differentials and/or clutches, a compound hybrid machine can be constructed by two principles. In the first principle, the system is capable of functioning as either series type or parallel type depending on each specific power requirement. However for a construction machine with multiple actuators, the power control design becomes extremely complex to reach the optimal efficiency. In the second principle, the system is the combination of both a parallel structure, normally applied to hydraulic actuators, and a series structure, normally applied to drivetrain and/or swing actuator. This design does not require many changes in the traditional architecture as well as the complex control [26]. Hence, most of compound HEMs are developed in this way.



(a) Compound type 1 (adding fuel tank to ICE)



(b) Compound type 2 (modifying the connection to wheels/swing)

Fig. 6. Typical compound hybrid configuration for HEM

Different from HEVs, event based on the same hybrid type, HEM designs are varied through different machine classes with different numbers of hydraulic actuators. In addition, due to the hybridisation cost as well as the high energy recuperability of excavators, wheel loaders, handlers, and forklifts, these machine types are specially commercialized. An example of series HEM is identified as a 6-ton hybrid excavator from Kobe Steel and NEDO [18]. Herein, six actuators are independently driven by electric motors/generators to reduce losses as well as to increase the recuperated energy. The ICE is downsized to 22kW by the use of the battery and capacitors. It was reported that 60% of fuel consumption can be saved with this design, compared to the traditional hydraulic version [18]. Using the concepts of parallel and compound hybrids, hybrid machines have been successfully developed, such as wheel loaders and 20-ton hybrid excavators from Hitachi (ZX200) [27, 28], 20-ton hybrid excavators from Komatsu (PC200-8) [29, 30], and 7-ton hybrid excavators from New Holland-Kobelco [31]. These wheel loaders and excavators use an ICE and an EM to drive the hydraulic systems using parallel concept and, use another EM to drive the wheels for the machine movement and the swing for the rotation. Thus, braking energy or kinetic energy can be recovered and converted directly into electricity. The fuel consumption of these hybrid machines can be cut down by 25–41%, compared to the conventional designs.

From the above analysis and a study on hybrid excavators in [17], a comparison of the three typical HEM configurations is then carried out as shown in Table 1 while a comparison of the performances between these configurations is carried out as shown in Table 2.

Table 1

A comparison of typical HEM configurations

Specification	Series HEM	Parallel HEM	Series-Parallel or Power split HEM
Powertrain characteristics	• Pure electrical power transfer • Complete modification of engine operating point possible • 2 electric machines • No transmission	• Pure mechanical power transfer • Modification of operating point dependent on electric power • Numerous technical designs: mild/full hybrid, torque distributor, single/double shaft • 1 electric machine • Transmission needed	• Both mechanical and electrical power transfer • Strong modification of operating point possible • 2 electric machines • CVT function may possible with power split
Advantages	• Complete variable engine operating point • Optimal operative strategy for fuel efficiency and exhaust emissions possible • Maximum regenerative braking	• Scalable system regarding electrical power • Good efficiency chain	• Wide range of operating point adjustment • High regenerative braking rate
Dis-advantages	• Efficiency chain with high losses (ICE, generator, EM) • Approximate 3 times of installed power need for permanent full load • Heavy weight • High cost • Package difficulty	• Limited modification of ICE operating point • Limited power assist and regenerative braking by low power of electric motor	• Partially unfavourable efficiency chain • Power management complex • Much high costs

Table 2

Comparison of machine performances between different hybrid architectures

HEM Type	Machine Performance (L – Low; M – Medium; H – High)					
	Engine Efficiency	Energy Recuperability	Valve Loss Reduction	Overall fuel Consumption	Implementation Cost	Payback time
Series	H	H	H	L	H	H
Parallel	M	M~H	L	H	L	M
Compound	M~H	H	M	M	M	L

2.1.3 HEM classification based on degree of hybridisation

Degree of hybridisation indicates how much importance of the EM in the vehicle propulsion. Thus, this factor can be evaluated as

$$DOH = \frac{P_{EM}}{P_{EM} + P_{ICE}} \tag{1}$$

From (1), it is clear that DOH can be varied from zero to unit, corresponding to non-hybrid vehicle to purely electric vehicle. With the increase of DOH within this range, HEMs can be categorized into three types: micro hybrid, mild hybrid, and full hybrid machines.

In a micro hybrid machine, an integrated starter/alternator is typically employed to couple with the ICE instead of using separately the traditional alternator and starter. The rotor of this electric machine then replaces the traditional flywheel while the stator is integrated in the flywheel housing. Unlike automobiles, a construction machines commonly stops at some positions to perform load tasks during its working cycles. It is necessary to keep the engine power at least at a minimum level to ensure a ready power existing in work hydraulics during the machine operation. Thus, the stop-start function of a hybrid vehicle cannot be simply utilized in a hybrid machine. Here, the ISA with small power (for example, 2.5kW at 12V) is used with three main functions, first, to start the engine, second, to shift the engine from lower idle rpms to higher idle rpms and, third, to assist the engine acceleration. For the engine start, due to the larger power requirement and less number of machine braking actions (regenerative braking) in comparison with an micro HEV, the battery supplies power for the ISA to only crank the engine from zero rpm to a low rpm before enabling the fuel injection to speed up the engine to a normal idle rpm. The battery can be re-charged during the machine deceleration or when the full output of ICE is not required. By running the machine in idle modes once less power is required, the fuel consumption can be saved up to 10% compared to the non-hybrid.

In order to increase the machine fuel economy with low-cost modification, the micro hybrid can be upgraded to a mild hybrid design. Here, the electric machine with a larger power is employed to provide, for example, a nominal output of 15kW at a rotational speed of 100Nm, and a peak capacity of 30kW at a rotational speed of 200Nm. The engine, therefore, can be quickly started from zero rpm to a normal idle rpm without requiring an injection. Besides idle modes, this makes it possible to implement a stop-start function whereby the ICE can be turned off when stationary and, immediately available when any task is given. The electric machine is switched to motor mode to provide additional torque for the engine during the hydraulic power boost/ machine acceleration and, to generator mode in case of less power requirements/machine deceleration. With the assembly of ISA, the engine fuel efficiency can be optimized and consequently, an anticipated reduction in fuel consumption of between 10 and 20% (or even above 20%) can be obtained. Due to these advantages, some mild hybrid machines have been successfully developed. In an early stage, Volvo unveiled their hybrid wheel loader (L220F) in 2008. It was reported that a traditional loader can spend up to 40% of time with engine idling and subsequently, leads to a low fuel efficiency. This problem can be solved by the L220F hybrid system with the use of an ISA for idle/stop-start control. In addition, the problem of low torque at low engine speeds is overcome by automatically offering a massive electric torque boost. According to Volvo, a 10% reduction in fuel consumption can be achieved [32]. Atlas Weyhausen also introduced their hybrid wheel loader (AR40) in 2010. The machine uses the HST for both the actuation and machine movement. The travel pump is adjusted by means of an electronic control device to improve the performance [33].

To downsize ICE of a machine, full hybridisation can be applied. In this case, the electric machine with a power of at least 50kW is typically used. In addition to having all functions available in a mild hybrid, the full hybrid allows the machine can be operated using only the electric machine at low power requirement regions. An energy saving over 30% can be then achieved. However, the product cost as well as control complexity of such a full hybrid is relatively high compared to a mild-hybrid. This leads to a long return-of-investment period which does not attract customer attention.

Table 3

A comparison of different hybridisation degrees

Specification	Micro hybrid	Mild hybrid	Full hybrid
Electric power	• Small power. E.g.: 2.5kW, 12V	• Medium power. E.g.: 10~20kW, 100~200V	• Large power. E.g.: 50kW, 200~300V
Functions	• Start-stop function	• Start-stop function • Regenerative braking features	• Start-stop function • Regenerative braking features

		• Some engine assist functions are possible	• Full propulsion using only ICE or only EM; many mixing modes are possible
Advantages	• Simple design	• Energy saved: 20~30% • Torque smoothing, power assist (boost) for better efficiency and fuel saving	• High energy saved: 30~50% • Full power assist with operating point modification
Dis-advantages	• Small energy saved: 5~10% • Low efficiency, much pollution and emissions • Actually not real hybrid system	• Limited hybridisation features	• Require high-capacity power pack (battery) • Power management complex • High costs

A comparison of the DOH-based hybrid systems is then carried out and analysed in Table 3. In summary, mild hybridisation can be realized as the most promising solution for construction machines in particular and, for industrial applications in general. The ISA is combined with an ICE to support the main functions, such as quick engine start, idle control, stop-start control, power boost control, engine efficiency optimization and regenerative braking. Without loss of generality, the following sections are mainly discussed on mild hybrid technologies, which are also applicable to micro hybrid systems.

2.2 Design considerations for micro/mild hybrid systems

2.2.1 Propulsion architectures

In applications to automobiles, there are two main mild hybrid drivetrain architectures which are recoginised as ISA-based mild hybrid and BSA-based mild hybrid (or parallel mild hybrid) [34-36]. It can be seen that in both the architectures, the main components comprises an ICE, an electric machine (motor-generator), electric energy storage devices (batteries with/without ultracapacitors), a transmission gear box, controllable clutches, final drive and wheels. Without a belt transmission, the ISA-based mild hybrid offers the compact design with less power loss compared to a parallel mild hybrid. However, the BSA-based hybrid mostly does not require any modification in the traditional system hardware which makes it possible as a low cost solution.

2.2.2 Energy storage devices

One of the biggest concerns in designing a hybrid system is the selection of energy storage devices. For mild hybrid applications, the current technologies enable the system to operate at low voltage ranging from 12V to 64V [34].

Battery, comprising one or more electrochemical cells to convert the stored chemical energy into electrical energy, is considered as the most popular choice for energy storages of vehicles and machines. Selection of batteries should be based on some outstanding characteristics, including battery capacity (Ah), energy stored in battery (Wh) and SOC (%) to satisfy the driving range requirements. It means a battery must store sufficient energy to provide adequate peak power to the system during acceleration and, to meet appropriate driving and working cycles. Furthermore, selected batteries must meet calendar life requirements.

With all battery chemistries, there are trade-offs between the energy density and useable power density of the battery [21]. For the uses in vehicles and machines, five main groups of batteries are available in the market: lead-acid batteries, nickel batteries, zero emissions batteries research activities (ZEBRA) batteries, lithium batteries, and zinc-air batteries [37]. Lead-acid-type battery is known as the most common and cheapest solution with intrinsic advantages, such as high power density, low self-discharge rate, and low maintenance cost. The main drawbacks of lead-acid battery are low energy density, short lifetime when facing with frequently high current charge-discharge and environment-irresponsible option. Hence, this type of battery is suitable for applications to heavy vehicles and machines in which power density is more important than energy density. Compared to the lead-acid one, a nickel-zinc battery is more environment-friendly. However, its applicability is limited due to the shorter life cycle, heavy weight, high maintenance cost and has high self-discharge rate. The self-discharge rate can be improved with a nickel-metal hydride (Ni-MH) battery. Nevertheless, this kind of battery needs longer charge time and releases more heat during charging. And therefore for the utilization, its leads to requirements of complex control and expensive chargers [38]. The ZEBRA-type battery with high temperature characteristic (270-350°C) [39] can be used to maintain an efficient operation. ZEBRA batteries offer low life cycle cost, high energy density, long lifetime, high ruggedness, fail-safe to cell failure, and overcharge/over-discharge resistance. Nonetheless, this battery type has high production cost and energy loss while not being used [37]. A lithium battery is one of the most promising solutions due to its advantages, such as light weight, high specific power and energy, high energy density, environment-friendly characteristic and fail-safe to cell failure. The main drawbacks of this type are high production cost and life cycle. At last with a zinc-air battery, although having high specific energy and energy density, the battery has low specific power and life cycle [38].

From the above analysis, the lead-acid-type battery is the most suitable option for mild HEMs. And in many mild hybrid designs, a 42V power source is employed rather than the traditional 12V one [40]. The 42V power supply is capable of meeting not only the high power requirements of MMH architectures but also the increase of other electrical loads [35]. However, the main issues for a 42V power system using lead-acid batteries are its capacity and life cycle time. Especially with MMH, there always exits a large number of high current charging/dis-charging actions which subsequently cause the energy source lifetime to be degraded. In order to overcome this limitation, ultracapacitors are necessary to be combined with lead-acid batteries to perform an energy storage with longer lifetime and higher power output [21, 40]. Herein, ultracapacitors are utilized to provide instantly high dis-charging and charging currents to start (or accelerate) and decelerate the engine, respectively.

2.2.3 Energy management strategies

Regardless of the mild hybrid architecture employed, energy management strategy for a mild HEV is designed to enable following modes:

- Cranking mode (including stop-start feature): is to crank the engine from zero rpm in fractions of seconds. During this phase, the electric machine functions as motor drawing a heavy current from the battery.
- Generator mode (battery charge mode): is to charge the battery in order to ensure a good performance with all electric load requirements. In this phase, the electric machine is switched to generator and driven by the ICE to perform like an alternator with voltage regulation.
- Hybrid traction mode (torque assist mode): is to combine both the engine and electric machine (as motor) delivering traction power to the drivetrain. Here, the motor produces a torque that complements the engine to satisfy the requirements, especially during high acceleration conditions.
- Engine-alone traction mode (ISA idle mode): is to use only the engine. In this mode, the SOC of the battery is in high region (fully charged) and then, the ISA is de-energized to avoid causing the engine to be with an additional load from the ISA. The engine alone can handle the power demands, especially in case of vehicle cruising at high speeds.
- Motor-alone traction mode: is to use only the electric machine as motor. This mode is enabled when the vehicle is at very low speeds (for example, less than 10km/h) or is stopping. Then, the engine is shut down and disengaged from the propulsion and the vehicle is propelled by only the electric machine. Also, the electric machine power is used for driving the air-conditioner compressor, power steering and other auxiliaries.
- Regenerative braking mode: is to save energy from a braking action. To enhance this task, the engine is switched off and disengaged from the propulsion. The electric machine is operated to provide a braking torque to the drivetrain. If the battery is not fully charged, the electric machine plays as generator to convert the vehicle kinetic energy to electric power stored in the battery.

- Hybrid braking mode: is to quickly reduce speed or stop the vehicle. Similar to regenerative braking mode, the engine is shut down and disengaged. Meanwhile, the electric machine is switched to motor function to combine with the mechanical brake to provide the braking torque.

The control strategy for a generic machine should consists of three main control modules: supervisory control with energy management, engine control module and electric machine control module (low-level control components). During the operation, the supervisory controller receives information from human machine interface (such as accelerator pedal and brake pedal) and signals from a number of sensors (such as traction speed, engine torque and speed, fuel consumption, battery SOC and temperature) as the inputs. To ensure the overall system performance, the outputs from this controller are engine throttle control signal sent to the engine controller, power control signal sent to the electric machine controller, and control signals for the transmission gear and clutches. Technologies to improve the performances of the low-level control components are clearly stated in existing studies [37, 41-43].

A mild hybrid system is considered as a time-varying plant of multi-domain variables with large nonlinearities and uncertainties. Therefore, an advanced supervisory controller is desired to manage efficiently the low-level control components. Using proper control logics, the supervisory controller updates online the machine information to define the most suitable mode among the desired modes (as presented above) for the machine in order to provide an optimal power spilt between the ICE and electric machine in addition to a smart and efficient co-ordination between multiple energy sources and converters.

In fields of HEVs, many efforts on the power control development have been carried out [44-47]. These efforts can be divided into two categories, rule-based methods and optimization methods. RB methods to generate the control system are largely dependent on human expertise with knowledge of the vehicle, such as dynamics, driving cycles and load profile. An RB controller can be constructed in a simple way, deterministic RB approach, or an intelligent way, fuzzy RB approach. A deterministic RB controller uses look-up tables to design deterministic rules. These look-up tables can be built with only on/off logics, or power follower logics, or strategy and state machine-based logics. Meanwhile, a fuzzy RB controller uses linguistic knowledge to calculate optimal working points [48-53]. On the contrary, OPT methods generally base on numerical analyses on the system to minimize pre-defined cost functions. An OPT controller can be constructed with a global optimization or with a real-time optimization. The basic concept of a OPT controller is to utilize the knowledge of future and past power demands to minimize a cost function of fuel consumption, and/or emissions, and/or time/distance travelled over a fixed driving cycle. Well-known global optimization approaches can be counted as model-based control [54], RB optimal control [54-56], optimal control [57], DP-based optimization [58, 59], and GA-based optimization [60]. Meanwhile, real-time optimization approaches are recognised as equivalent fuel consumption minimization [61], robust control [62], and real-time predictive optimization [63].

Particularly focusing on mild HEVs, there are already some interesting studies on EMSs. The simplest control is acknowledged as simple RB logics defined from the vehicle working modes [64]. For a smooth shifting between these modes, advanced control techniques are implemented, for example, optimal control as DP [65], model-based control [66], model predictive control [67], and intelligent control as fuzzy-based control strategy [68] or neural network-based control strategy [69].

2.3 MMH design challenges for construction machines

Although many technologies have been introduced for mild HEVs as found on the horizon, there exist a lot of technological challenges toward the implementation of micro/mild hybridisation in construction machinery. Some major challenges are discussed as below.

2.3.1 Machine architectures

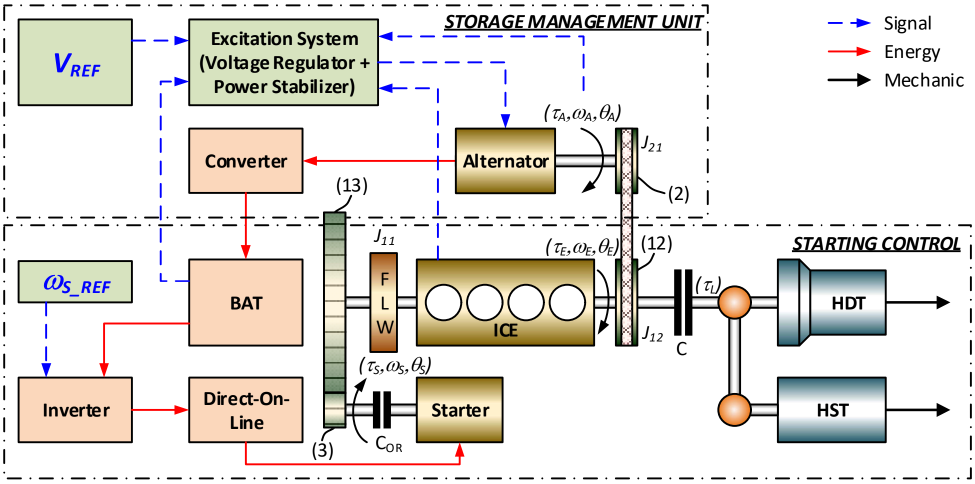


Fig. 7. Reference architecture of generic mild hybrid machine

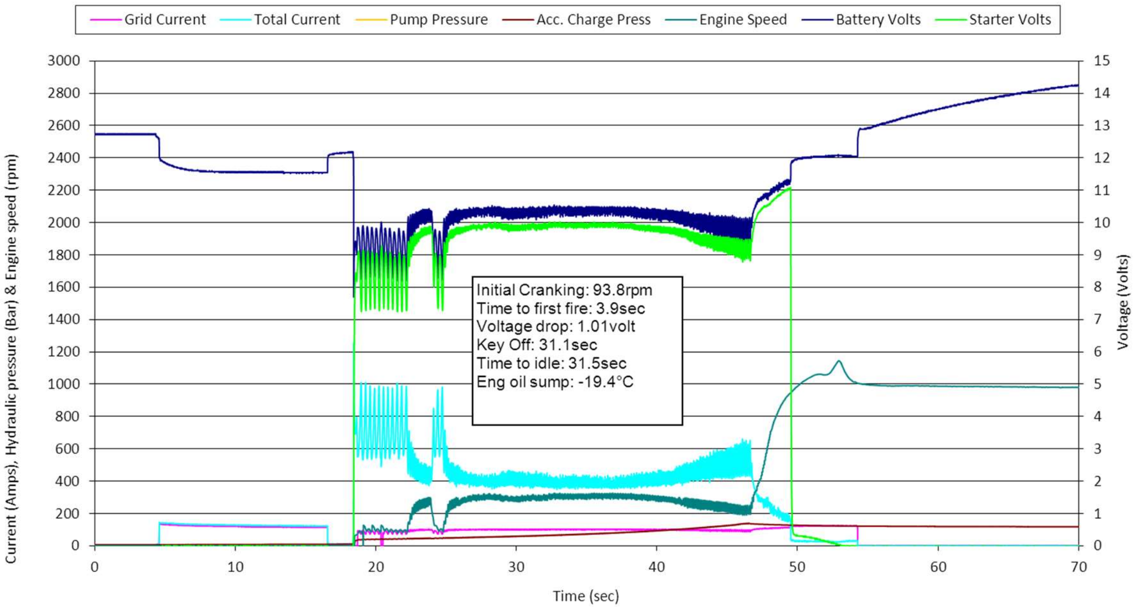
A BSA-based mild hybrid architecture of a generic construction machine is shown in Fig. 7. Regarding the architecture, the main difference in comparison with a mild hybrid vehicle is the mechanism after the final output shaft of the power source, which in this case is the ICE coupled with the electric machine. There are normally two available options, first, HDT and HST, and second, HST only to distribute the power flow to the machine wheels/tracks and hydraulic actuators. It is necessary to consider the power requirements of both the drivetrain and hydraulic actuators in the selection of key components for the mild hybridisation. The existence of these actuators also leads to an increase in working modes preferred for the hybrid machine.

2.3.2 Energy storage devices

With traditional construction machines, lead-acid batteries are mostly used as the energy storage devices for the starter and other electric loads due to their low cost and robustness over rigorous working conditions. Thus, it is also suitable for mild hybrid machines.

Here, the battery efficiency is strongly affected by the temperature and working profile. Working under cold temperature conditions, the battery capacity may be only at 70% of its rated capacity [70]. This causes difficulties for the engine start including stop-start feature which normally requires a peak power from the battery. Especially with construction machines, an engine cold-cranking can last for a minute. An example of cranking performance of a backhoe loader with 81kW engine under -20ºC is demonstrated in Fig. 8. Thus, carrying out a proper method to maintain an optimum and uniform temperature is essential to obtain the peak battery performance. In addition, due to the short working cycles with quick variations in power demands, it is necessary to investigate other energy storage units to combine with the batteries in order to improve the battery performance as well as the system fuel economy. Similar to mild hybrid automobiles, ultracapacitors can be integrated to produce the high current charging and dis-charging. Additionally, flywheel and/or accumulator can be inserted into the hybrid configuration with following functions:

- To enable a smooth SOC profile for the batteries.
- To directly and effectively recover, store and reuse regenerative braking energy and, actuator potential and/or kinetic energy as the extensional features.



Initial Cranking: 93.8rpm
Time to first fire: 3.9sec
Voltage drop: 1.01volt
Key Off: 31.1sec
Time to idle: 31.5sec
Eng oil sump: -19.4°C

Fig. 8. Cranking performance of a backhoe loader under -20°C (*Source: JCB*)

Nevertheless, the more components added, the more complex the energy management system is. Besides, recycling of used batteries and recycling cost on a per-machine basis also need to be addressed in future MMH.

2.3.3 Energy management strategies

Design of energy management strategies for a mild HEM is more complex than for a mild HEV. Herein, an energy management strategy generally needs to be designed with following modes:

- Cranking mode, generator mode and engine-alone mode are the same as in a mild HEV.
- Regenerative braking mode and hybrid braking mode have similar functionalities as those of a mild HEV. However, the concept of braking for a machine consists of not only the machine stop (or deceleration) but also the stop of swing actuators if having. The power requirement as well as energy recuperability is then totally varied though each machine variant.
- Hybrid traction mode (torque assist mode): is to combine both the engine and electric machine (as motor) deliver power to the transmissions. Here, the motor produces a torque that complements the engine to satisfy the requirements, such as machine acceleration and/or power boost of hydraulic actuators.
- Motor-alone traction mode: is to use only the electric machine as motor. This mode is only enabled when the total required power is significantly small, for example, during a low idle period between two continuous work tasks, in which the machine is with free load. Then, the engine is shut down and disengaged from the propulsion and the vehicle is propelled by only

the electric machine. Also, the electric machine power is used for driving the air-conditioner compressor, power steering and other auxiliaries.

- Idle control mode: to optimize the fuel economy of the engine during low load conditions, including hydraulic workloads. The electric machine is then operated with motor function to shift smoothly the engine between different idle levels once demanded. Special case of idle control mode is engine stop-start. This function is activated to shut down the engine when the machine does nothing for a pre-determined time period or the cab door is opened. Once any command is given by the operator, the electric machine is directly operated under the cranking mode.

In addition, depending on transmission technologies existing in the machine, the degrees of freedom for the power control are varied. For example with a wheel loader using only HST, the fuel consumption can be optimized through not only engine-electric machine power splitting but also load sensing feature of the hydraulic pumps and motors. Therefore, it is clear that the control strategy is more complex compared to the control system for a mild HEV.

Although OPT approaches like DP [71] can enhance an optimal performance by the use of cost function minimization, the selection of cost function is not an easy task due to the difficulties in updating the machine information, such as fuel consumptions, emissions and machine dynamics including load variations on the actuators. Furthermore, training process is necessary to build the OPT structures. Hence, a big data analysis and/or a complex online/offline optimization are other restrictions of these methods.

A RB method based on pre-defined machine states and fuzzy logics can be then considered as a potential solution with less complexity for managing the machine power system. Among the modes suggested for a mild HEM, the idle control mode needs to be effectively implemented in the EMS. For example [32], up to 40% of a wheel loader time is for only idling. Hence, the fuel economy can be significantly improved by utilizing this mode. However, it is hard to determine the machine is idle or not due to the intricate operation.

In order to cope with this problem, automatic idle control approaches are studied recently [72, 73]. In these studies, the basic concept is to automatically shift the engine working point from the normal power region to idle power regions. Although these approaches could make a fuel saving over idle conditions possible, their applicability is still limited. The reason is that to make a mode decision which is mostly suitable for the current machine states, the power controller requires a pre-defined time period (using a timer) which should be large enough to take an observation and analysis on the machine states. Meanwhile, a working cycle of a construction machine is not long, for example 10s to 20s with excavator. Therefore, the time period required for the machine state checking is remarkable in comparison with the duration of idle stages. This leads to a reduction in the fuel saving capability during the machine idle.

2.3.4 Other technological challenges

Standards of working profiles

Unlike automotive research and development, there is no standard definition of working profiles for construction machines. It is clear that working profile of a machine is periodically repeated. Hence, it is possible and essential to find out a numerical method to perform a big data analysis of various machine types in order to produce approximately working profiles for these machines. This will then allow both scientists and makers to perform fully theoretically analyses and simulation-based evaluations of new machine designs and control algorithms before going to practical testing and production.

Load sensing control

A hydrostatic transmission is employed for most of construction equipment, in which displacements of the main hydraulic pumps are self-controlled by the system working pressure through hydro-mechanical load sensing systems. This pressure-dependence can deplete the system energy efficiency. Therefore, a simple replacement of traditional hydro-mechanical load sensing systems by electronic load sensing systems can be considered as an additional feature of a mild HEM. By utilizing this simplification of the load sensing system, the machine performance can be improved.

Applicability

For a machine type, it is necessary to define a cost function to evaluate the potential of this machine for hybridisation. A cost function should include some major factors, such as acceptable production and maintenance cost compared to the traditional architecture, ease of implementation, ratio of idling time to total operating time, fuel used in idle, and payback time.

Safety and reliability

A mild HEM should be constructed in such a way as to ensure that as few hazardous situations as possible arise. Following aspects should be guaranteed:

- The machine should work robustly under hazardous conditions.
- Any fault in the hardware or software of the machine should not lead to hazardous situations.
- Any error in the energy management system should not give rise to hazardous situations.
- Any mistake from the operator should not give rise to hazardous situations.

- During information exchange through communication channels, an automatic stop should be activated once any communication problems occur.

3. Role of construction machinery in UK and potential for MMH

3.1 Overview of supply and demand for construction machines

Construction machinery sales occur within an environment which is conveniently characterized by supply and demand factors. Regarding the machinery supply, original equipment manufacturers market their products on the basis of innovative technologies and customer benefits, such as safety, reliability, fuel economy and environmental friendliness. For example, OEMs in UK recently launched a cleaner engine for construction machines, especially excavators, fulfilling with new legislative limits on diesel particulate emissions (U.S. EPA 2011) that remove the need for exhaust particulate filtration while offering up to a 10% decrease in the fuel consumption. Regarding the machinery demand, buyers constantly seek machines that maximizes productivity with minimal cost requirements. Additionally, there is a demand that machines need to adapt well with changes in working conditions evolving environmental, health and safety requirements. Other factors affecting the machinery supply and demand are known as economic climate, availability of funds, and projected workload [74, 75].

Especially, the energy (fuel) consumption and CO_2 output is under a constant challenge to be reduced. In the United States of America, the Environmental Protection Agency (EPA) produced a report on how to reduce emissions in the construction sector [76], this showed that the US construction industry is responsible for 100 million metric tons of CO_2 through fossil fuel combustion alone. As reported in [3], manufacturing and construction sector accounts for 13.8% of total CO_2 emissions, second only to Electricity and heat, so is an obvious targets to help countries meet their climate change commitments. There are clear worldwide pressures to reduce CO_2 and the construction industry is under both legal and political obligations to make these improvements, emphasising the business case for MMH technology.

3.2 Current development and MMH potential of construction machines in UK

Within the Global construction equipment market, demands on machine types and quantities are varied through different countries and regions. However, the four most popular types in the UK construction equipment market [77] are acknowledged as compact excavators (Fig. 9a), telescopic handler (Fig. 9b), tracked excavator (Fig. 9c) and wheeled loading shovels (Fig. 9d) which also have the largest percentages of sales in the global market in 2015 (see Fig. 10, [7]). It also indicates that there are significant correlations between annual sales of machine types. For instance, sales of compact excavators show highly significant and strong positive association with sales of heavy (tracked) excavators while sales of telescopic handlers have very positive influences on sales of heavy excavators, mini excavators and wheeled excavators. Based on the study on UK construction machinery [77], the sales trend of new machinery in UK is upward, although the latter recession has had a more adverse effect on sales than downturns of previous years.

In order to evaluate the potential of UK construction equipment for utilizing MMH technology, a simple analysis over a data set taken randomly from the network dataset collection of 2000 JCB's telescopic handlers in UK has been done as presented in Table 4 and Table 5.

(a) Compact excavator (b) Heavy excavator (c) Backhoe loader (d) Telescopic handler

Fig. 9. Four most popular machine types in the UK construction equipment market (*Source: JCB*)

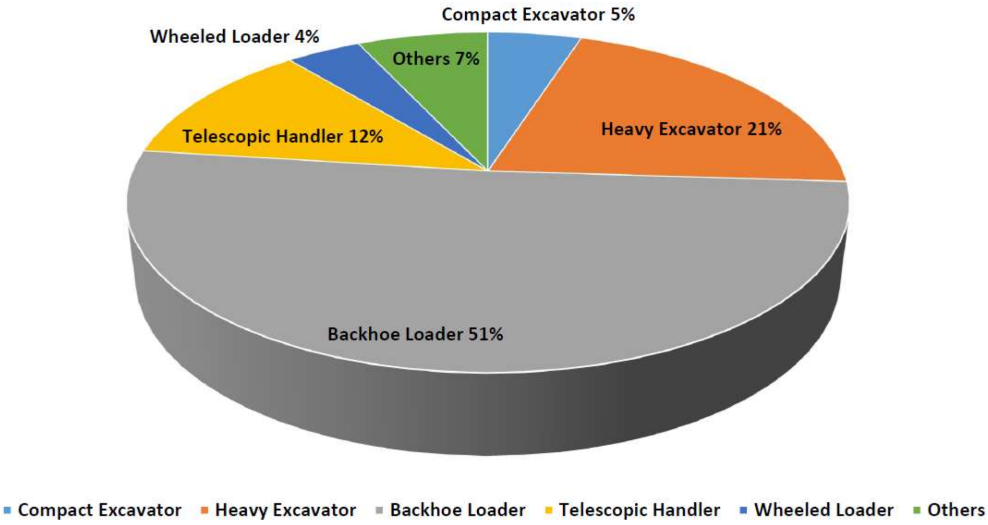


Fig. 10. Structure of sales in the global construction equipment market in 2015 ([7], *Source: Off-Highway Research*)

Table 4

Engine total run time against engine speed/torque demand of a typical telescopic handler in UK

% Total Rune Time		Engine Speed						
		0-1000	1000-1250	1250-1500	1500-1750	1750-2000	2000-2250	2250-2500
Torque % of Reference	66-100	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%
	60-66	0.00%	0.00%	0.10%	0.23%	0.01%	0.00%	0.00%
	54-60	0.00%	0.07%	0.30%	0.68%	0.46%	0.01%	0.00%

Value (1000Nm)	48-54	0.02%	0.27%	0.50%	0.52%	0.87%	0.41%	0.01%
	42-48	0.21%	0.43%	0.54%	0.57%	0.32%	0.52%	0.24%
	36-42	0.48%	0.75%	0.65%	0.59%	0.35%	0.21%	0.40%
	30-36	1.36%	1.46%	1.07%	0.81%	0.44%	0.28%	0.69%
	24-30	2.72%	2.24%	1.72%	0.91%	0.53%	0.32%	0.98%
	18-24	8.05%	3.84%	1.93%	1.38%	0.72%	0.36%	0.88%
	0-18	***42.48%***	6.77%	2.91%	1.99%	1.05%	0.54%	0.79%

Table 5

Total fuel consumption of engine against engine speed/torque demand of a typical telescopic handler in UK

% Total Rune Time		Engine Speed						
		0-1000	1000-1250	1250-1500	1500-1750	1750-2000	2000-2250	2250-2500
Torque % of Reference Value (1000Nm)	66-100	0.00%	0.00%	0.03%	0.04%	0.00%	0.00%	0.00%
	60-66	0.00%	0.02%	0.32%	0.86%	0.09%	0.00%	0.00%
	54-60	0.00%	0.16%	0.80%	2.40%	1.83%	0.10%	0.00%
	48-54	0.04%	0.52%	1.19%	1.55%	3.28%	1.67%	0.04%
	42-48	0.26%	0.74%	1.18%	1.55%	1.03%	2.00%	0.96%
	36-42	0.50%	1.17%	1.26%	1.40%	0.98%	0.67%	1.44%
	30-36	1.32%	1.97%	1.80%	1.63%	1.05%	0.75%	2.17%
	24-30	2.30%	2.51%	2.39%	1.53%	1.04%	0.73%	2.62%
	18-24	5.60%	3.49%	2.18%	1.86%	1.13%	0.66%	1.88%
	0-18	***17.34%***	3.59%	2.22%	2.01%	1.38%	0.98%	1.77%

Table 4 shows the average amount of time (as a percentage of their lifetime) that the sampled machines spent at a given engine speed-load set point. The cell with number in bold-italic format could be classed as the machine idle point. On average, in excess of 40% of the machine life was seemingly spent at idle – being un-productive and wasting fuel. A study by Lewis et al. [78] cited figures of 34% for a fleet of heavy excavators and 32% for wheeled loaders which they tested, further improving confidence in the approximation. Further analysing the data set, the average amount of fuel consumed (as a percentage of the total lifetime consumption) at each engine speed-load set point can be calculated as shown in Table 5. The cell with number in bold-italic format shows the average amount of fuel consumed whilst the machines were at an idle point. In excess of 17% of fuel is consumed for zero productivity.

From these tables, it is conservatively estimated that a reduction in fuel consumption approaching 10% could be realised through the application of MMH. It may still be necessary to allow the engine to operate at idle whilst performing certain duties or when defined operating conditions aren't met hence savings approaching the full 17% would not be realistic. A report by the United States Environmental Protection Agency [76] states that "*Without data on the total idling hours for construction vehicles and equipment in the United States, the total potential emissions reductions possible through sector-wide idling reductions could not be estimated*". The report continues to state that for the US market alone, if their construction industry could reduce fuel consumption by 10% then the reduction in CO_2 would equate to 6.73 million metric tons [76]. Clearly there is a large opportunity to stop the vehicle engine from running during these periods. This would have a measurable impact upon reducing fuel consumption, CO_2 output, NOx formation and particulate emissions.

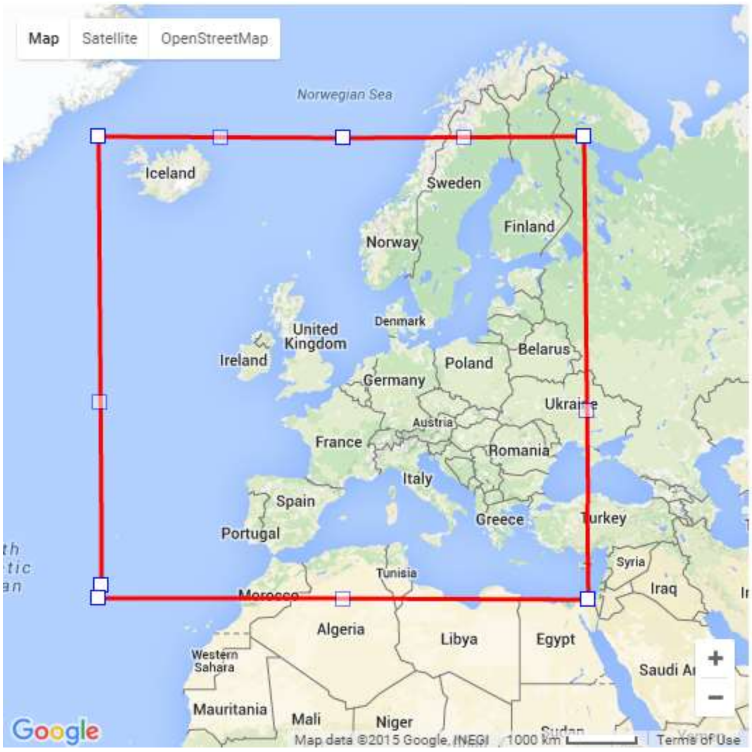
4. Big data management and analysis approach for construction equipment fleet

In order to develop the big data management and analysis approach for construction equipment fleet, the primary requirement is to have an appropriate data capturing and extraction strategy. Based on the obtained data package, a data compression and mining process is then introduced.

4.1 Data capturing and extraction

4.1.1 Selected machines and study location

Without loss of generality, the following works pay attention to develop the data management and analysis approach for construction machines manufactured by JCB. JCB is known as the world's third largest construction equipment brand by volume, after Caterpillar and Volvo. JCB is the market leader in UK, Europe, India and Russia/CIS with 22 plants around the world, of which 11 are in UK. Thus, it is reasonable to select JCB machines for this study. For the investigation, 20 machine variants of the four main classes from JCB have been selected, including compact excavators, heavy excavators, backhoe loader and telescopic handlers. Here, for each class, n machine variants are indexed from 1 to n corresponding to their engine powers from the smallest to largest capacity. In consideration of MMH for construction machinery in UK, it is worth selecting the primary study area in Europe. The selected region is drawn in Fig. 11.



Location Range:

Latitude: 64° 4'42.34"N (64.07843)
Longitude: 27°48'21.04"W (-27.80584)

Latitude: 64° 4'42.34"N (64.07843)
Longitude: 32°44'29.49"E (32.74153)

Latitude: 32°52'28.55"N (32.87460)
Longitude: 27°48'21.04"W (-27.80584)

Latitude: 32°52'28.55"N (32.87460)
Longitude: 32°44'29.49"E (32.74153)

Fig. 11. Selected region for JCB product investigation (*Source: Google Maps*)

4.1.2 Telematics and LiveLink for data capturing

Along with the development of construction machinery, there is a high demand on availability of detailed data of vehicles and machines for ease of monitoring and maintenance, and evaluation of machines efficiency, productivity and profitability. And recently with the rapid evolution of information and communication technologies, telematics, known as the combination of telecommunications and informatics, is specially paid attention to. The use of the telematics technology has the capability to enhance construction equipment fleet management to a whole new level of data gathering and data mining to maximize the benefit of both the manufacturers and users/owners.

The most commonly telematics solutions for vehicles and machines can be categorized into three categories which are integration features, usability features and service region [79]. Herein, integration features relate to operation of a vehicle/machine, including location, safety, diagnostics, communication, and interactivity. Usability features relate to the usability of the solution, stating how data is filtered and presented to the user and, how data is integrated into company operations. Meanwhile, service region providers vary greatly not only in comprehensiveness of solutions but also in their service regions, especially the United States, Canada, the United Kingdom, Ireland and the European Union.

In UK, JCB utilizes their proprietary LiveLink telematics system to collect detail data on their entire machine fleet [80]. LiveLink is capable of collecting real-time 'rich' operating data from machines via CAN bus, including GPS, track work levels (load states and fuel utilization), total time and fuel consumption, productivity, engine load, engine idle time and diagnostic data. Remote configuration of ECUs (including calibration and control strategy), early warning prognostic and vehicle owner/operator advice are also offered as a service. Additionally, as JCB designs and manufactures its own powertrains, the 'richness' and understanding of the engineering data is greatly enhanced, using LiveLink, and at a level which is inherently more detailed than what many competitors can offer. To date, JCB has developed over 100,000 vehicles with the LiveLink system fitted, covering 70 product variants and to 130 different countries.

4.1.3 Data extraction and structure

By using LiveLink, the huge data extraction from the 20 machine variants distributed within the selected area has been carried out for one year, June 2014 to June 2015. Subsequently, 12,000 machines were randomly selected for the investigation. Here, each machine operation can be represented by a set of 2 data file types in *.csv format in which file type 1 contains general information of any events of the machine while file type 2 comprises summary information of the machine when its engine is operated. As a result, 12,000 data file sets with the size of approximate 193GB were acquired. By using LiveLink, these data file sets were stored in different locations according to different machine classes and variants as following format: 'Main data folder/Machine class i^{th}/Machine variant j^{th}/Data files, in which i and j are in turn within range [1, 4] and [1, 20], and a set of data files named as 'machine_ID_all_events.csv' and 'machine_ID_events_summary.csv'.

4.2 Data compression and mining

From Section 4.1, it is clear that there is a challenge on how to compress the big amount of data package, 193GB, into another data storage format with small size for easy mining. Here, the all-in-one concept is introduced with the use of MATLAB.

4.2.1 Parameter identification

All the parameters that can be used to evaluate the machine performance are needed to be determined for the data compression. From the two data files' formats achieved by LiveLink, these parameters are determined as shown in Table 6.

Based on the parameter identification, following information about machines can be pulled out:

- Machine location (GPS), to have a brief understanding about the working environment;
- Actual operating time of each machine within a year, to investigate the effect of seasonal factors on machine performance;
- Total fuel consumption, total engine working time, percentage of machine time and fuel consumption during idle, average engine power: to evaluate the machine efficiency and productivity;
- Total machine operating time, number of machine key ON/OFF events per day, to support guarantee service.

Table 6

Parameter identification for big data compression

CSV file type 01 (All events)		CSV file type 02 (Events summary)	
Parameter	Unit	Parameter	Unit
Machine ID 1	-	Machine ID 2	-
Tracked Event ID 1	Date-Time	Tracked Event ID 2	Date-Time
Latitude	GPS	Total engine duration	s
Longitude	GPS	Total engine duration per event	s
Total power ON duration	s	Engine idling time per event	s
		Fuel consumption per event	l
		Fuel consumption during idle per event	l
		Time in engine torque band i^{th} per event*	s
		Fuel for engine torque band i^{th} per event*	l

(*) Please note that torque and speed ranges of each machine are categorized into *n* speed bands and *m* torque band (in percentage, %), respectively.

4.2.2 Data fusion

Due to the identified parameters coming from the two data file streams as described in Section 4.2.1, it is necessary to implement a fusion sorting technique before going to data compression process. Sorting is one of the most common operations in engineering especially in database applications. Among sorting algorithms, bubble sort is known as one of the efficient solution due to its simple formulation and easy implementation [81]. However, in this study, there is a requirement to extract the necessary machines' parameters from the string data in *.csv file streams. Moreover, the standard bubble sort algorithm could lead to a high computation cost when dealing with a large number of string data. Thus, a fusion sorting method named advanced string-based bubble sort (ASBBS) is proposed to deal with these problems. The detailed ASBBS procedure is given in Appendix-A.

4.2.3 Data compression and mining

In this section, a data compression approach based on the all-in-one concept is proposed to compress the huge amount of machine information into a small-scale data package. The key idea is to store all the identified parameters with their database into a file with format *.mat in MATLAB. This *.mat file named as 'MachineDataPool' is a structure data which manages all the machine information by using specified fields and values. The structure of this MachineDataPool.mat file can be described in Fig. 12. Here, most of machine information are extracted directly from the data fusion process (see Section 4.2.2), except the analysis of machine idle. Herein, the idle state of each machine as well as engine performance can be determined as:

- Machine idle condition is defined by the experts at JCB and based on the definition of torque-speed band of each specific machine variant;
- Time ratio of idling per event is computed as:

$$\%T_{idle}^{event} = \frac{T_{idle}^{event}}{T_{full}^{event}} \tag{2}$$

where, T_{full}^{event} and T_{idle}^{event} are are obtained from LiveLink.

- Fuel consumption ratio of idling per event is computed as:

$$\%Fl_{idle}^{event} = \frac{Fl_{idle}^{event}}{Fl_{full}^{event}} \tag{3}$$

where, Fl_{full}^{event} and Fl_{idle}^{event} are obtained from LiveLink.

- For each speed and torque band, it is capable of determining the average fuel consumption and engine efficiency in the real working conditions. For each event, the actual fuel consumption rate, Fl_{rate}^{band}, for each torque and speed band, τ_E^{band} and n_E^{band}, can be derived as:

$$Fl_{rate}^{band}\left(\tau_E^{band}, n_E^{band}\right) = \frac{Fl_{act}^{band}}{T_{act}^{band}} \tag{4}$$

where, Fl_{act}^{band} and T_{act}^{band} are obtained from LiveLink.

- The engine efficiency for each $\left(\tau_E^{band}, n_E^{band}\right)$ can be derived as:

$$\eta_{act}^{band}\left(\tau_E^{band}, n_E^{band}\right) = \frac{\int_0^{T_{act}^{band}} \left(\frac{\pi \tau_E^{band} n_E^{band}}{30}\right) dt}{Fl_{rate}^{band}\left(\tau_E^{band}, n_E^{band}\right) \frac{E_{rate}^{th}}{Fl_{rate}^{th}}} \eta_{th}^{E} \tag{5}$$

here, Fl_{rate}^{th}, E_{rate}^{th} and η_{th}^{E} are obtained from the engine manufacturer.

However, it is difficult to perform this data compression due to the database of each machine coming with different factors, such as machine class, machine variant, machine ID, and data length. Hence, to simplify the data compression process, all the logics for the data compression have been developed using following steps:

- Step 1: using 'text' commands with general forms in which all the variables and operators are put into string arrays. Thus, all the logics are converted into 'string' expressions.
- Step 2: using 'eval' command from MATLAB to execute 'string' expressions.

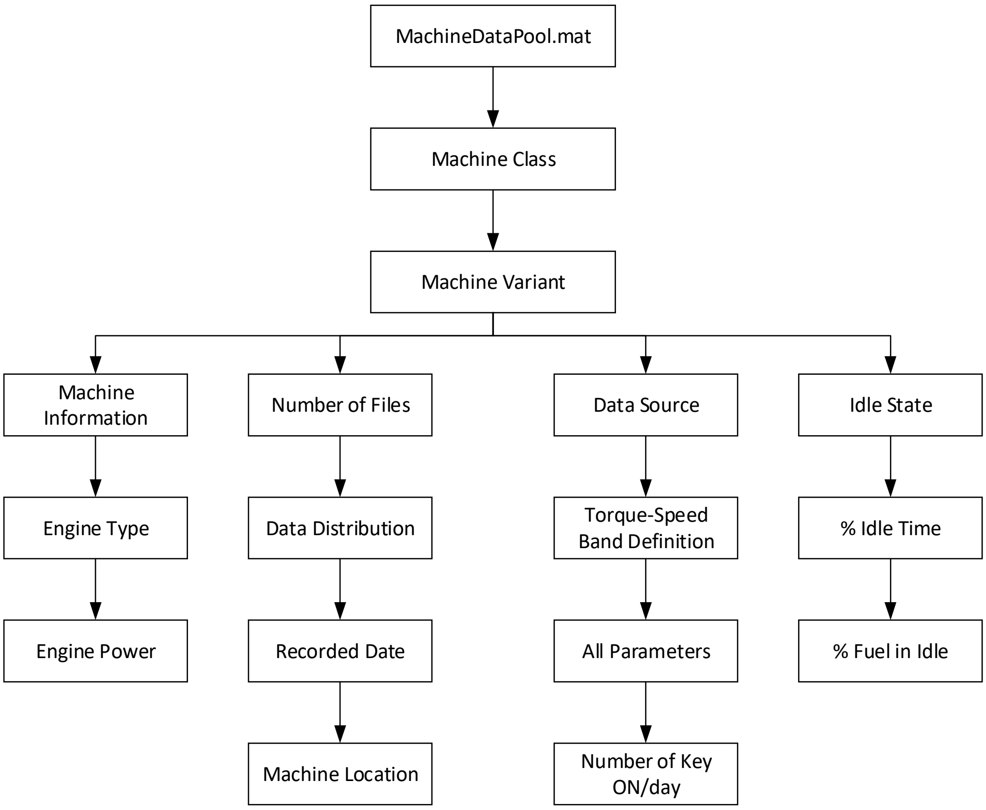


Fig. 12. Structure of 'MachineDataPool.mat' file using all-in-once concept

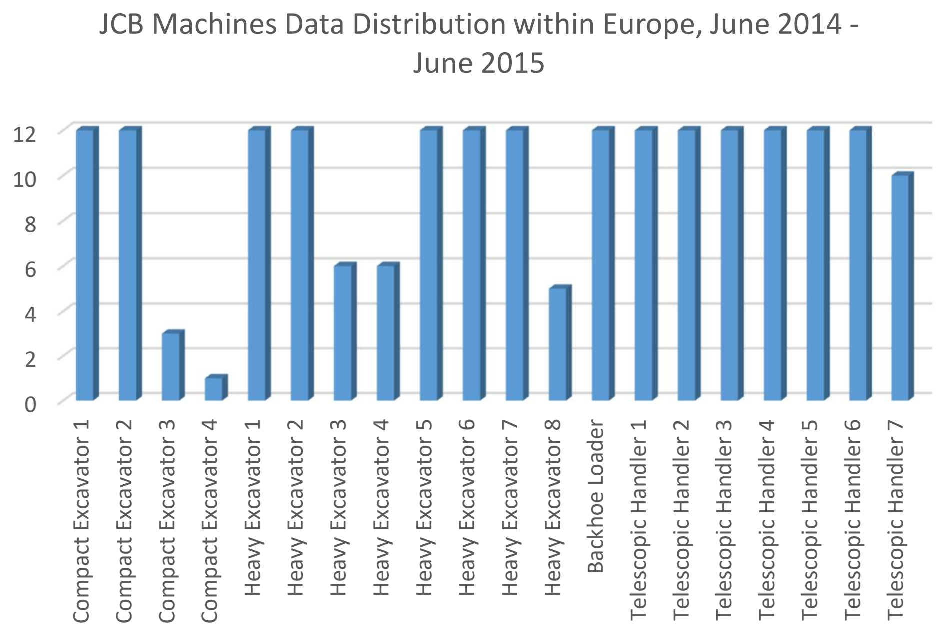


Fig. 13. Sample machine distribution vs. date

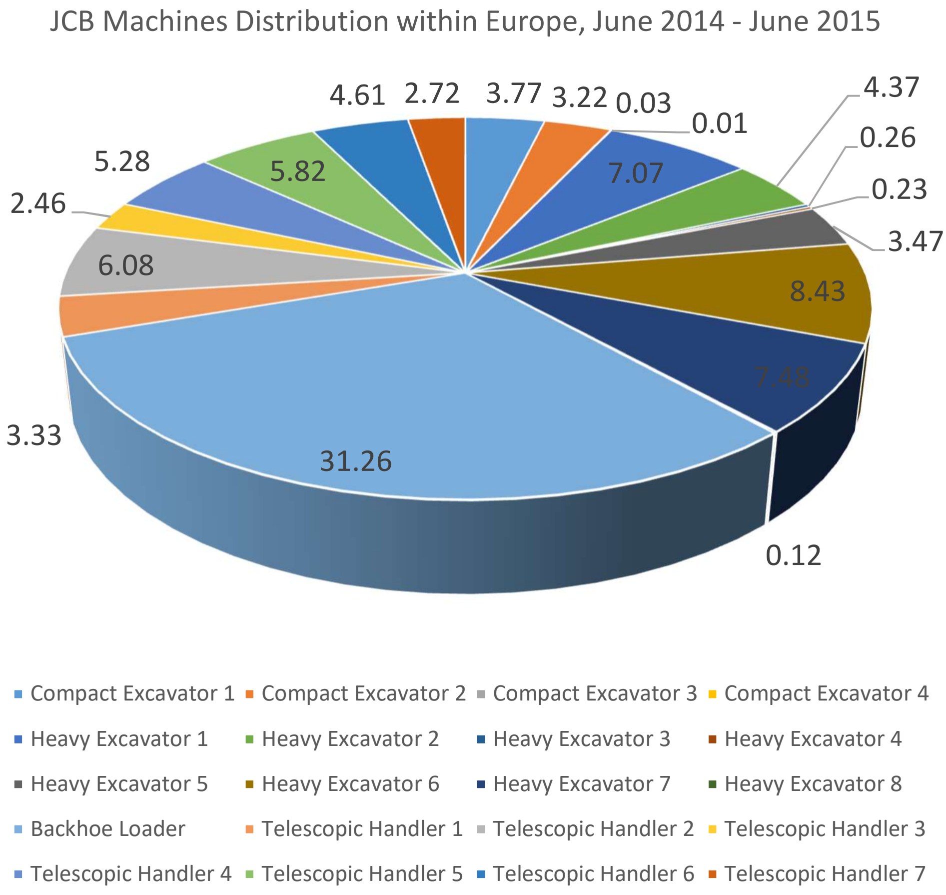


Fig. 14. Sample machine distribution vs. location

By using the proposed data compression approach, the large-scale data package of 193GB has been compressed into a new MachineDataPool.mat file with a size of only 7.43GB (96% was reduced). This, therefore, enables users to be able to access the machine data easily and efficiently for the performance analysis as well as other activities mentioned in Section 4.2.1.

The analysis results of the actual engine performance can be used for both modelling and model-based stop-start control design applications. Meanwhile, the machine idle state analysis supports to evaluate the MMH potential of each machine variant. In addition based on the compressed database, the distributions of sample machines over location and date are detected as plotted Fig. 13 and Fig. 14. These results imply that for a whole year 2014-2015, some machine types were popular and usually used in EU but some types were used with small numbers of machines during just a few months. These factors also need to be taken into account when evaluating the MMH potential.

5. Decision tool design for target machine selection

In this section, a decision tool is developed in order to investigate the idle states of different machine types and consequently, to define which machine is most suitable for utilizing the MMH technology. And fuzzy cognitive maps are able to deal with processes like decision making that is based on human reasoning process [82]. Due to this advanced fundamental, FCMs have been successfully used for many applications, ranging from medical fields, agricultural applications and environmental areas to energy problems [82-84]. In this study, a FCM-based decision tool is then suggested to support decision making for MMH utilization of the studied machine types. This decision tool is built with a number of cost factors defined from the big data mining and knowledge of experts, along with the proper selection of fuzzification and defuzzification functions. The procedure to construct this FCM-based decision tool is introduced as the followings.

5.1 Fuzzy cognitive map architecture

An FCM designed for a system is graphically represented by a frame of nodes and connection edges. The nodes (or concepts) stand for different behaviours of the system. Each concept can be an input/output variable, a state, or an event of the system. In addition, these nodes interact with each other and therefore, are capable of representing the system dynamics. The interactions between nodes are modelled by connection edges of which the directions and weights indicate the directions and degrees of the causal relationships, respectively. Without loss of generality, a generic FCM with five concepts is depicted in Fig. 15.

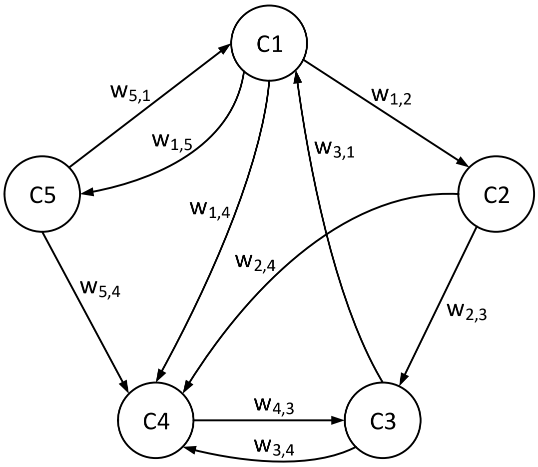


Fig. 15. A sample FCM with 5 concepts

Herein, the concepts are denoted as a set of nodes C_i with $i = 1,\ldots,N$ (N is the number of FCM nodes, N=5 in this case). Each node is characterized by a specific value, x_i, which is fuzzified from the real system behaviour value into the closed universe [0, 1]. Between each two nodes, i and j, there are three possible relationships which are known as positive, negative or neutral causality and can be expressed by weight factors, w_{ij}, which is then interpreted using linguistic variables in a normalized range [-1, 1]. A weight set of a generic FCM therefore can be defined as

$$W = \begin{bmatrix} w_{1,1} & \cdots & w_{1,N} \\ \vdots & \ddots & \vdots \\ w_{N,1} & \cdots & w_{N,N} \end{bmatrix}$$

$$w_{ij} \in [-1,1], \qquad i = 1,\ldots,N;\ j = 1,\ldots,N$$

Thus, the value, x_i, of node C_i at step $(k+1)^{\text{th}}$ can be computed based on the influence of the other interconnected nodes, C_j, on node C_i, as

$$x_i^{k+1} = f\left(x_i^k + \sum_{j=1,j\neq i}^{N} x_j^k w_{ji}\right) \tag{6}$$

where f is the activation function which is selected based on different applications. For decision making, it is realized that sigmoid function is one of the feasible choices [85]. Thus in this study, the sigmoid function is employed as the FCM activation function:

$$f(a) = \frac{1}{1+e^{-\lambda a}} \tag{7}$$

where $\lambda > 0$ is the steepness parameter and selected as unit.

5.2 Selection of cost factors for FCM-based decision tool

In order to utilize a FCM to design the decision tool, the prior task is to select properly a set of concepts. Here, the concepts are the cost factors (α) which are mainly related to the MMH potential. Subsequently, twelve factors have been selected and defined in Table 7. Here, the first seven factors ($\alpha_1$to α_7) are come from the data mining process introduced in Section 4.2.3, other four technical and commercial factors (α_8 to α_{11}) are indicated by experts in construction machinery, and the last factor (α_{12}) is the MMH potential.

Table 7

Definition of cost factors for the FCM-based decision tool

Factor	Definition	Physical meaning
α_1	Idling time ratio per event	Percentage (%)
α_2	Idling fuel consumption ratio per event	Percentage (%)
α_3	Idling fuel consumption per event	Large value means long time in idle
α_4	Standard variation of idling time ratio per event	Large value means unstable idling time ratio
α_5	Standard variation of idling fuel consumption ratio per event	Large value means unstable idling fuel consumption ration
α_6	Standard variation of idling fuel consumption per event	Large value means unstable idling fuel consumption
α_7	Machine power	Large value means large machine
α_8	Technical ease of installation	Small value means easy
α_9	Cost for implementation	Large value means expensive solution
α_{10}	Payback time	Large value means long payback time
α_{11}	Machine potential in market	Large value means high sale in market
α_{12}	MMH potential	Large value means high potential to implement MMH

Table 8

Cost factors evaluation for different machine variants

Class	Variant	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}
Compact Excavator	1	5	3	4	9	4	16	2	6	2	2	10
	2	4	2	6	11	2	17	2	5	1	1	13
	3	6	5	5	3	3	19	3.556	4	4	3	19
	4	1	1	20	20	1	20	3.556	3	3	4	20
Heavy Excavator	1	12	10	8	6	17	5	20	2	6	6	4
	2	16	18	13	5	20	2	20	1	5	5	9
	3	14	13	10	10	16	4	12	7	7	10	16
	4	19	19	2	1	19	1	12	8	8	11	17
	5	20	20	7	2	18	3	12	9	9	7	11
	6	8	16	1	4	15	6	9.333	10	10	8	2
	7	10	15	3	7	13	7	9.333	11	11	9	3
	8	2	17	14	8	14	15	9.333	12	12	12	18
Backhoe Loader	1	3	4	18	17	12	8	9.333	20	20	19	1
Telescopic Handler	1	11	6	9	16	10	13	12	13	15	15	12
	2	9	7	17	19	11	12	9.333	15	14	14	5
	3	17	14	16	13	9	14	3.556	18	13	13	15
	4	13	9	11	12	7	10	9.333	17	16	16	7
	5	18	12	19	18	6	11	3.556	19	17	17	6
	6	15	11	12	14	8	9	9.333	14	19	18	8
	7	7	8	15	15	5	18	3.556	16	18	20	14

By using the data mining results in Section 4 and the evaluation from experts on the 20 machine variants, values of the chosen factors α_1 to α_{11} can be derived and normalized into range 1 to 20 as shown in Table 8.

5.3 FCM-based decision tool design and MMH potential evaluation

In this section, the FCM is constructed with the selected cost factors as its inputs. With the knowledge of experts, the interrelation between the FCM inputs therefore can be described as in Fig. 16 (note that, $\alpha_i \equiv A_i$).

Firstly, the values of the FCM nodes are derived as the normalized values of the cost factors using proper gains. Next, the influence between the FCM nodes are analysed. Due to the symmetric design of weight factors, their amplitude tagged as 'INF' can be represented by linguistic variables while their signs are defined based on the direction of the connection edges. Here, five triangle membership functions tagged as 'Z', 'S', 'M', 'B', and 'VB', which in turn stand for zero, small, medium, big, and very big, are uniformly distributed within the closed universe [0, 1] to describe the influence (see Fig. 17).

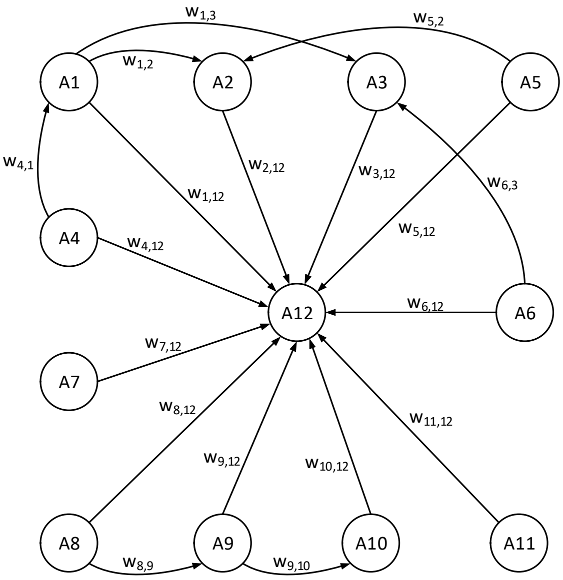


Fig. 16. Fuzzy cognitive map design for machine cost factors

Secondly, the definition of the FCM weights is carried out using the knowledge of experts. A survey on the impacts between the defined cost factors has been performed by 10 experts in the fields of construction machines and hybrid technologies. Based on their evaluation sheets (as summarized in columns E1 to E10 of Table 9), the decision on FCM weights is made by the defuzzification using the centre average algorithm. By combining the resulting weights with the signs of these weights based on Fig. 16 and column WS of Table 9, final values of the FCM weights are derived as the last column in Table 9.

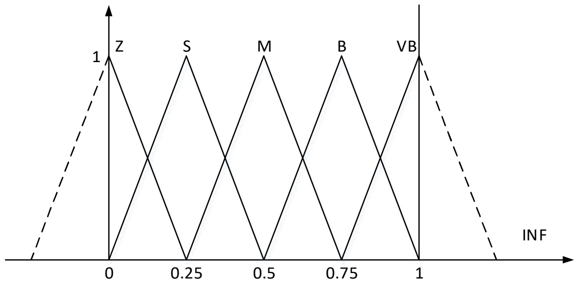


Fig. 17. Membership function design for the node influence

Table 9

Survey on Weight Evaluation (generated based on knowledge from experts)

	W	WS	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	FW
1	$w_{1,12}$	+	VB	B	B	B	VB	B	B	B	B	B	0.8
2	$w_{2,12}$	+	VB	B	VB	VB	B	VB	B	B	VB	VB	0.9
3	$w_{3,12}$	+	VB	B	VB	B	VB	VB	VB	VB	VB	B	0.925
4	$w_{4,12}$	-	S	S	B	S	S	B	B	B	S	S	-0.45
5	$w_{5,12}$	-	B	S	B	S	B	B	S	S	S	S	-0.45
6	$w_{6,12}$	-	B	S	B	S	S	B	S	S	B	S	-0.45
7	$w_{7,12}$	+	S	B	B	B	S	B	S	B	B	B	0.6
8	$w_{8,12}$	+	M	S	B	S	S	S	S	S	S	S	0.325
9	$w_{9,12}$	-	B	VB	B	VB	VB	VB	B	B	B	VB	-0.875
10	$w_{10,12}$	-	VB	VB	B	VB	VB	VB	VB	B	B	VB	-0.925
11	$w_{11,12}$	+	VB	VB	B	B	B	B	B	B	VB	B	0.825
12	$w_{1,2}$	+	VB	VB	VB	VB	VB	VB	B	VB	B	VB	0.95
13	$w_{1,3}$	+	VB	VB	B	B	B	VB	VB	B	VB	VB	0.9
14	$w_{4,1}$	-	M	M	B	M	B	M	M	M	M	B	-0.575
15	$w_{5,2}$	-	M	M	B	M	M	M	B	M	M	M	-0.55
16	$w_{6,3}$	-	M	B	M	B	M	B	M	B	M	M	-0.6
17	$w_{8,9}$	-	B	B	VB	VB	VB	B	VB	VB	VB	VB	-0.925
18	$w_{9,10}$	+	VB	VB	B	VB	B	B	VB	B	B	VB	0.875

(WS – Sign of weights; FW – Final weight values evaluated based on expert evaluation E1-E10 and WS)

Finally, the FCM-based decision tool is constructed in which the factor, α_{12}, is selected as the output and, computed based on the FCM algorithm ((6) and (7)) and the final FCM weights (the last column in Table 9). The resulting value of the output factor representing the MMH potential is then re-scaled into range 1 to 20. The machine with the highest value of α_{12} will has the most suitable for hybridisation. As a result, the MMH evaluation with the 20 machine variants is performed and the result is shown in Table 10. From this result, it is realized that the heavy excavator – type 2 has the highest MMH potential and, therefore, it has been selected for utilizing the MMH technologies.

Table 10

Cost factors evaluation for different machine variants

Class	Variant	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}
Compact Excavator	1	5	3	4	9	4	16	2	6	2	2	10	**10.328**
	2	4	2	6	11	2	17	2	5	1	1	13	**11.447**
	3	6	5	5	3	3	19	3.556	4	4	3	19	**13.265**
	4	1	1	20	20	1	20	3.556	3	3	4	20	**13.306**
Heavy Excavator	1	12	10	8	6	17	5	20	2	6	6	4	**14.242**
	2	16	18	13	5	20	2	20	1	5	5	9	**17.711**
	3	14	13	10	10	16	4	12	7	7	10	16	**15.093**
	4	19	19	2	1	19	1	12	8	8	11	17	**15.957**
	5	20	20	7	2	18	3	12	9	9	7	11	**16.437**
	6	8	16	1	4	15	6	9.333	10	10	8	2	**9.561**
	7	10	15	3	7	13	7	9.333	11	11	9	3	**9.652**
	8	2	17	14	8	14	15	9.333	12	12	12	18	**12.107**
Backhoe Loader	1	3	4	18	17	12	8	9.333	20	20	19	1	**3.559**
Telescopic Handler	1	11	6	9	16	10	13	12	13	15	15	12	**7.643**
	2	9	7	17	19	11	12	9.333	15	14	14	5	**7.428**
	3	17	14	16	13	9	14	3.556	18	13	13	15	**12.581**
	4	13	9	11	12	7	10	9.333	17	16	16	7	**8.101**
	5	18	12	19	18	6	11	3.556	19	17	17	6	**9.301**
	6	15	11	12	14	8	9	9.333	14	19	18	8	**8.291**
	7	7	8	15	15	5	18	3.556	16	18	20	14	**5.989**

6. Conclusions

This paper reviews the architectures of both automobiles and construction machines with current hybridisation technologies and then, pays attention to the applicability of micro/mild hybridisation for construction machinery in UK. The challenges for this development as well as the outcomes from this study can be summarized as follows:

- There are technological gaps between hybrid electric vehicles and hybrid electric machines, including system architecture and components, working cycles, energy management system and reliability.
- Based on these gaps, the design challenges of a micro/mild hybrid machine are pointed out. These comprise machine architectures, energy storage devices, energy management strategies, additional features, and applicability.
- Focusing on the UK construction market, it is recognized that there are suitable conditions for the utilization of MMH technology. Over 12,000 sample machines manufactured by JCB have been selected for the further analysis and machine development.
- The big data management approach using the ASBBS method and all-in-one concept has been developed. Using this approach, the large data amount from various JCB machine variants,

193GB, has been compressed remarkably into the small data package, only 7.43GB (96% of the data package size could be reduced). This allows users to store and access easily any necessary data for machine analyses as well as other maintenance services.

- The FCM-based decision tool is constructed in order to find out which machine variant has the highest potential for MMH technology implementation. The evaluation with 20 typical machine variants has been then performed using the designed tool and the experts' knowledge. The evaluation result has indicated that the heavy excavator – type 2 with the highest MMH potential is the best choice for the MMH implementation. In addition, this tool enables the markers go quickly in developing their new product lines which satisfy all design requirements.
- Based on the outcomes of this study, the next research stage is to design the MMH technologies, starting from micro hybridisation for the target machine, a heavy excavator – type 2 from JCB, including machine powertrain modelling, energy management strategies, simulations and real-time implementation.

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Appendix-A, (ASBBS Procedure)

The ASBBS procedure can be described as following steps:

- Step 1: Select specific machine class and variant as the current location for data fusion.
- Step 2: Re-arrange all data files in the current location in alphabetical order and count total file number (stored in variable 'total_files'); next, define 3 variables with initial values: file_index = 1, event_index1 = 1 for master files, event_index2 = 1 for slave files.
- Step 3: Go to an outer loop:

```
While (file_index <= total_files/2)
    Label – 'Loading a data file set'
        Load a data file set with respect to file_index;
```

```
    If any file of this set = empty
        Remove this file set and return to Label – ‘Loading a data file set’;
Select ‘machine_ID_events_summary.csv’ as the master file and the other,
‘machine_ID_all_events.csv’, as the slave file;
Check number of engine events in these master and slave files and store in variable
‘total_eng_events1’ and ‘total_eng_events2, respectively;
Convert all cells of ‘tracked_event_ID’ columns of both the files into numbers, mark these
numbers with their original row location (using location stamps), and sort them in ascending
order;
Label – ‘Modified bubble sort’
    While (event_index1 <= total_eng_events1)
        If event_index1 = 1
            Set initial value of event_index2 = floor(total_eng_events2/2);
        While (tracked_event_ID1(event_index1) ~= tracked_event_ID2(event_index2))
            If (tracked_event_ID1(event_index1) > tracked_event_ID2(event_index2))
                event_index2 = floor(event_index2/2 + total_eng_events2/2);
            Else
                event_index2 = floor(event_index2/2);
        Combine machine performance information from the two files with respect to the event
        index ‘event_index1’ based on the location stamps;
        Increase event index: event_index1 = event_index1 + 1;
        Return to Label – ‘Modified bubble sort’;
```

- Step 4: Set: file_index = file_index + 1, event_index1 = 1 for master file, event_index2 = 1 for slave file, and go to Step 3. Once (file_index > total_files/2), go to Step 5.

Step 5: Return to Step 1 until machine data of all variants are combined. Finish.

References

[1] Khan MI, Yasmeen T, Khan MI, Farooq M, Wakeel M. Research progress in the development of natural gas as fuel for road vehicles: A bibliographic review (1991–2016). Renewable and Sustainable Energy Reviews. 2016;66:702-41.

[2] Popescu F, Ionel I. <Anthropogenic Air Pollution Sources_Intech.pdf>. In: Kumar A, editor. Air Quality. Croatia: InTech; 2010. p. 1-22.

[3] Anderson J, Fergusson M, Valsecchi C. An Overview of Global Greenhouse Gas Emissions and Emissions Reduction Scenarios for The Future. In: Goossens Y, editor. European Parliament: DG Internal Policies of The Union - Policy Department Economic and Scientific Policy; 2008. p. 1-28.

[4] Global Status Report: Towards zero-emission efficient and resilient buildings. Global Alliance for Buildings and Construction; 2016.

[5] Huang L, Krigsvoll G, Johansen F, Liu Y, Zhang X. Carbon emission of global construction sector. Renewable and Sustainable Energy Reviews. 2018;81:1906-16.

[6] Peters VA, Manley DK. An examination of fuel consumption trends in construction projects. Energy Policy. 2012;50:496-506.

[7] Global Report Construction Equipment 2017. In: Woof M, editor. World Highways. UK2017.

[8] Outlook for global construction equipment markets: Europe. Global Report: Construction Equipment 2016 [cited 2017 August]; Available from: http://wwwroplcom/special-publications/special-reports/global-report-construction-equipment/outlook-for-global-construction-equipment-markets-europe/.

[9] Final Report Executive Summary. UK: Low Carbon Construction Innovation & Growth Team; 2010.

[10] Low Carbon Construction Action Plan, Government response to the Low Carbon Construction Innovation & Growth Team Report. UK2011.

[11] Fuhs AE. Hybrid Vehicles and the Future of Personal Transportation. Boca Raton, United States of America: CRC Press; 2009.

[12] Tatum C, Vorster M, Klingler M. Innovations in Earthmoving Equipment: New Forms and Their Evolution. Journal of Construction Engineering and Management. 2006;132:987-97.

[13] Böhler F, Thiebes P, Geimer M, Santoire J, Zahoransky R. Hybrid Drive Systems for Industrial Applications. SAE Technical Paper Series DOI 2009-24-0061. 2009:1-9.

[14] Lin T, Chen Q, Ren H, Huang W, Chen Q, Fu S. Review of boom potential energy regeneration technology for hydraulic construction machinery. Renewable and Sustainable Energy Reviews. 2017;79:358-71.

[15] Lin T, Wang Q, Hu B, Gong W. Development of hybrid powered hydraulic construction machinery. Automation in Construction. 2010;19:11-9.

[16] Wang D, Guan C, Pan S, Zhang M, Lin X. Performance analysis of hydraulic excavator powertrain hybridization. Automation in Construction. 2009;18:249-57.

[17] Kwon T-s, Lee S-w, Sul S-K, Park C-G, Kim N-i, Kang B-i, et al. Power Control Algorithm for Hybrid Excavator With Supercapacitor. IEEE Transactions on Industry Applications. 2010;46:1447-55.

[18] Kagoshima M, Komiyama M, Nanjo T, Tsutsui A. Development of new hybrid excavator. Kobelco Technology Review. 2007;27:39-42.

[19] Mousavi G SM, Faraji F, Majazi A, Al-Haddad K. A comprehensive review of Flywheel Energy Storage System technology. Renewable and Sustainable Energy Reviews. 2017;67:477-90.

[20] Wasbari F, Bakar RA, Gan LM, Tahir MM, Yusof AA. A review of compressed-air hybrid technology in vehicle system. Renewable and Sustainable Energy Reviews. 2017;67:935-53.

[21] Burke AF. Batteries and ultracapacitors for electric, hybrid and fuel cell vehicles. Proceedings of the IEEE: IEEE; 2007. p. 806 - 20.

[22] Xiao Q, Wang Q, Zhang Y. Control strategies of power system in hybrid hydraulic excavator. Automation in Construction. 2008;17:361–7.

[23] Lin X, Pan S-x, Wang D-y. Dynamic simulation and optimal control strategy for a parallel hybrid hydraulic excavator. Journal of Zhejiang University SCIENCE A. 2008;9:624-32.

[24] Takahashi K, Kishimoto S, Takebayashi Y, Mori K, Nakamura N. Hybrid Working Machine. 2015.

[25] Choi J, Kim H, Yu S, Yi K. Development of integrated controller for a compound hybrid excavator. Journal of Mechanical Science and Technology. 2011;25:1557-63.

[26] Moriki H, Kaneko S, Hoshino M, Ikimi T, Ito N. Electronically Driven Working Vehicle. 2015.

[27] Riyuu S, Tamura M, Ochiai M, Kasuya H. Hybrid construction machine. In: Patent J, editor. Japan2003.

[28] Ochiai M. Development for environment friendly construction machinery. Construction. 2003;9:24-8.

[29] Naruse M, Tamaru M, Kimoto K. Hybrid Construction Equipment. 2002.

[30] Inoue H. Introduction of PC200-8 Hybrid Hydraulic Excavators. Introduction of Product: Komatsu; 2008. p. 1-6.

[31] Geske DM. New Holland "Ex"-ercises Hybrid Option. Diesel Progress International Edition: New Holland; 2007. p. 1.

[32] Volvo CE Unveils Hybrid Wheel Loader. Green Car Congress: Volvo; 2008.

[33] Further developments in hybrid technology. Contractors World. Contractors World Bauma Review - A Show of Optimism - Part III ed. Bauma: Atlas Weyhausen; 2010.

[34] Vallur AR, Khairate Y, Awate C. Prescriptive Modeling, Simulation and Performance Analysis of Mild Hybrid Vehicle and Component Optimization. SAE International. 2015;2015-26-0010:1-17.

[35] Teratani T, Kuramochi K, Nakao H. Development of Toyota Mild Hybrid System (THS-M) with 42V PowerNet. Electric Machines and Drives Conference (IEMDC'03): IEEE; 2003. p. 3-10.

[36] Song J, Zhang X, Tian Y. Research on Control Strategy of Mild Parallel Hybrid Electric Vehicle. International Conference on Electric Information and Control Engineering (ICEICE). Wuhan, China: IEEE; 2011. p. 2512 - 6.

[37] Tie SF, Tan CW. A review of energy sources and energy management system in electric vehicle. Renewable and Sustainable Energy Reviews. 2013;20:82-102.

[38] Kopera JJC. Inside the Nickel Metal Hydride Battery. COBASYS; 2004. p. 1-14.

[39] Dustmann C-H. Advances in ZEBRA batteries. JournalofPowerSources.127:85–92.

[40] Lee B-H, Shin D-H, Song H-S, Jeong J-B, Kim H-J, Kim B-W. The Dynamic Control of Hybrid Energy Storage System for Mild HEV. Vehicle Power and Propulsion Conference (VPPC 2007). Arlington, Texas: IEEE; 2007. p. 796 - 801.

[41] Li T, Deng K, Peng H, Wu C. Independent fuel injection strategy based on the initial piston positions for HEV engine quick start. Fuel. 2014;117:733-41.

[42] Bendu H, Murugan S. Homogeneous charge compression ignition (HCCI) combustion: Mixture preparation and control strategies in diesel engines. Renewable and Sustainable Energy Reviews. 2014;38:732-46.

[43] Thounthong P, Raël S, Davat B. Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications. Journal of Power Sources. 2009;193:376–85.

[44] Erdinc O, Uzunoglu M. Recent trends in PEM fuel cell-powered hybrid systems: Investigation of application areas, design architectures and energy management approaches. Renewable and Sustainable Energy Reviews. 2010;14:2874-84.

[45] Zandi M, Payman A, Martin J-P, Pierfederici S, Davat B, Meibody-Tabar F. Energy Management of a Fuel Cell/Supercapacitor/Battery Power Source for Electric Vehicular Applications. IEEE Transactions on Vehicular Technology. 2011;60:433-43.

[46] Salmasi FR. Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison, and Future Trends. IEEE Transactions on Vehicular Technology. 2007;56:2393-404.

[47] Pisu P, Rizzoni G. A Comparative Study Of Supervisory Control Strategies for Hybrid Electric Vehicles. IEEE Transactions on Control Systems Technology. 2007;15.

[48] Won J-S, Langari R. Torque Control Strategy for A Parallel-Hybrid Vehicle Using Fuzzy Logic. Expert Systems. 2002;19:4-10.

[49] Lee H-D, Koo E-S, Sul S-K, Kim J-S. Torque Control Strategy for A Parallel-Hybrid Vehicle Using Fuzzy Logic. IEEE Industry Applications Magazine. 2000;6:33-8.

[50] Baumann BM, Washington G, Glenn BC, Rizzoni G. Mechatronic Design and Control of Hybrid Electric Vehicles. IEEE/ASME Transactions on Mechatronics. 2000;5:58-72.

[51] Langari R, Won J-S. Intelligent Energy Management Agent for a Parallel Hybrid Vehicle—Part II: Torque Distribution, Charge Sustenance Strategies, and Performance Results. IEEE Transactions on Vehicular Technology. 2005;54:935-53.

[52] Langari R, Won J-S. Intelligent Energy Management Agent for a Parallel Hybrid Vehicle—Part I: System Architecture and Design of the Driving Situation Identification Process. IEEE Transactions on Vehicular Technology. 2005;54:925-34.

[53] Schouten NJ, Salman MA, Kheir NA. Fuzzy Logic Control for Parallel Hybrid Vehicles. IEEE Transactions on Control Systems Technology. 2002;10:460-8.

[54] Waldman C, Gurusubramanian S, Fiorentini L, Canova M. A model-based supervisory energy management strategy for a 12 V vehicle electrical system. Control Engineering Practice. 2015;44:20-30.

[55] Goerke D, Bargende M, Keller U, Ruzicka N, Schmiedler S. Optimal Control based Calibration of Rule-Based Energy Management for Parallel Hybrid Electric Vehicles. SAE International. 2015;2015-01-1220:178-89.

[56] Zhao D, Stobart R. Real-Time Optimal Energy Management of Heavy Duty Hybrid Electric Vehicles. SAE International. 2013;2013-01-1748:369-78.

[57] Dib W, Chasse A, Moulin P, Sciarretta A, Corde G. Optimal energy management for an electric vehicle in eco-driving applications. Control Engineering Practice. 2014;29:299-307.

[58] Zou Y, Li D-g, Hu X-s. Optimal Sizing and Control Strategy Design for Heavy Hybrid Electric Truck. Mathematical Problems in Engineering. 2012;2012:1-15.

[59] Cipek M, Čorić M, Škugor B, Kasać J, Deur J. Dynamic Programming-based Optimization of Control Variables of an Extended Range Electric Vehicle. SAE International. 2013;2013-01-1481:1-13.

[60] Jun W, Wang Q, Wang P, Han B. The Optimization of Control Parameters for Hybrid Electric Vehicles based on Genetic Algorithm. SAE International. 2014;2014-01-1894:1-7.

[61] Park J, Park J-H. Development of Equivalent Fuel Consumption Minimization Strategy for Hybrid Electric Vehicles. International Journal of Automotive Technology. 2012;13:835-43.

[62] He Y, Chowdhury M, Pisu P, Ma Y. An energy optimization strategy for power-split drivetrain plug-in hybrid electric vehicles. Transportation Research Part C. 2012;22:29-41.

[63] Styler A, Nourbakhsh I. Real-Time Predictive Optimization for Energy Management in a Hybrid Electric Vehicle. Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence. Texas, USA2015. p. 737-43.

[64] Gao Y, Ehsani M. A Mild Hybrid Drive Train for 42 V Automotive Power System–Design, Control and Simulation. SAE International. 2002;2002-01-1082:1-7.

[65] Lin C-C, Peng H, Grizzle JW, Kang J-M. Power Management Strategy for a Parallel Hybrid Electric Truck. IEEE Transactions on Control Systems Technology. 2003;11:839-49.

[66] Gupta S, Sharma R, Yuaraj KB, Yadav AK, Narula M, Sahoo T. Supervisory Control Strategy for Mild Hybrid System - A Model Based Approach. SAE International. 2015;2013-01-0503:1-9.

[67] Rotenberg D, Vahidi A, Kolmanovsky IV. Ultracapacitor Assisted Powertrains: Modeling, Control, Sizing, and the Impact on Fuel Economy. IEEE Transactions on Control Systems Technology. 2011;19:576-89.

[68] You C-Y, Park W-Y, Jeong G-M, Moon C. A Comparative Study of Fuzzy Logic-Based Control Strategies for a Parallel Mild Hybrid Electric Vehicle. International Conference on Control, Automation and Systems. Seoul, Korea: IEEE; 2008. p. 1042-6.

[69] Feldkamp L, Abou-Nasr M, Kolmanovsky IV. Recurrent Neural Network Training for Energy Management of a Mild Hybrid Electric Vehicle with an Ultra-Capacitor. Workshop on Computational Intelligence in Vehicles and Vehicular Systems (CIVVS '09). Nashville, Tennessee: IEEE; 2009. p. 29 - 36.

[70] Dhameja S, Sway-Tin M. Traction Batteries - Their Effects on Electric Vehicle Performance SAE International.1997-02-24.

[71] Casoli P, Gambarotta A, Pompini N, Riccò L. Hybridization methodology based on DP algorithm for hydraulic mobile machinery — Application to a middle size excavator. Automation in Construction. 2016;61:42-57.

[72] Park KS, Kim SI, Jeong HJ. Low Idle Control System of Construction Equipment and Automatic Control Method Thereof. In: Patent U, editor.2013.

[73] Frellch TA. Autoadaptive Engine Idle Speed Control. In: Patent U, editor.2014.

[74] Holt GD, Edwards DJ. Innovation or business survival?: A preliminary, qualitative study of UK construction plant supply chains. Construction Innovation. 2012;12:99-122.

[75] Segerstedt A, Olofsson T. Supply chains in the construction industry. Supply Chain Management: An International Journal. 2010;15:347-53.

[76] Potential for Reducing Greenhouse Gas Emissions in the Construction Sector. U.S. Environmental Protection Agency 2009.

[77] Holt GD, Edwards DJ. Analysis of United Kingdom Off-Highway Construction Machinery Market and Its Consumers Using New-Sales Data. Journal of Construction Engineering and Management. 2013;139:529-37.

[78] Lewis P, Leming M, Rasdorf W. Impact of Engine Idling on Fuel Use and CO2 Emissions of Nonroad Diesel Construction Equipment. Journal of Management in Engineering 2012;28:31-8.

[79] Trimble TE, Bowman DS. Market Guide to Fleet Telematics Services Creating a Consumer's Guide to Currently Available Aftermarket Solutions. Blacksburg, Virginia Housed at the Virginia Tech Transportation Institute; 2012.

[80] Livelink: Latest Technology to Help Manage Your Fleet, JCB, [cited 2015 December]; Available from: https://gunn-jcb.com/aftermarket/livelink/.

[81] Cormen TH, Leiserson CE, Rivest RL, Stein C. Introduction to Algorithms. Third Edition ed. Cambridge, Massachusetts, UK: MIT Press and McGraw-Hill; 2009.

[82] Kyriakarakos G, Patlitzianas K, Damasiotis M, Papastefanakis D. A fuzzy cognitive maps decision support system for renewables local planning. Renewable and Sustainable Energy Reviews. 2014;39:209-22.

[83] Yaman D, Polat S. A fuzzy cognitive map approach for effect-based operations: An illustrative case. Information Sciences. 2009;179:382-403.

[84] Stylios CD, Georgopoulos VC, Malandraki GA, Chouliara S. Fuzzy cognitive map architectures for medical decision support systems. Applied Soft Computing. 2008;8:1243-51.

[85] Bueno S, Salmeron JL. Benchmarking main activation functions in fuzzy cognitive maps. Expert Systems with Applications. 2009;36:5221–9.