FEASIBILITY OF INDUSTRIAL INTERNET OF THINGS (IIoT) IN FLOW ASSURANCE AND PRODUCTION ENGINEERING

A Diploma Thesis by

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Presented to

The Faculty of the Department of Mineral Resources Engineering

Technical University of Crete

Submitted in partial Fulfilment of the Requirements for the Degree

MASTER OF SCIENCE IN PETROLEUM ENGINEERING

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Chania, May 2020

"Several times in the past we have thought we were running out of oil whereas actually we were only running out of ideas."

– Parke A. Dickey, geologist, 1958

"From conceptual standpoint, IoT is that ability to create digital awareness of the physical world we live in. It's a digital pulse made up of data that we can aggregate to improve the world around us."

– John Rossman

ACKNOWLEDGEMENTS

This work was completed with the assistance and supervision of Prof. Bahman Tohidi who offered me the opportunity to do this research at Hydrafact's Ltd office, the Edinburgh-based, Heriot-Watt University Spin-off Company where he is the Managing Director. I appreciate his genuine technical and personal support throughout this work. He has been a real source of motivation during the study, by assigning me challenging tasks and developing my engineering way of thinking.

I would like to deeply thank my second supervisor, Professor Nikolaos Varotsis. He is always close to his students when they need help and his hard-work and knowledge has always been an inspiration to me.

A very special thanks goes to Assist. Prof. Vasilis Gaganis, my third supervisor, whose knowledge, expertise and skills have guided me through the journey of this Master program. He provided me with direction, technical advice and became more of a mentor and friend, than a Professor.

I greatly appreciate the committee of this thesis Prof. B. Tohidi, Prof. N. Varotsis and Assist. Prof. V. Gaganis for their precious time and valuable suggestions. I would also like to thank all the professors at the MSc Petroleum Engineering program for their teaching and effort to inspire my classmates and me, but mainly for preparing us to become professionals and successful in our future engineering life within the petroleum industry.

I am also grateful to all my friends, classmates and colleagues at the Institute of Petroleum Engineering and Hydrafact Ltd who made this year pleasant and memorable.

Last but not least, I would like to express my appreciation to my family for their care and support they provided me through my entire life and in particular, my mom Ntia, my dad Vasilis and my sister Emily.

ABSTRACT

The advent of mechanical production systems, mass production and finally automation of production processes led to the fourth industrial revolution which points toward intelligent and networked systems. At the heart of ''industry 4.0'' lies the Internet of Things (IoT) using digital technology. For Oil and Gas, digital transformation has been one of the most important strategic objectives with IoT device installation increasing exponentially over the past decade.

The IoT is a system of interconnected computing devices, mechanical and digital machines with particular attributes and the ability to collect and share data over a network without requiring human-to-human or human-to-computer interaction. Any physical object can be transformed into an IoT device if it can be connected to the internet to be controlled or transmit information.

IoT and Cloud computing are closely attached. IoT creates immense amount of data, while Cloud computing provides the pathway to present this data in a useful way to the end user. The main objectives of this digitalization in the operational context are real time monitoring, optimization and achievement of superior predictive capabilities.

In the present thesis the IoT is discussed and analysed, with focus on Industrial applications (IIoT) within the Oil and Gas sector, and in particular, flow assurance issues and production engineering. It clarifies the drivers of IIoT, presents the advantages and benefits and describes the challenges faced during the implementation. The goal of this research is to apply further automation with implementation of IoT on a company's existing conventional technology, aiming to increase production, efficiency, minimize downtime and reduce costs.

This study is the outcome of research done in collaboration with Hydrafact Ltd, an Edinburgh, UK based company providing consulting and technology expertise on Upstream O&G. The main focus of the study was the implementation of IoT on Hydrafact's sensor, HydraCHEK. This product is an analytical solution for monitoring the concentration of hydrate inhibitor and salt in produced water from a pipeline. The Cloud platform used was from IBM and the IoT device was a Raspberry Pi, a small scale computer capable of accomplishing a desired task. The Raspberry Pi, was connected to HydraCHEK and the IBM Cloud through programming, enabling communication and data exchange between the sensor and the user.

Programming was done both in Python language and Node-Red visual programming tool, due to the fact that both pre-exist in the Raspberry Pi and IBM Cloud. However, Python appeared to be more feasible solution.

The proposed study indicates the feasibility of implementation of IoT in Oil and Gas and flow assurance. With use of such "smart" technology, operations are more efficient, production is optimised and cost is reduced.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
Capex	Capital Expenditure
CDC	Centres for Disease Control
CPS	Cyber-Physical Systems
DCS	Distributed Control System
DMS	Distribution Management Systems
EMS	Energy Management Systems
EOR	Enhanced Oil Recovery
EPR	Electron Paramagnetic Resonance
E&P	Exploration and Production
GDP	Gross Domestic Product
GPIO	General-Purpose Input/Out
GPS	Global Positioning System
HD	High Definition
HDMI	High Definition Multimedia Interface
HMI	Human-Machine Interface
IIoT	Industrial Internet of Things
IOsA	Internet Of Smart Agriculture
IOsC	Internet Of Smart Cities
IOsE	Internet Of Smart Environment
IOsH	Internet Of Smart Health
IOsE	Internet Of Smart Energy
IOsI	Internet Of Smart Industry
IOsL	Internet Of Smart Living
IoT	Internet of Things

IT	Information Technology
KHI	Kinetic Hydrate Inhibitors
LAN	Local Area Network
LDHI	Low Dosage Hydrate Inhibitors
LNG	Liquefied Natural Gas
LPWAN	Low Power Wide Area Network
MAC	Media Access Control
MES	Manufacturing Execution System
ML	Machine Learning
MPFM	Multi-Phase Flow Meters
MQTT	Message Queuing Telemetry Transport
M2M	Machine to Machine
NPT	Non Productive Time
OEE	Overall Equipment Effectiveness
O&G	Oil and Gas
OT	Operational Technology
OPC UA	OPC (foundation) Unified Architecture
OPEX	Operational Expenditure
PAN	Personal Area Network
PLC	Programmable Logic Controller
PSO	Pump Stroke Optimization
PTC	Phase Transition Control
PVT	Pressure-Volume-Temperature
RFID	Radio-Frequency Identification
ROA	Return On Assets
SCADA	Supervisory Control and Data Acquisition
SD	Secure Digital

SQL	Structured Query Language
S/N	Signal to Noise
SPM	Strokes Per Minute
3-D	Three Dimensional
THI	Thermodynamic Inhibitors
UAV	Unmanned Aerial Vehicles
USB	Universal Serial Bus
USN	Ubiquitous Sensing Network
VCD	Video Compact Disc
WAN	Wide Area Network
WSN	Wireless Sensor Networks

CHAPTER 1: Introduction

1.1 IoT and IIoT

The term ‘’Internet of Things’’ (IoT) describes the technologies that connect objects to the internet. It is a network of devices/manufacturing machines (e.g. Wearable devices, vehicles, equipment, buildings) and advanced analytics embedded with electronics, sensors, actuators, software and network connectivity that enables these devices to engage in real-time information exchange. [1]

The network connectivity allows for data collection, analysis and exchange, aiming at improved and efficient productivity as well as economic benefits. The ability of transferring data without requiring human interaction, enables big amounts of data to be gathered and transferred among other devices, or through a central platform. [2]

Figure 1.1: *Internet of Things* [3]

The goal of the Internet of Things is to manage ‘’things’’ or devices to be connected anytime, in any place and with any other device, using any service and network. At the moment, around seven billion IoT devices are being connected worldwide, with this number projected to grow rapidly. [4]

Respectively, the term ‘’Industrial Internet of Things’’ (IIoT) refers to the impact of this innovation, of the Internet of Things, on industrial applications.

1.2 IIoT Technologies

The IIoT is enabled by technologies such as Cloud computing, edge computing, cyber-security, mobile technologies, machine-to-machine, 3D printing, advanced robotics, big data, internet of things, RFID technology, and cognitive computing. The technologies most related to the Internet of Things are listed below:

- Cyber-Physical Systems (CPS): It is the main technology platform for IoT and IIoT and thus the main mean of connecting physical machines.
- Cloud computing: With Cloud computing IT services can be sent to and restored from the Internet. That way, the data can be saved on Cloud-based storage systems instead of local ones.
- Edge computing: With edge computing, computer data storage is used with the necessary way in order to transform productivity, products and services in the industrial world.
- Big data analytics: It is the process of examining large data sets, or as commonly described, big data.[5]
- Artificial Intelligence (AI): It is a field in computer science where intelligent machines function and react like humans.
- Machine learning: It is an essential component of AI which allows software to more carefully predict results without explicitly being programmed. Machine learning facilitates analytics required for predictive modelling, by applying statistical methods.[6]

1.3 IIoT vs Machine Learning (ML), Artificial Intelligence (AI), Big Data and Edge Computing

The Industrial Internet of Things (IIoT) is related but it is not a synonym for Machine Learning (ML). Neither is it a synonym for Big Data and Artificial Intelligence (AI).

In general, Machine Learning requires big and varied amounts of data (Big Data). The scope of the IIoT industry definitely encompasses Big Data, ML, and AI. But ML and AI are conducted on data, not on devices. In fact, ML and AI are utilizing data that have been prepared, cleaned, and verified – not raw information straight out of a sensor. However, IIoT enables ML and AI to assess a task, it handles the outcomes from ML and AI to optimize a task, but it does not necessarily require ML and AI to accomplish an assignment. [7]

Often, interconnected IIoT edge-point devices through networks, are organised into the narrower category of edge computing. While edge computing requires computational capabilities, IIoT edge-point devices do not necessarily require edge computing. [8]

1.4 History of the IIoT

The history of the IIoT commences in 1968 with the apparatus of the Programmable Logic Controller (PLC) by Dick Morley. The PLCs permitted the better control of machines in the manufacturing chain. In 1975, Honeywell and Yokogawa created the world's first DCSs. The DCSs were the next step in allowing flexible process control all through a plant. [9]

In 1980 the Ethernet was introduced and people started to explore the concept of a network consisting of smart devices, when a modified Coke machine, at Carnegie Mellon University became the first internet-connected appliance with the ability to report its inventory and whether lastly imported drinks were cold.

The concept of the internet of things first appeared in 1999, at the Auto-ID Center at MIT. At that point, Kevin Ashton, one of the founders of the original Auto-ID Center considered radio-frequency identification (RFID) as a qualification for the IoT while, if all objects in daily life and people were supplied with identifiers, computers could manage and reserve them.

The today’s approach of the IIoT only derived in 2002, after the evolution of Cloud technology which enabled the data storage to examine historical tendencies, and the progress of the OPC Unified Architecture protocol in 2006, which permitted protected, faraway communications among devices, programs, and data sources without the demand for human interference or interfaces. [3]

1.5 Transition from Industry 3.0 to Industry 4.0

For over 40 years, the third industrial revolution (Industry 3.0), consisting of ''SCADA'', has been used in numerous industries to monitor and handle their functions and practices in order to boost the efficiency of operations and reduce costs. However, after three generations of SCADA – stand-alone, distributed and networked with technological advances and with the connection of the world through smartphones and internet Cloud technologies, several industries start to utilize the fourth generation SCADA application (Industry 4.0), what is known to be the Internet of Things.

Industry 4.0 is an era in which emerging trend automation and data transfer in manufacturing technologies allow a change from commonly implemented SCADA to IoT. With SCADA, cyber-physical systems, IoT, Cloud computing and Cognitive computing, Industry 4.0 can alter the dynamics of the whole automation industry.[11]

Originally, IoT should be considered as a technology that is implemented on top of SCADA. It provides standardisation, scalability, interoperability, data analytics and increased security by introducing the conception of the IoT platform. Moreover, reduced cost, ease of installation, enhanced information accuracy and global remote monitoring are things that IoT offers to industries in addition to SCADA. [12] However, both technologies are used to increase overall productivity, efficiency and decrease downtime and the extension of equipment life.

Nevertheless, as IoT is a relatively new technology compared to SCADA and PLC, its capabilities are easily adaptable to the demands of the current industry.

Below the most important terms are explained in details:

- PLC

PLC stands for ''Programmable Logic Controller'' and is used to receive information from connected sensors, to process this data and to deliver outputs formed on pre-programmed parameters. Typically, a PLC can monitor and record data (operating temperature or machine productivity) in real-time. It is also able to automatically begin and stop processes and generate alarms in case of system malfunctions. Many of the functions of PLC, SCADA and IoT operate in parallel. Despite the fact that it is a form of technology believed to have become quite outdated due to the increase of IoT developments within Industry 4.0, programmable controllers are still managed to transmit data through a web browser, connect to databases through Structured Query Language (SQL) and to the Cloud through Message Queuing Telemetry Transport (MQTT).

- <u>SCADA</u>

The term ''SCADA'' stands for "Supervisory Control and Data Acquisition." It is a system used in the industry that combined with software and hardware, is able to monitor, gather and process real-time data to oversee operations locally or remotely. It also permits explicit communication with smart devices and human-machine interface software. [13] SCADA systems are usually cabled with (PLC) wireline and used in demanding industrial applications such as water leakage detection. However, enhancing SCADA with wireless is relatively new.

SCADA systems are still prevalent within heavy asset industries: They are applied in the oil and gas industry to monitor extraction processes and remotely placed pipelines and in the mining industry for environmental monitoring and asset tracking. In addition, power utilities use SCADA in Energy Management Systems (EMS) as well as Distribution Management Systems (DMS) to optimise the performance of transmission and distribution networks and to protect the grid network. [14]

In the traditional wireline SCADA, the internet is not in the loop as in the IoT. This is the primary difference between the two. As a result, the PLC makes the decision. In addition, SCADA's targets on monitoring and controlling. On the contrary, with IoT, the data need to be transmitted through the internet to a Cloud-based server before a decision is formed and the control signal returns over the internet to the sensor. Furthermore, the IoT is mainly focused on examining machine data to enhance productivity. The compulsion of Internet, makes IoT architecture less robust than traditional SCADA.[15]

Both platforms offer plethora of benefits, but provide few disadvantages as well. It is predicted that by 2020, 50 billion devices will be connected to the internet. As a result, the possibility of an Internet-based control system is gradually evolving into a real concept.

In the long-term, SCADA systems are expected to emerge into IoT. Both equipment and PLC will become more intelligent obtaining the ability to integrate different Cloud platforms. Data produced from SCADA systems will act as data sources for IoT. Therefore, IoT will begin where SCADA and PLC end. But as long as the IoT market is in early production, it can coexist with SCADA. This will empower new surveillance platforms to further secure any data being recorded. [15]

1.6 Integration of IIoT equipment (Sensors)

Sensors in their infancy, were complex and with difficult configuration. In order to make them easy to set up and use, manufacturers designed them with the intelligence to gather large amounts of data, process it, and give a straightforward on/off signal.

Today this has changed as the value of the data is recognised and it is desired to turn it into meaningful information. The knowledge of what the data interprets, and where it appears from, can improve a process. Therefore, the sensors used in the industry are becoming smarter and better connected. [4]

Below, an example of the process of implementing additional sensors into manufacturing systems is described, using a) Traditional b) IoT configuration:

a) <u>Traditional Process: Including sensors in 12 steps:</u>

As an example, a proximity switch is going to be added to a manufacturing line to count the number of units produced. The process includes the following steps:

1. Recognize the need.

2. Determine requirements and indicate wiring and hardware.

3. Define an open connection on a digital input module or include a costly high-speed counting module, depending on speed demands and engineering in first step.

4. Acquisition or buy of the sensor.

5. Mechanically installation of the proximity switch.

6. Awaiting for downtime on production systems.

7. Addition of a new module to the PLC rack, if required.

8. Run cable from the proximity switch to the input module.

9. Modification of the PLC program to execute logic based on the new range of capabilities, to count pulses and spotting when the counter will roll over to prevent an overflow situation.

10. Examination of the PLC program logic.

11. Development of a Human-Machine Interface (HMI) display, to utilise production counts, or configuration of a historian to dialog production counts.

12. Optionally, addition of further steps to bond the new counter into higher level Manufacturing Execution System (MES)/line performance system to capture Overall Equipment Effectiveness (OEE).

To add one sensor and utilise the data that it maintains, writing the PLC code, and building the suitable applications, important time and money investment are necessary. This becomes more challenging if the equipment is ageing and does not include a PLC.

b) IIoT Process: Adding sensors in 6 steps:

1. Recognize the need.

2. Acquisition or bought of the IIoT device and sensor.

3. Mechanically installation of the proximity switch.

4. Connection of the IIoT device to a wireless network, hardwired Ethernet, or acquisition of the IIoT device with on-board 2G/3G connectivity already initiated.

5. Plug into 120 v or 24 VCD power.

6. Set up of an account in the Cloud web application to storage, visualise and analyse the data.

No engineering and no coding is needed. [16]

1.7 Fundamental characteristics of IoT

The Internet of Things is characterised by:

- Interconnectivity: Concerning the IoT, all devices can be interconnected with the global information and transmission infrastructure.

- Dynamic changes: The state of devices changes dynamically, for example from connected to disconnected, or the framework of devices including location and speed. In addition, the number of devices can change effectively.

- Things-related services: The IoT provides thing-related services within the restraints of things, such as privacy protection and semantic consistency between physical things and their correlated virtual things.

- Safety: It refers to the safety of personal data and physical well-being by securing the endpoints, the networks, and the data transmitted across all of it.

- Heterogeneity: The IoT devices are heterogeneous since they are built on different hardware platforms and networks. There is interaction with other devices or service platforms through different networks.

- Enormous scale: The number of devices that are connected to each other and need to be managed are at least an order of magnitude bigger than the number of devices linked to the current Internet.

- Interoperability: The IoT's objective is to integrate the physical world with the virtual world by using the Internet as the means of data transfer. Interoperability is the first requirement of Internet connectivity so that "connected" systems can be able to "talk the same language" of protocols and encodings. The meaning of interoperability can be better understood by the following figure. [3]

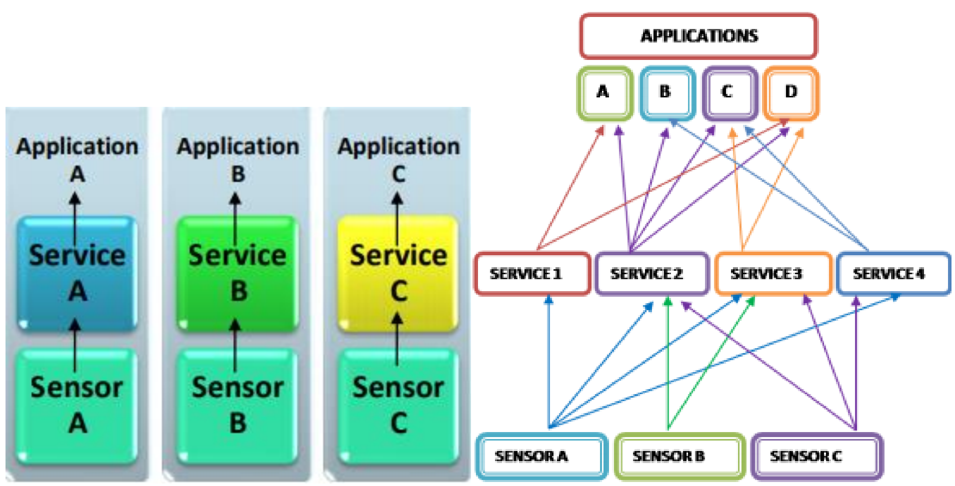

Figure 1.2: *(left) a non-interoperable diagram, (right) an interoperable one*.[3]

1.8 Main components of IoT:

1. Embedded systems (sensors, boards, modules)

Figure 1.3: *Embedded systems* [17]

2. Communication network

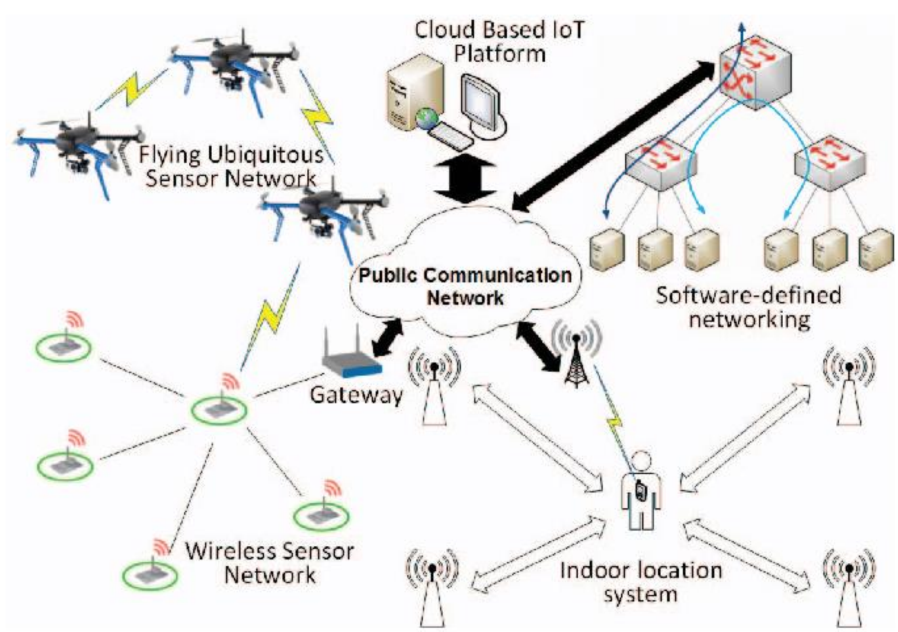

Figure 1.4: *Communication network* [18]

3. IoT platform. An IoT platform is defined by:

a) Smart product applications: Software applications that handle remotely the monitoring, control, optimization and autonomous operations of product functions.

b) Rules/Analytics engine: The rules, business logic, big data and analytical capabilities that occupy the algorithms involved in product operation and show it's information.

c) Application platform: The creation of an application and the execution of an environment permitting the rapid development of smart, connected applications using data access, visualization and run time tools.

d) Product database: A big data system that allows normalization and management of real time and historical product information.

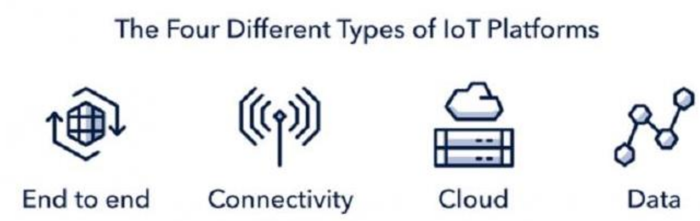

Figure 1.5: *IoT platforms* [19]

4. Application and services

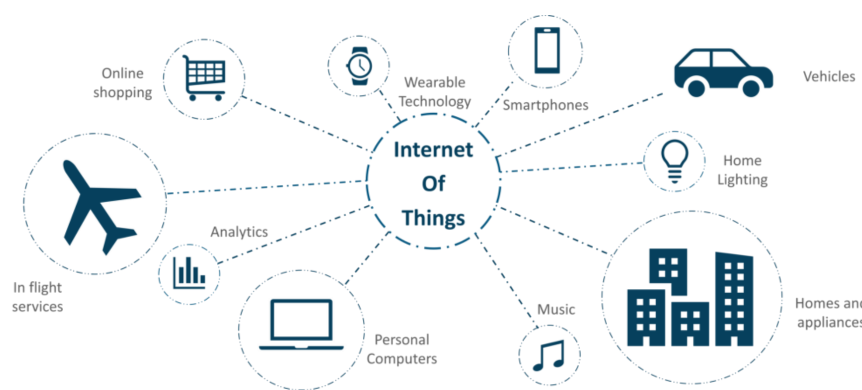

Figure 1.6: *IoT applications and services* [20]

1.9 IoT Architecture

IoT architecture is comprised of multiple layers of technologies that support the IoT. It is used to present how different technologies correlate and to describe the scalability, modularity and configuration of IoT deployments in various scenarios. [3]

An IoT system is considered as a layered modular architecture of digital technology. The smart device layer declares the physical components: Sensors or machines. The network layer contains physical network buses, Cloud computing and communication protocols that accumulate and transfer the data to the management service layer, which manipulates and combines data into information that can be presented on the driver's dashboard. These data are used in the applications layer. The last one is the content layer or differently called "the user interface".

The capabilities of each layer are mentioned below:

a) Smart device / Sensor layer:

It is the lowest layer, constructed from smart objects unified with sensors. The sensors make the interconnection of the physical and digital worlds feasible, enabling real-time information to be gathered and processed. There are numerous sensor types for various purposes. The sensors have the capacity to measure physical properties like temperature, air quality, speed, humidity, pressure, flow, movement and electricity and convert them into signal that can be read by an instrument.

Most sensors need connectivity to the sensor gateways. This can be in the form of a Local Area Network (LAN) such as Ethernet and Wi-Fi connections or Personal Area Network (PAN). For sensors that do not need connectivity to sensor aggregators, their connectivity to back-end servers/applications can be supported by Wide Area Network (WAN). Sensors that use low power and low data rate connectivity, usually structure networks frequently known as wireless sensor networks (WSNs). [21]

b) Gateways and Networks:

Big quantities of data are generated by small sized sensors and that, requires a robust and high performance wired or wireless network infrastructure as a transition medium. Present networks, linked with different protocols, have been utilised to manage Machine-to-Machine (M2M) networks and their applications.[22] With demand required to handle a wider range of IoT services and applications, various networks with different technologies are required to collaborate in a heterogeneous configuration. These networks can be in the form of private, public or hybrid models and are constructed to support the communication demands for latency, bandwidth or security.

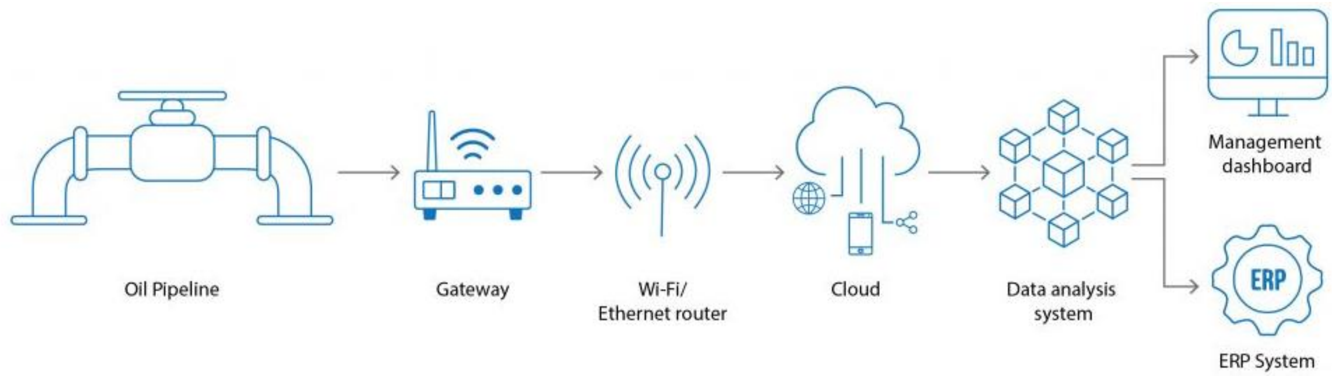

Figure 1.7: *IoT architecture* [24]

c) Management Service Layer:

The management service is responsible for the information process through analytics, security controls, process modelling and management of devices. IoT delivers connection and interaction of objects and systems together, providing information such as temperature, present location and traffic data. Few of these events need filtering, while others demand response to immediate situations such as reacting to emergencies on patient's health conditions. The rule engines support the formation of decision logics and generate collective and automated processes to implement a more responsive IoT system.

As far as analytics is concerned, different analytics tools are utilised to extract information from big amount of raw data in order to be processed at a faster rate. Data management is the ability to manage data information flow. In the management service layer, information can be accessed, integrated and controlled. Higher layer applications can be shielded from the need to process unnecessary data and reduce the risk of privacy disclosure of the data source. Data filtering techniques are utilised to conceal the information details, while providing only essential information required for the relevant applications. Security must be imposed across the entire

IoT architecture from the smart object layer to the application layer. Security of the system prevents system hacking and compromises by unauthorized user, having as a result reduced risks possibility. [23]

d) Application Layer:

The IoT application consists of “smart” environments in domains such as: Transportation, Building, City, Lifestyle, Retail, Agriculture, Factory, Supply chain, Emergency, Healthcare, User interaction, Culture and tourism, Environment and Energy.

e) User Interface Layer:

The final layer is the user interface, where the data extracted appear to a dashboard, in a user friendly and readable form for the user to understand the information.

CHAPTER 2. Impact of the IIoT on Oil and Gas Industry

2.1. O&G powered by the IoT

In 2014, the price of oil reached $100/barrel. Then, when fracking and other excavation technologies made their appearance in the market, the previously high price dropped down to $50. On top of that decline, regarding the value of petroleum services, the oil and gas industry mainly consists of an ageing workforce, most of whom will retire within the next decade. [25]

For companies in asset-intensive industries, including oil and gas, mining, energy, utilities, healthcare, construction, rail, and logistics, the overall performance relies on their assets. They face the same challenges that need to be addressed in order to improve reliability, enhance operational performance and achieve their production goals. Monitoring the performance of every asset is a big challenge. The time when assets are not functioning, a company does not make any income. On the other hand, these companies require large capital expenditures and so, their financial accomplishment depends on the Return On Assets (ROA).

In more details regarding the Oil and Gas industry, upstream companies (e.g. exploration and production) focus on optimization and gain operational insights by analysing diverse sets of data. However, considering the variety of the resource base (conventional onshore and shallow water, deep-water, shale oil and gas, oil sands), improving operational efficiency has become more complex.

In the midstream segment (e.g., transportation, pipelines and storage) although being a reliable field connecting settled demand and supply centres, the ascent of US shale has changed the supply-demand balance, with the increasing exports of liquids and natural gas, and expanded midstream companies' complexity. Midstream companies focus on maintaining and optimizing their networks, with technology that already exists but that needs to become fully integrated across the full network of pipelines and associated infrastructure.

On the contrary, the downstream sector (e.g. petroleum products refiners and retailers) is quite mature in risk monitoring and process optimization due to their regulated operations and long history of automation and process-control systems. But the reducing need growth globally, the increasing competition from new refineries in the Middle East and Asia, and the altering product markets pressure downstream players to develop new ways of optimization and expand their value beyond the refinery. The most encouraging opportunities lie in revenue generation by increasing visibility within the hydrocarbon supply chain and aiming at digital consumers through new way of connected marketing.

The figure below, shows the technology maturity of each sector. [25]

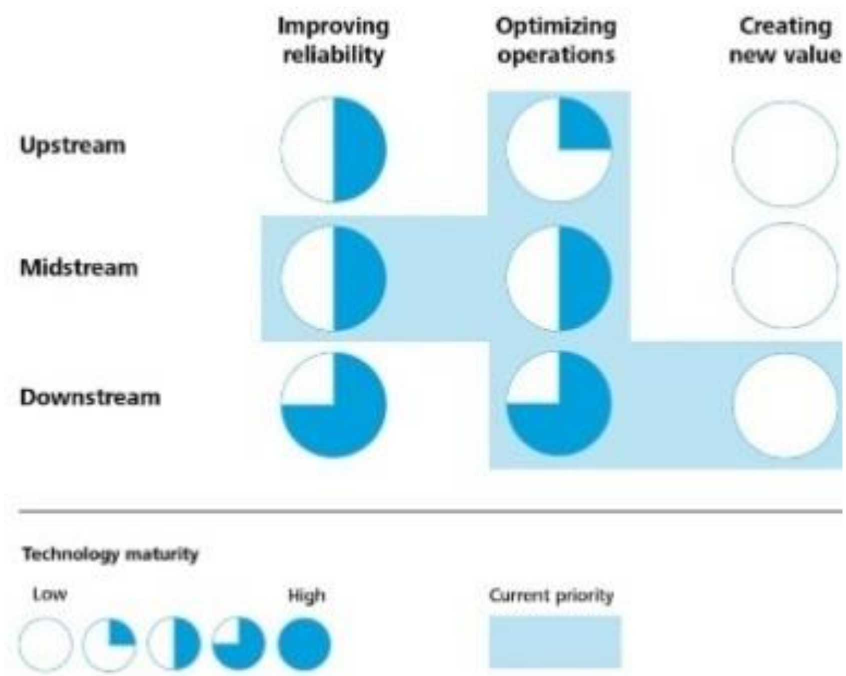

Figure 2.1: *Technology maturity and business priorities* [25]

All these have made automation an imperative for the oil and gas industry which is one of the early adopters of the IoT. Efficiency and safety are the two most pivotal aspects in the energy and utility industry. Greater interconnection is increasingly becoming an essential need for businesses existing in this filed. According to “The Global Interconnection Index”, a market study published by Equinix, it is estimated that the installed, worldwide interconnection bandwidth capacity within the energy and utility industry could increase each year by 73% between 2016 and 2020.[26]

The Internet of Things (IoT), is set to aid companies face their challenges. The IoT’s promise does not lie so much on sensors and "smart" devices that help O&G companies reorganize old data and immediately manage their existing assets and supply chains, rather than on the creation of new data, by establishing approaches for managing data, leveraging IoT infrastructure, and exploring new business models. [27]

The Oil and Gas industry is quite resistant in embracing these new technologies. During the past five decades, innovative progresses like geo-phones, robots, satellites, and advanced workflow solutions have been created and applied, either primarily functioning at an asset level, or without being integrated across a variety of disciplines or without incorporating business data. According to MIT Sloan Management Review and Deloitte's 2015 global study of digital business, the O&G industry's digital maturity is one of the lowest, at 4.68 on a scale of 1 to 10, with 1 being least mature and 10 being most mature.

In an interview, Satyam Priyadarshy from Halliburton said: ''The oil and gas industry commenced its digital revolution around a decade ago. This first revolution commonly known as digital oilfields, entailed digitization and some effort towards digitalization. Oil and gas industry needs to leverage digital technologies at a much faster rate, with an agile and adaptable mind-set.'' [28]

In addition, it is predicted that only 1 percent of the information collected becomes available to O&G decision makers. Enhanced data capture and analysis can save millions of dollars by eliminating as many as half of a company's unplanned outages.

However, deploying technology does not automatically create economic value. To achieve that, companies need to link IoT deployments with particular business priorities, which can be defined, broadly, using three categories of ascending sphere. In the narrowest sense, companies aim at minimizing the risks to health, safety, and environment by cutting down disruptions (improving reliability). Next, companies seek to increase the cost and capital efficiency of processes by productivity improvement and supply chain optimization. At the largest scope, companies seek to pursue new sources of revenue and competitive advantage which transform the business (creating new value). [25]

Figure 2.2 *IoT in Oil and Gas industry* [10]

The IoT transforms the oil and gas industry in the following ways:

- Improved operational efficiency: Better asset management and wise distribution of funding helps increase efficiency in operations. A typical oil drilling platform uses 30000 sensors watching over the performance of various systems.

- Revenue: The industry's wide adoption of IIoT Cloud is estimated to increase the GDP by 0,8% or to $816 billion by the next decade. [29]

- Pipeline surveillance: Sensors are attached to pipelines running in and around the rig in order to monitor any leaks or cracks in the pipe.

- Low Power Wide Area Network: LPWAN is used in sparsely populated areas in order to establish M2M configuration in oil and gas.

- Maintenance cost: With IoT there is a 15 to 25% reduction in primary preventative maintenance costs.

- Predictive analysis: Big data analytics provide deep insight into the working conditions of the pumps and valves. These data with the help of sensors do predictive analysis for any future maintenance or breakdown.

- Real time data: Engineers can point their devices towards the machinery and view the performance status in real time on their devices.

- Less environmental footprint: In order to abide by the rules, experts use artificial intelligence in order to reduce their environmental footprint.

- Supply chain management: The entire ecosystem of oil and gas industry being connected online, brings more transparency and authenticity.

- Less safety risk [30]

Figure 2.3 *IoT in Oil and Gas Industry* [31]

2.2 IoT in O&G Industry powered by machine learning, Big Data and Cloud:

The oil and gas industry stands in an era where the convergence of big data, analytics and intelligent systems is priority. This movement towards convergence, challenges the today's divergent technologies, from traditional SCADA and asset management, to historian and decision support systems. These challenges lead the pathway for advanced, emerging solutions that drive data and predictive analytics into the edge, the data centre, and the Cloud. [32]

Utilised in many areas of the O&G industry to improve efficiency, IoT has advanced with mobile and Cloud innovation, progress in Big Data, and predictive analytics based on in-memory computing. Artificial intelligence, machine learning, automation and IoT drive the Oil and Gas technology solutions to a new level. [31]

This combination aims at greater management of remote facilities so they can function in real-time as safety and regulatory issues arise. Moreover, it is becoming more practical and affordable as the price and size of sensors shrink. O&G companies that adopt these innovative technologies can achieve advantage. [33]

Figure 2.4: *Analytics enhancing IoT in O&G* [25]

2.3 IoT and Fibre Optic Technology

The IoT sector consists of an overwhelming number of data and network capacity that appears to be too complicated for conventional connections. The wireless ability can limit the potential of industries to automate. Without the narrow possibilities of a wireless connection, the companies would be able to operate with improvement in work functioning and quality output. The communication medium needs to be rapid and reliable to interact with IoT Cloud s platforms. Fibre optics can give the solution while they have the ability to drive the enormous amount of data and networking requirement of the Internet of Things.[34],[35],[36]

The Internet of Things involves fibre optic networks in the following ways:

- Enhanced bandwidth

In a house, each IoT device sends limited amounts of data, so individually it does not drive a need for additional fibre to the premises' connections. What it requires is cost - effective connectivity that can manage IoT alongside other applications such as streaming 4K/Ultra HD TV, HD video and Cloud - based storage. With large bandwidth, internet capability is faster and installation time is reduced.

- In-building fibre deployments

The IoT leads to a growth of in-building fibre deployments within industry and also for remote areas and harsh environmental conditions that make wireless networks impossible to operate. The same need for connections that can cope with challenging conditions is driving the adoption of fibre networks within the industry. Factories and warehouses implement the IoT for the control of machines which requires reliability in data transmission. Fibre optic cables serve as the most suitable means of managing this data and sending it around a facility.

- Fibre sensors

Fibre optics provide the actual sensor required in IoT applications. The ability of optical fibres to measure across a wide frequency band, with good light transmission performance, makes the fibre an ideal means of transmission in areas where sensitivity and high performance are important.

- Security

It is the most secure and extremely difficult to hack without being detected.

- Industry

Fibre Optic capabilities improves the efficiency and productivity of industrial operations, such as asset tracking, monitoring, maintenance, and autonomous robots.

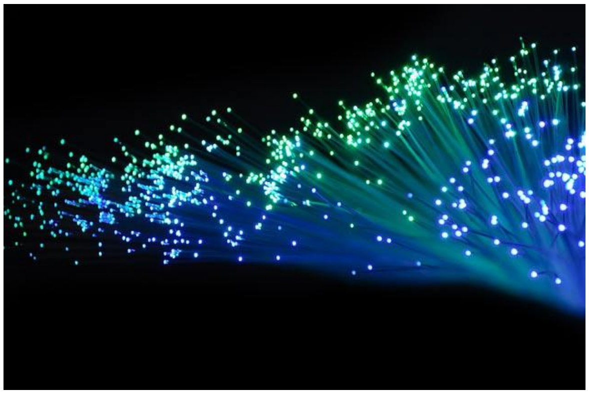

Figure 2.5: *Fibre optic cables* [17]

Fibre optic cables replace internet connections with enhanced speed and reliability. The cables, are made of a glass or special plastic fibre, with the material exploiting the speed of light and transmitting data at extremely high speeds. The optical fibre has a high capacity of carrying data in the way of transmitting light waves. Fibre optics work as passive sensors. A fibre optic sensor is mainly composed of light source, optical fibre, photo detector and a signal processing part. The

IoT is based on Internet with RFID technology, infrared sensors, GPS and laser scanners and other information sensing equipment items and Internet connection. The utilised fibre, reacts to the environmental surroundings and modifies the input accordingly. [38],[39]

The rising need for O&G has caused enormous growth and investment to increase production efficiencies. Many evolving technologies boost the oil and gas production and unleash new resources to expand the lifetime of an offshore oilfield. With IoT and fibre Optic installation, companies can explore the O&G industry, retrieving the present challenges and leveraging the benefits while at the same time enhancing their accuracy and operational performance. The usage of the fibre industry is developing at an average of 5.5 percent per year, with a major part of it due to the Internet of Things. [17]

Advantages of fibre optics in IIoT:

- Rapid data delivery
- Improved security of data transmission
- Reduced cost
- High sensitivity
- Improved efficiency and productivity
- High capital but high longevity
- Conducts only light and therefore, cannot inflict damage
- Predictive analysis
- Long term benefit

Applications of fibre optic technology in IoT for O&G:

- The sensing system of optical fibre provides the optical continuity between fibre optic sensors, installed in the well. Combined with IoT, the real-time data and data provided, share a deep understanding of real-time operations and predictive modelling. The fibre optic system maintains profitable data and better performance even at high temperatures and pressure.

- Optical fibre systems help in detecting pipe leakages. Pipelines have been the safest means of transporting oil and gas. Pipeline leakage of oil and gas causes damage to the environment, loss of product, as well as loss of life because of hazardous incidents. These are few of the challenges that fibre optics can solve with real time data and prediction of upcoming conditions.

- Optical fibres are a great source of developing a distributed sensing system. Distributed sensing systems aid in monitoring the temperature and the formation of hydration in pipelines. Changes in pressure or temperature, alter the backscattering profile, which permits the measurement of the backscattered light. The velocity of the light gives information on the basis of the location and the measurement. With fibre optic solution, a large amount of data like temperature, vibrations, asset locations, and oil reserve levels can be sent through reliable and ultra-fast fibre connections and monitored.

Fibre optics provide real-time data from the entire pipe length and monitors the pipeline's mechanical structure. Hence, fibre optics in IoT and oil and gas play a significant role in sensing the data. [40]

2.4 Applications of IIoT

The IoT can have plentiful and various applications, penetrating into mostly all fields of every-day life, and concerning individuals, businesses, and community. These applications cover "smart" environments/spaces in domains such as: Transportation, Building, City, Lifestyle, Retail, Agriculture, Factory, Supply chain, Emergency, Healthcare, User interaction, Culture and tourism, Environment and Energy. A survey created by software company Infor, showed that 52% of manufactures believe IoT is a priority for their business.

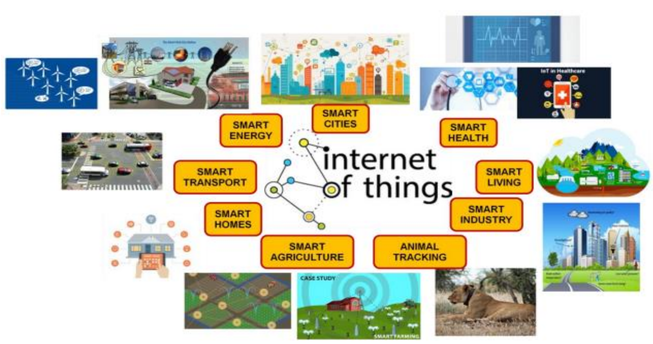

Figure 2.6: *Applications of IoT* [3]

IoT applications for each domain:

A. IOsL (Internet of smart living):

- Remote control devices to prevent accidents and conserve energy.
- Weather: Displays outdoor weather conditions with ability to transmit data over long distances.
- Smart Home Appliances: Refrigerators with LCD screen indicating food that's about to expire or ingredients need to buy, kitchen ranges permitting remotely alterable temperature control, washing machines allowing to monitor the laundry remotely
- Safety monitoring: cameras, and home alarm systems for safety reasons
- Detection systems: Detection of window and door openings and violations to prevent intruders
- Energy and water use: Monitoring of energy and water reserve consumption.

B. IOsC (Internet of smart cities):

- Structural Health: Monitoring of vibrations and textile status of constructions.
- Lighting: Smart and weather adaptive street lighting.
- Safety: Digital video monitoring, fire control supervision, public broadcast schemes.
- Transportation: Intelligent roads and smart high-ways with warning alarms and diversions depending on climate conditions and unforeseen events such as accidents or traffic jams.
- Smart parking: Real-time monitoring of parking spaces availability.
- Waste management: Detection of rubbish levels in containers to optimize the trash collection routes.

C. IOsE (Internet of smart environment):

- Air pollution monitoring: Reporting of CO_2 emissions from factories, pollution emitted by cars and toxic gases produced in farms.
- Fire detection: Monitoring of combustion gases and pre-emptive fire conditions to determine warning zones.

- Weather monitoring: Observation of weather conditions, earthquake early detection, water quality.

- River floods: Control of water level fluctuations in dams, rivers and reservoirs.

- Wildlife protection: Tracking collars use of GPS modules to detect wild animals and transmit their coordinates through SMS.

Moreover, this digital revolution has major applications to industry too. Rather than targeting life hacks like IoT, the Industrial Internet of Things (IIoT) using machine-learning, machine-to-machine communication, big data, artificial intelligence, applies IoT technologies to industrial concerns and in the process enhances operational productivity and efficiency.[4]

D. IOsI (Internet of smart industry):

- Explosive and hazardous gases: Gas level and leakage check in industrial environments, chemical factories and mines, toxic gas and oxygen level control within chemical plants to secure workers and good’s safety, water, oil and gas level monitoring in storage tanks.

- Maintenance and repair: Early predictions on equipment failure and service maintenance to monitor and report, smart meters, oil and gas pipelines equipped with sensors that detect leaks and alert repair teams, so that issues are fixed before they can cause problems.

<u>More specifically, applications of IoT in O&G industry:</u>

<u>Applications of IoT in Upstream</u>

- Problems: Loss of billions of dollars each year as a result of non-productive time (NPT), deadly accidents and non-optimized processes.

- IoT Solution: With the use of IoT, accidents can be avoided and processes can be optimized.[23]

<u>Application of IoT in Midstream</u>

- Problems: Transportation of numerous volumes and grades of products from various locations to new end-users and market, connection of pipeline networks, sensors, leak detection, alarms and emergency shutdowns to interact seamlessly.

- IoT Solution: With the use of IoT to be accessible for analysis and interpretation in real time, it would significantly decrease few of the larger risks that this field is concerned with.

Application of IoT in Downstream

- Problems: Refinery shutdowns, managing of multiple grades of crude oil, and change of environmental restrictions push gross refining margins down to a minimum.

- IoT Solution: With the use of IoT, refineries can control their shutdowns, minimize their downtime, and improve safety records. [31]

E. IOsH (Internet of smart health):

- Patients’ surveillance: Monitoring patients’ conditions.

- Medical fridges: Control of conditions inside freezers, storing vaccines and medicines.

- Detection: Assistance for elderly or disabled people who live independent.

- Dental: Bluetooth connected toothbrush that provides information of the brushing habits.

- Physical activity monitoring: Wireless sensors planted across the entire surface, sensing small motions such as heart rate and breathing, providing data.

F. IOsE (internet of smart energy):

- Smart grid: Energy usage monitoring and management.

- Wind turbines: Monitoring and analysis of the energy flow from wind turbines to examine consumption patterns.

- Power supply controllers: AC-DC power supply regulators that define the required energy, and increase energy efficiency with less energy waste for power supplies related to telecommunications, computers and consumer’s electronics applications.

- Photovoltaic installations: Monitoring and optimization of performance in solar energy plants.

G. IOsA (internet of smart agriculture):

- Green houses: Monitoring of micro-climate conditions to maximize the production of fruits and vegetables and their quality.
- Compost: Humidity and temperature level monitoring to prevent microbial contaminants.
- Animal farming/Tracking: Location and identification of animals, examination of ventilation and air quality in farms and detection of harmful gases from excrements.
- Offspring care: Control of growing conditions of the offspring to secure its survival and health.
- Field monitoring: Reducing spoilage and crop waste with better monitoring, accurate real time data acquisition, and management of the agriculture fields.
- Futuristic farming: Implementation of smart, connected IIoT projects, enables farmers to utilize the massive amounts of data produced on their farms.

2.5 IoT Solutions in O&G Industry

UPSTREAM:

O&G upstream is divided into three business segments: Exploration, drilling and production. Exploration is associated with seismic acquisition, data processing and interpretation. Drilling consists of real-time process monitoring, predictive maintenance and completion. Production involves remote pump and tank monitoring, reservoir simulation and recovery optimization. Problems common to all three segments, are these, related to transportation, asset management and safety.[30]

Problems in the upstream:

- Loss of money due to non-productive time (NPT)
- Pipeline leakage
- Dangerous physical on-site inspections
- Low asset value and unplanned downtime

- Limited data from equipment is being analysed
- Equipment failure
- Non optimized processes

<u>IoT solutions for upstream:</u>

- <u>In seismic exploration</u>: IoT sensors connected with fibre optic wires, assist oil exploration with subsurface mapping of drilling sites to define drilling locations and optimize the results of operational sites. [30] The sensor-based system enhances the new and existing drilling rig productivity and decreases the time required for site-selection data analysis. Sensors also can gather data on surface materials, temperature and the way the equipment performs in various environments.
- <u>In drilling and extraction operations:</u> It has been predicted that only 1% of the data collected from wells is becoming available to the oil and gas decision-makers. For long time SCADA has been the upstream segment's centrepiece for well performance management. However, while SCADA permits the basic visualization of well data and analysis, it does not provide advanced analytics capabilities of IoT, in order to increase the performance of drilling and extraction activities.
- <u>In pipeline monitoring:</u> IoT smart valves are installed at multiple points throughout the pipeline to remotely measure temperature, pressure, flow, compressor condition, density inside the pipelines. One of the major concerns of oil and gas pipelines is leakage as well as the financial and environmental effects that could arise. A non-burnt methane gas release, has about 25 times the impact on climate change than carbon dioxide would have within a century. There is also high explosion risk for a gas leak when it is exposed to atmospheric pressure. IoT solution, ensures non-invasive and non-destructive leak detection. With real time pipeline leakage monitoring, irreversible damages can be avoided and preventive measures can be taken before it is too late. [24]
- <u>In remote monitoring:</u> For onshore and offshore operations.

O&G companies originally have numerous remote assets that require monitoring. Traditionally, the following monitoring methods have been applied:

- Programmable logic controller (PLC) systems: These cabled IoT communications that collect data using wires is an expensive process with more complex architecture and high set up cost.

- Satellite communications: Satellite connectivity can be expensive and Satellite monitoring quite complex.

- Physical monitoring: Employing individuals to physically monitor levels and measurements by hand is relatively straightforward and easy to implement but the time and labour costs can be high, especially in remote locations. [41]

<u>With the advent of IoT the traditional methods are replaced by:</u>

- Digital twins: Digital replicas of physical assets give oil and gas companies the ability to drill down virtually to get project progress updates, increasing knowledge-gathering efficiency and allowing to "look around the platform". [42]

- Use of automated drones improves the oil and gas inspections. The use of automated drones or Unmanned Aerial Vehicles (UAVs) is steadily expanding and lately has become prominent in the oil and gas segment. Acting either as a sensor or as a connection between sensors and data, collection points can carry all range of sensors and are autonomous machines capable of gathering massive amounts of significant data. They are used to detect repair and maintenance needs before they can become dire, to place bottlenecks, and to protect civilians, workers, facilities and the environment. Automated drones also aid sensors to detect gas or chemical leaks, enabling the fastest possible response to an emerging incident. What is the most important is the fact that all the things mentioned, can be achieved without threatening human inspectors, and preventing the need to shut-down equipment or operations.[43]

- Smart dust: The concept of smart dust consists of very small sensors in the size of a sand grain, with the ability to detect everything, from chemicals to vibrations. Applications in the IIoT are endless, from oil exploration companies spreading smart dust to monitor rock movements to small sensors throughout a factory equipment that continuously look out for changes and issues. [44]

Remote monitoring with the use of IoT can improve the health and safety. The majority of O&G sites are in hazardous and distant locations that are not favourable for the worker's or the planet's health and safety. [45] Reservoirs can be submerged to depths of up to 3 Km offshore and rigs may be far offshore, placed near fault-lines where dangerous conditions could happen at any time.

According to the Centres for Disease Control (CDC), between January 2015 and January 2017, O&G extraction workers were involved in 602 incidents, 481 hospitalizations, and 166 amputations. Hazardous working environments, oil rigs and gas plants can take advantage of IoT connections that permit remote monitoring of operations without the need for individuals to travel to sites not knowing what and where an issue has occurred and whether or not it is a safe to reach.

This enables companies to better predict when equipment needs maintenance, to track spare parts on rigs, to know whether contract workers are authorized to be in specific areas and to define the exact number of people to evacuate when an incident occurs. [23]

In addition, remote monitoring aids to maintain a sustainable environment. Industry regulators have specified the demand for better, more accurate, and real-time monitoring to identify any impact to the environment. With the ability to monitor the assets in real-time and watching data points jointly with each other, prediction of potential environment impact can be done more accurately and in less time.

Therefore, with the use of IoT and real-time data, to achieve predictive maintenance, oil and gas companies can benefit from the remote monitoring of equipment through sensors to make significant decisions about whether or not something needs to be shut down, fixed, or replaced. Sensors gather data and send to companies a warning when machines need to be maintained, preventing expensive equipment failure, wasted money and manpower, improving safety, enhancing efficiency, reducing operational risks, lessening unplanned downtime and increasing production flexibility.[46]

- <u>In offshore O&G rig monitoring</u>

Most offshore O&G production takes place in harsh environments where often, cellular networks are not an option and so, critical data is usually extracted with satellite communications or cabled networks. This makes monitoring temperatures, pressures, flow rates, and other characteristics tough and costly. Using IoT solution, LPWANs, a lot more monitoring points can be connected in nearly low cost. LPWANs allow for remotely monitoring parts of the ship, that personnel do not usually go to (or are relatively impossible to reach).[21]

Furthermore, machine learning algorithms can be applied to data to extract patterns and derive predictive capabilities. Enabled by the IIoT, Oil and Gas companies can obtain real-time data about the whole process, which is quite difficult in case of extreme environments where the existing communication networks available are very little. It ultimately aids businesses to decrease operational and maintenance costs while encountering compliance regulations and ascending productivity. [33]

- In well and field work optimization:

With the production of millions of oil barrels per day from rigs around the globe, collecting and managing data has never been more crucial. By some estimations, internal data produced by large integrated O&G firms, today it exceeds 1.5 terabytes a day. With IoT giving the ability to handle and utilise that data, efficiency of workflow, supply chain and people management is increased. [47]

- In asset tracking and monitoring

Oil and gas is an industry where asset monitoring is very important. It is crucial during exploration to ensure that costly rigs are not malfunctioning, while parts are sourced and corrective maintenance is performed. The production phase also requires asset management to eliminate downtime, reduce operational costs due to interruptions and ageing infrastructure, and keep the oil pumping. With asset tracking, all details of assets are recorded, and they are integrated into one unit to enable firms digitally transform their processes, monitor multiple wells or sites at the same time and maximize overall site productivity asset performance.[24]

An IoT-enabled asset monitoring solution can give visibility across operations and enable companies to track asset performance so that they can monitor accidents remotely and minimize unscheduled downtime. In addition, with IoT Oil and Gas firms are able to connect their entire field equipment with on-shore equipment to track all high-quality assets. [27]

- <u>In equipment maintenance:</u>

With the use of the following IoT enabled technologies, equipment maintenance in the O&G industry can be improved. [42]

1) Sensor-based tank monitoring: Sensors collect data to provide to Cloud - based digital dashboards in order to monitor inventory levels and real-time equipment performance.

2) Acoustic operations monitoring: Sensors repeatedly measure flow rates and oil composition to reduce expensive equipment use.

3) Digital twin for assets: Digital replicas of physical assets enhance maintenance operations.

<u>MIDSTREAM</u>

<u>IoT problems for midstream:</u>

- Transportation of variable volumes of products from numerous locations to new end-users and markets

<u>IoT solutions for midstream:</u>

- Real time tanker/fleet tracking and management

IoT sensors placed inside tankers, enable real-time tracking of location, health of vehicle and safety of the driver. Their use, helps reduce unnecessary fuel consumption, traffic accidents, increase productivity and improve profits, all within a reasonable time frame and budget.

- Acoustic operations monitoring:

IoT sensors can repeatedly measure flow rates and oil composition to reduce expensive equipment use.

In midstream companies, IoT aids in connecting pipeline networks, in leak detection systems and in emergency shutdown of systems immaculately. All this equipment together provides valuable data for interpretation and deep analysis. This helps in significantly decreasing the biggest issues related to the O&G industry.

DOWNSTREAM:

IoT problems for downstream:

- Refinery shutdowns
- Tank monitoring

In accordance with a report by Deloitte University Press, there were more than 2,200 unscheduled refinery shutdowns in the U.S. alone between 2009 and 2013, and each of those shutdowns costed the worldwide operation industries 5% of their total production, or $20 billion per year. Ineffective maintenance practices end in unplanned downtime that costs to global refiners on average an additional $60 billion per year in processing costs.[48]

IoT solutions for downstream:

- Refineries can arrange their shutdowns, eliminate their downtime, and enhance safety records.
- Procurement planning and scheduling: Real-time monitoring of equipment performance, inventory levels, tank level and temperature, remote oil wells, oil tanks, water pressure, pipe thickness, flow rate and pipe pressure.
- Supply chain: Detection of crude oil types and blends that are incoming and the storage location of each type.
- Reduction of refinery money loss by minimizing the personnel required to manually monitor, or the amount of equipment that needs cabled communications. Furthermore, IoT can give better understanding and additional information about the flow, allowing the refinery to run at higher capacity.

Below, an example of end to end IoT solution in the O&G industry is provided by Biz4Intellia:

Biz4Intellia provides a complete end-to-end IoT solution for oil and gas, including every O&G industry to make operations more efficient and effective, to monitor the current condition of the plant or the refinery. This enables the O&G industry to take real-time decisions, minimize equipment failure, improve safety, eliminate downtime and decrease wastage, giving as a result a complete plant automation. [49],[50]

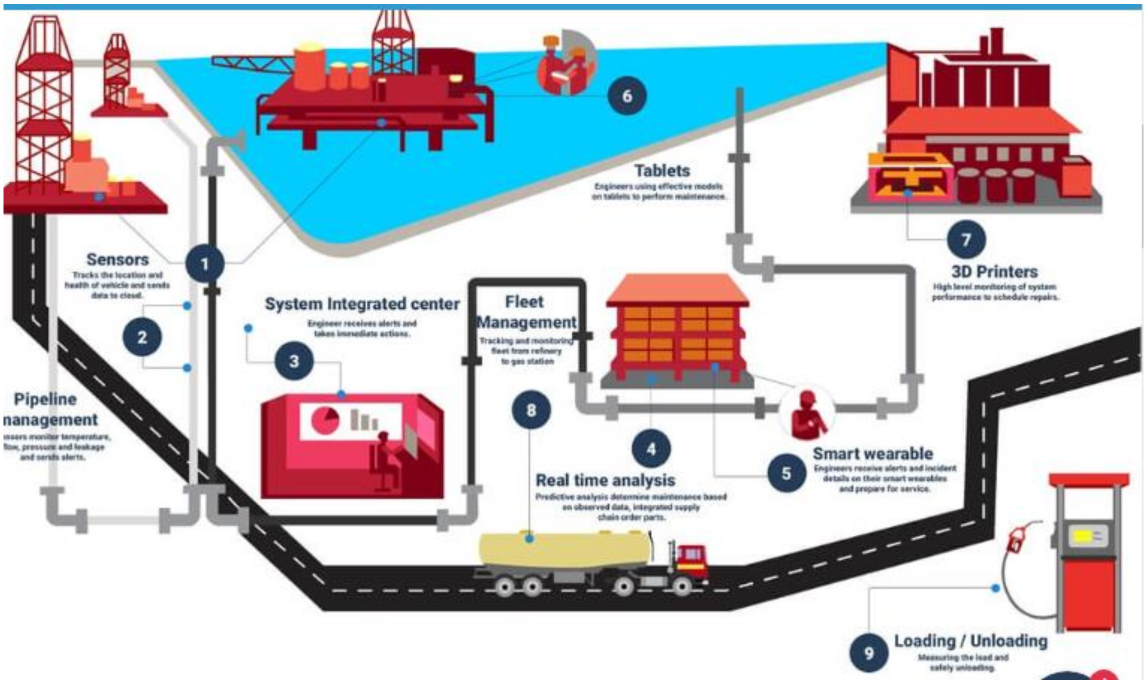

Figure 2.7: *End-to-End IoT solution for oil and gas* [49]

<u>1. Sensors</u>

IoT sensors scan the appropriate data, such as pressure, flow rate, temperature. Then gateways at the site connect these sensors to wireless networks and then these, connect to smartphones so that the data can be interpreted by the engineers in the field.

<u>2. Pipeline Management</u>

Moving from upstream to downstream, a higher network integrity appears. At the midstream, aspects such as downtime, gets decreased, and regular maintenance gets planned with the pipeline help. The pipeline system needs to be connected to a central controlling arrangement using IoT sensors, embedded to the pipeline array. The IoT sensors monitor factors such as temperature, pressure and flow and are then inspected by end-to-end pipelines.

IoT smart valves are also placed at numerous locations throughout the pipeline to remotely control the flow inside them.

3. System Integrated Center

This step assimilates the IoT platforms with core business operations. At the midstream sector, the system is relatively more mature in risk monitoring and process optimization as the systems are highly automated and operations are controlled. The system rapidly integrates the data gathered from all other devices and sends warnings for taking immediate actions.

4. Real-Time Analysis

Whenever there is a big quantity of complicated data, predictive analysis becomes a considerable concern. Predictive analysis keeps the track of the real-time data and allows the company to know even about the instant changes happening in the performance of an equipment. When a failure occurs, alerts are delivered to the engineer and adjustments are made. IoT sensors, installed at multiple locations make it possible to ingest data from various sources. This, results in O&G asset and production optimization, from enterprises to wells and from refineries to smart stations.

5. Tablets and Smart Wearables

With IoT, the systems are connected to one network and programmed to transmit data back to a device, like smartphone or tablet that is connected to the same network. With these IoT tools, O&G workers can have access to collected information and understand how the system performs. They can also monitor the systems and analyse key information from any location.

6. 3-D Printers

Advanced products and steady operation function are all achievable with the 3-D printing in the O&G industry. 3-D printing is an industrial IoT solution for oil and gas that has made the description of the assets more profitable and the operations faster. When the data gets examined from respective devices, then, one can know whether the substitute part can fit in the existing part, and the documentation informs on how to improve the design of a product and reproduce the tooling components. It is a concept of reverse engineering practiced in the O&G industry that measures the shape and size of every tool.

7. Fleet Management

The off-road IoT sensors and the sensors placed inside the fleet enable real-time tracking of the location and health of the vehicle. The advanced and bright fleet system increases the overall efficiency and reduces traffic accidents. Sensors help data monitoring from various locations and track the equipment so that risks can be minimized.

8. Loading and Unloading

The capacity assessment of a truck has been a crucial issue while using the assets for transportation and logistics. With IoT in the O&G industry, a company can monitor in real-time the loading and unloading with smart truck weighing solutions.

2.6 Flow Assurance and Production Engineering

Flow assurance, focuses on engineering and production of the whole life cycle, from the reservoir to refining, and deals with a cost-effective approach to produce and transport fluids from the reservoir to a processing facility. During production and transportation of crude oil, knowledge of fluid properties and processing conditions is critical to prevent formation and deposition of undesired solids (e.g. hydrates, wax, asphaltene, and scales). In cases of extreme temperatures and pressures, it is possible that gas hydrates crystallize or asphaltene precipitate in the pipeline. If not properly controlled, the hydrate crystals, asphaltene, or wax particles may precipitate and agglomerate to the point of plugging the pipeline. Removal of a hydrate or asphaltene plug in a subsea pipeline can be very expensive and dangerous.[51]

2.6.1 Flow Assurance Challenges

Flow assurance challenges are rising due to the transition from conventional oil reserves to mature oil fields. As oil fields mature, water fraction increases. In some cases, operators inject water in mature oil fields to enhance oil recovery. Water-in-crude-oil emulsions further complicate flow assurance policies. The existence of formation or injection water along with calcium carbonate can result to scaling under specific conditions. Calcium carbonate scaling can cut off the pipeline and full production equipment leading to less profitable mature oil fields. Most of the commercially available hydrate inhibitors and anti-agglomerants become less effective as water-cut increases. Eventually the emulsion needs to be separated to oil and water. Separating emulsions with physical or chemical methods can be very costly, especially for heavy oil emulsions that contain emulsion-stabilizing solids such as asphaltene. In addition, flow assurance issues increase as the flow-line length and water depth increase. Other critical situations like wearing down of the choke, equipment failure and leakage or blockage of pipelines can also arise. [52],[53] Therefore, it is critical to study and develop cost-effective flow assurance strategies to take control of solids and emulsions to reduce economic risks over the lifetime of an oil field.

2.6.2 Flow Assurance Applications

Multiphase pipeline flow frequently occurs under extreme temperature and pressure making off-line sampling and analysis difficult or impossible. Off-line samples are often handled with dilution or dispersion which can change the multiphase components. Off-line measurements often are not applicable in order to do real-time process optimization and decision control. With the advent of in situ particle characterization technology, the particle phase behaviour can be measured in situ, without pulling samples. [54]

Flow assurance applications include:

- Asphaltene Precipitation - Emulsion

Oil industry suffers from flow assurance issues that occur in upstream and downstream operations. One of the most common flow assurance problem derives from precipitation and deposition of asphaltene in multiple locations along the oil production pathway including near wellbore section in the reservoir, production tubing, flow-lines and separation unit at the surface.

Asphaltene are complex mixtures of poly-aromatic compounds with hetero-atomic species such as nitrogen, oxygen, and sulphur along with organometallic such as iron, nickel, and vanadium. Asphaltene are typically described as the fraction of crude oil insoluble in alkanes (e.g. n-heptane or n-pentane) but soluble in aromatic solvents (toluene or benzene). Alterations in crude oil composition, temperature and pressure conditions can destabilize asphaltene. For example, pressure depletion during crude oil production can lead to undesired asphaltene precipitation and deposition in wellbore and reservoirs.

Asphaltene precipitation depends on several parameters, including temperature, pressure, and fluid composition. Similarly, asphaltene deposition in a pipeline can depend on flow rate, interaction between the particles, interaction between the particles and pipe surface. Such changes in processing conditions occur during various recovery operations (natural depletion, gas injection, chemical injection, etc.) as well as production and mixture of different oils during transportation. Asphaltene precipitation/deposition leads to formation damage, stable emulsions difficult to separate, and partial or complete plugging of the pipeline.

- Gas Hydrate Formation

Gas hydrates are ice-like crystalline molecular complexes shaped from mixtures of water and gas molecules under high pressure and low temperature. The water molecules, upon hydrogen bonding, form lattice structures with various interstitial cavities. The guest molecules can occupy the lattice cavities, and when a minimum number of cavities is filled, the crystalline structure becomes steady and solid gas hydrates form. Fundamental knowledge about structural transitions, formation mechanism, and formation kinetics are still unclear for gas hydrates.

The formation of gas hydrates that block pipelines is, along with other flow assurance problems like waxes, asphaltene, and scales, a significant concern in the O&G industry for preserving integrity of pipeline flow. Gas hydrates are a challenge in offshore and onshore hydrocarbon drilling and production operations because they can cause major, and potentially threatening flow assurance issues, causing pipeline blockages leading to undesired downtime and notable economic losses for operating companies. The danger is particularly high in offshore oil platforms, which are increasingly moving to deep-water operations, as the fluid may cool to low temperatures, below those required to avoid hydrate crystal growth in hydrocarbons for the (usually) high flowing pressures, resulting to forming large, solid plugs in the flow-line or in the production facilities. Formation of the hydrate plug adversely affects fluid flow, in some extreme cases even complete blockage of the pipeline. Hence, gas hydrate formation have costly implications due to interrupted production through flow restriction or plugging, equipment damage, and safety risks to operators. Below on Figure 2.8, the hydrate formation process is shown.[55],

Hydrates form fast at specific pressure and temperature conditions, and can lead to serious production level decrease, safety issues, equipment damage and even emergency equipment shutdown. To minimize this risk, operators typically inject chemical inhibitors into the hydrocarbon flow to avoid the formation of hydrates or other threats during production.

Thermodynamic Inhibitors (THI) are industry standards for prevention of hydrates despite the high cost, the environmental concerns and the high operating. Alternatively, less expensive ‘’Low Dosage Hydrate Inhibitors’’ (LDHI) can extend induction time or prevent agglomeration of primary hydrate particles and maintain a transportable slurry.

Control of hydrate formation in gas systems is generally associated with injection of methanol or glycol at a point where the fluids are above the hydrate formation temperature, with downstream separation and recycling typical for glycols. Control of hydrate formation in oil systems generally requires heat-conserving flow-lines, with appropriate procedures for transient operations such as cold start-up. Constant methanol injection, mainly due to the preference of the methanol for the oil compared to water phases, remains non beneficial economically for most oil systems due to large dosage requirements.[51]

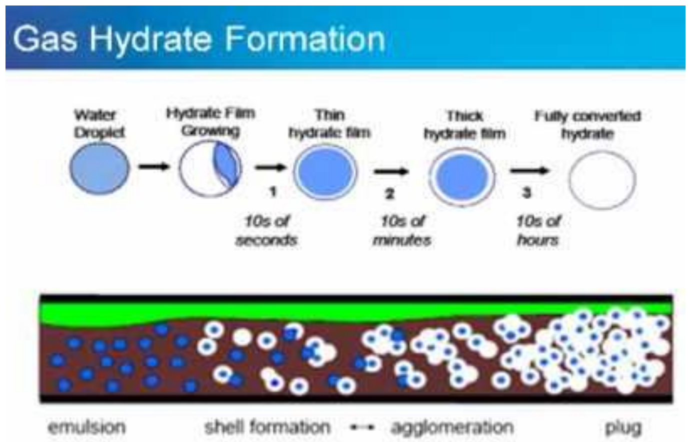

Figure 2.8: *Hydrate formation* [56]

Recognition of temperature and pressure conditions favourable for hydrate formation is a mature technology, with the ability to accurately model impact of dissolved salts and inhibitors. In order to develop new, cost effective strategies to manage the hydrates rather than completely prevent their formation, it is critical to develop a good understanding of hydrate crystallization, agglomeration and deposition mechanisms.

Using reliable in situ technologies to monitor real time hydrate crystallization and agglomeration enable operators to i) Optimize the use of expensive THI, ii) Evaluate the reliability of less expensive LDHI, and iii) Develop robust strategy utilizing both THI and KHI.

During the plant design phase of oil and gas offshore platforms, modelling and simulation software and pre-operation field test data is utilized to optimize the pipeline network design and measure the amount of inhibitor needed to prevent hydrate formation. During operations too, field operators utilise the simulation results to measure the amount of inhibitor required to be injected into the flow. Injection rates are frequently reviewed by field experts, but without real-time visibility of the actual condition of the pipeline, operators tend to overdose the inhibitor to provide an adequate buffer for daily operational conditions and to compensate for changes in field properties within time. This can output to excessive chemical use and increased operating expenses.

- <u>Scales Precipitation - Corrosion</u>

Oilfield corrosion can be divided into corrosions due to oxygen, "sweet" corrosion, and "sour" corrosion due to H2S.

Corrosion due to oxygen is found in surface equipment and down-hole with the oxygen introduced by water-flooding, pressure maintenance, gas lifting, or completion and work over fluids.

Salts (e.g. NaCl, KCl) immediately adhere to surfaces, especially rough surfaces, and are capable of forming very dense plugs, harshly restricting flow and as a result, production efficiency. Salt scaling is particularly severe in wells with high saline (>200 g/l) formation brines which may be near saturation with respect to sodium chloride. The event occurs more frequently in gas wells than in oil wells, and can be caused by decreasing temperatures, low pressures and the addition of organic hydrate inhibitors.

As brine, oil and gas proceed from the formation to the surface, temperature and pressure change, and specific dissolved salts, can precipitate. This is called “self-scaling.” If a brine is injected in the formation to maintain pressure and sweep the oil to the producing wells, there will eventually be a blend with the formation water. Additional salts may precipitate in the formation or in the wellbore (scale from “incompatible waters”). Many of these scaling processes occur simultaneously.

- <u>Wax deposition</u>

Wax deposition in pipelines and risers is a significant issue. It can cause increased pressure drops and temperature reductions, leading to decreased throughput and so, to reduced profit. In more extreme cases, processing facilities and pipelines can plug. There are successful preventative solutions, such as chemical treatments and hot oiling.

Temperature decrease is the most frequent reason for wax deposition because wax solubility in hydrocarbon fluids reduces as the temperature drops. Reservoir fluid cooling takes place all over the producing fluid system. Cooling can occur by oil and gas expansion at the formation face:

- Through casing perforations, or through other restrictions.
- By dissolved gas getting freed from solution.
- By heat radiation from the fluid to the surrounding formation as it flows up the well-bore.
- By fluid transfer through low-temperature surface facilities.
- By injection of water or other fluids at temperatures below the reservoir's.

Pressure changes generally have a small effect on wax precipitation temperatures and amounts. However, changes in the original equilibrium composition of the fluids can lead to a loss of wax solubility. A fairly consistent tendency is that the lightest components in a crude oil act as good solvents for waxes. Liberation of solution gas from a crude oil as pressure decreases below the bubble-point of the fluid has appeared to increase the Cloud-point temperature of the oil.

IoT enhances flow assurance:

With the IoT, real-time visibility of the actual condition of the pipeline and the fluid properties is achievable.

IIoT O&G field developments are progressing and often include subsea installations and satellite wells. Long multiphase lines and subsea production and processing can bring different operational challenges. [57]

2.7 Industrial IoT solutions for flow assurance (Field Case studies)

Oil companies are embracing internet of things (IoT) technology and solutions as a way to improve productivity and face some of the industry's challenges:

- **SHELL:** Use of the Internet of Things (IoT) connectivity as a solution to enhance the company's monitoring capabilities at their operations in Nigeria.

SHELL, used IoT connectivity solution to provide pipeline surveillance and wellhead monitoring of remote infrastructure in the Niger Delta. This solution, was a combination of IT automation and instrumentation technologies to implement a support platform to use remote field data while optimizing operational efficiencies. This integrated technology platform provides more rapid analysis and more efficient data management to provide better understanding of the field processes, giving as a result safe and efficient oilfield operation.

In addition to the IoT network, Shell evaluated communication solutions, which demanded compelling infrastructure investment for radios, towers, data communication equipment, logistics, battery banks and installation and led to a field data gathering, related to pipeline temperature, pressure and flow. The remote terminal units and wireless pressure and temperature transmitters were installed in flow stations, manifolds, and wellheads to offer connection from the field to the back office, with the goal to ensure reliable data transfer.

- **SHELL:** Installation of Smart field sensors such as pumps and valves to oil wells fitted in challenging areas, thousands of meters underground.

Several oil wells exploited by Shell are placed in challenging areas, thousands of meters underground. To help the extreme operations function more accurately, Shell implemented Smart Field Technology. They installed thousands of sensors on their equipment, like valves and pumps. The sensors read data on temperature, pressure, and other measurements, and transmit them to control centers back on land where engineers receive the measurements and monitor production in real time so they can optimize each process individually.

Smart Field Technology is more than just monitoring and transferring information. It is a whole package of integrated solutions that includes high-quality video conferencing, reservoir surveillance, smart wells and fibre optics for real-time monitoring. It connects the appropriate data with the appropriate person so that issues can be addressed in a time effective way. [58]

- **Rockwell Automation:** IoT solution to monitor each stage of the petroleum supply chain.

Rockwell, uses Microsoft's IoT services, a combination of Cloud - based solutions, sensors, software and devices, to predict equipment failures, monitor real time performance and help refine designs and processes in order to avoid future failures.

To avoid loses, such as pump failure in an offshore rig that can cease operations and cost from $100,000 up to $300,000 a day in lost production, Rockwell outfitted their pump's electrical variable speed drives to an IoT Cloud so that they could be monitored in real time, providing to engineers data captures for temperature, pressure, flow rates and other measurements.

Rockwell are also creating gas pumps smart by installing Cloud gateway appliances at each station. These pieces of equipment gather data and securely send it to a Cloud platform. That information is brought to a dashboard that can be viewed on a PC or phone.[58]

- **Orange Business Services**: IoT solution for remote tank monitoring

Cooperating together with Swiss O&G company, Orange Business Services monitored more than 60,000 tanks in industrial and business facilities across 60 countries. They cover devices with 3G and 4G connections. The sensors are installed straight in the oil or propane tank and frequently send through the network, tank level measurements to the Cloud, where the data is automatically processed. [59]

- **ConocoPhillips:** Big Data For Gas Well Gains

ConocoPhillips achieves gas production optimization with more wells connected, gathering more frequent data. Plunger-lift technology exists for decades, so wells dating to the 1950s provide only basic flow-rate and gas pressure data. ConocoPhillips, using a custom-built plunger-lift optimization tool have increased production from more than 4,500 natural gas wells by 30%, applying it to thousands of additional plunger-lift-style gas wells in the U.S. and Canada. As part of the PLOT initiative, ConocoPhillips are installing more sensors to capture far more pressure and temperature measurements and they are sampling these readings every 30 to 60 seconds, as opposed to once per hour or day. By calculating temperature and pressure differentials at various parts of a well, ConocoPhillips can spot the wells that are producing efficiently and those that are not. The PLOT idea introduced 43 performance dashboards for individual wells and gas fields. Simple alerts allow well operators to know when plunger-lift operating cycles should be adjusted to minimize fluid build-ups that restrict the gas flow.

To get more wells connected repeatedly, the firm built their own 130-foot and 80-foot radio and Wi-Fi towers to supply remote energy fields in South Texas, where commercial carriers do not provide mobile coverage. This private communications network keep wells in correspondence with the company’s data centers in Houston and Bartlesville, where the data is cleaned up, analysed and stored.

Enhanced efficiency is a reward and in the case of PLOT, benefits accrue at multiple levels: Improving the company's revenue and the value of their wells, reducing greenhouse gas emissions from inefficient wells and minimizing unnecessary visits to each well by applying remote monitoring. [60]

- **Equinor:** Enabling autonomous well optimization through IoT devices and machine learning in Bakken horizontal wells.

Equinor deployed IoT technology on 50 horizontal wells in Bakken. The device was connected into the rod pump controller. Differences in key down-hole parameters were immediately observed while comparing the results from the traditional rod pump controller and the IoT device. The higher-accuracy physics-based inputs were fed in machine learning algorithms, which dynamically classify wells into key operating conditions of under-pumping, over-pumping, and dialed in.

Utilizing enhanced down-hole information, Equinor was able to automate well optimization set-point decisions, giving as a result reduced well volatility, better pump efficiency, and increased pump fill-age. Equinor managed to achieve these improvements while maintaining production in all cases. By identifying wells that were over-pumping and under-pumping to optimize Strokes Per Minute (SPM) set-points, Equinor achieved higher efficiency outcomes with equal or increased production. For wells that were under-pumping, Equinor was able to increase oil production by up to 33%. For wells that were over-pumping, Equinor managed to decrease the number of strokes by 11% and increase pump efficiency by 14%. [61]

- **BGHE:** Ubiquitous sensing network for continuous monitoring and measurement of methane emissions.

BGHE, achieved methane emission real-time monitoring with Ubiquitous Sensing Network (USN). The technology integrates wireless methane sensor nodes, weather sensors, edge-based devices and is powered by a self- contained solar-battery powered system. A Cloud -based data analytics IoT solution manages sensor monitoring repeatedly.

The initial results demonstrate that the developed technology can measure the emission rate (scfh) within 1% and 45% error, and a localization error within 6 feet to 50 feet provided a test area of 10,000 square feet. This integrated solution is being ruggedized and the analytics are being optimized for continuous monitoring of methane emissions at customer sites for safety, product loss prevention, and regulatory compliance. [62]

- **ADCO:** Asphaltene studies in on-shore Abu Dhabi fields and development of a surface sensor.

ADCO implemented IoT for asphaltene monitoring to achieve the development of a device that can be plumbed permanently in the flow-line (wellhead) and will send surface data every 5 minutes. The spectral output gives a direct reading of spin concentration and thus, the percentage of asphaltene flowing. Such an IIoT device can enable the optimization of chemical program and asphaltene remediation by incorporating the surface data into an integrated flow assurance management system.

The selection of optimal chemical solutions to an asphaltene challenge has been an integral part of the flow assurance strategy for a big on-shore field in Abu Dhabi. Previous studies in the particular field have showed good performance by mixing heavy aromatic naphtha with some dispersant chemicals and then bull-heading that mix to allow to soak and then flow back. Laboratory studies utilising dispersant tests were performed to provide an insight into the effectiveness of carrier solvent and dispersant mixtures. The economics of different fluid delivery methods (jet blasting, bull-heading, etc.) were analyzed for cost-effectiveness and significant field-testing was made to validate the integrated approach. Despite all that activity, there was still no direct measurement. Inferences of asphaltene removal or re-deposition needed to be done from indirect sources like flow meters and surface pressure gauges or through intervention, like running an accessibility check using gauge cutters. In addition, there was no hardware available in the industry for direct measurement of the asphaltene. This led the operating company to help sponsor the development of a real-time sensor. An improved version of that sensor has been completed in a field-test in Abu Dhabi.

The physics required for the built of the sensor relies on the use of a known quantum property of asphaltene, particularly, that asphaltene free-radicals can be resonated by an external magnetic field with a specific ratio of frequency to magnetic field strength, an effect known as Electron Paramagnetic Resonance (EPR). Contributions from metal ions like manganese, nickel, vanadium and iron can also be resonated. Spectrometers utilising the EPR phenomenon, have been used, as an example, in the geo-chemical industry for concentration analysis of organic free matter, but only inside committed laboratories. To bring the asphaltene study to the next level, real-time data would be required directly from the wellhead.

By focusing mainly on the asphaltene response, rather than on a broad range of chemicals, it proved feasible to miniature and ruggedize the device for oilfield applications. Fluid can enter and exit the device through side-streams from the main flow-line. The spectral result gives a direct measurement of spin concentration and so, the percentage of asphaltene flowing past.

The target of the first field test was to certify the device resolution in a field application. It is known from previous field and laboratory data that the total asphaltene ratio should be less than 1%, so the EPR signal might be expected to be small. Results exceeded the expectations and repeatability was better than 0.1%. One initial surprise was that the asphaltene level in each well changed with time, even during steady production. Few wells showed serious variation from one day to the next with a standard deviation close to 5%. Other wells demonstrated barely 1% variation. The wells with the highest standard deviation seemed to correlate against the wells which had historically faced more problems.

While the system was functioning, the operator found the opportunity to investigate the cleanup response. It was determined that after flow back was displaying 100% crude then the surface asphaltene level was low and would stay low for nearly 24 hours before returning back to the baseline level. The data is indicative of the deposition in the wellbore and the initial hypothesis is that the asphaltene was at least partially re-depositing into sections of the tubular cleaned by the solvent.

This is the first time in industry that asphaltene data is being available at the wellhead on a continuous basis. The field test also showed the need of more frequent sampling, which led to the launch of a device upgrade that can be placed permanently in the flow-line and which will send surface data every 5 minutes. It is assumed that such an IIoT device will make possible the optimization of chemical program and asphaltene remediation by integrating the surface data into an incorporated flow assurance management system. [63],[64],[65]

- **Woodside Energy:** Expansion of IoT across entire operations.

Woodside energy implemented IoT to ''Pluto'' LNG (liquefied Natural Gas) plant, to all onshore and offshore facilities, for maintenance and process-control in production operation, to detect foaming problems. The company did an initial trial on a piece of treatment plant at their Pluto LNG Park facility near Burrup in Western Australia. The plant had already around 10,000 sensors reading variables such as pressure and temperature, but Woodside wanted to see whether the data they generated could be aggregated and utilised to predict potential issues during the gas liquefication. The problem they wanted to detect was “foaming” – which usually occurs as a by-product of gas purification. But it can shut the plant down for weeks or months.They Installed 200,000 magnetic sensors from which, data was ingested into Cloud infrastructure before being transmitted to “over 6,000 analytics models” which run more than three million calculations per day.

Woodside combined a mix of technology, data science and operational expertise at the problem, providing a two hour, 72 hour and up to a one week forecast of when foaming might occur while the prototype took just six weeks to build. [66]

- **Woodside Energy**: Design of their own magnetic IoT sensors.

Woodside Energy has attached thousands of home-built magnetic sensors to equipment in their gas plants to enhance monitoring of machine health. They installed a whole new data-driven nerve system. The company designed 7cm by 12cm smart sensors in-house, which can sense and transfer data of equipment performance. The sensors achieve this by monitoring changes in vibrations and temperature, with data sent back to a central point in real-time. They can be easily retrofitted to the existing plant, using magnets.

If the firm bought the sensors commercially and tried to accurately install them to equipment, the unit cost would be around $30,000. Instead, Woodside managed to reduce the price to purchase and fit a device, to less than $300.

These technologies gave the company the ability to detect and respond to emerging problems at the facilities before they interrupt operations.[67]

- **Shell:** Picks a digital platform to build their AI future.

Shell, used the enterprise-wide analytics platform developed by Silicon Valley-based C3 IoT on Microsoft’s Azure Cloud service.

Shell started their trials with the C3 IoT platform by using it to automatically predict maintenance needs of gas compressors, and was successful in identifying failure risks up to 48 hours in advance.

The plan is to expand this use case to hundreds of thousands of machines around the world on the company's offshore facilities and onshore refineries. In addition, Shell's expectations include the use of the C3 IoT's platform to support their supply chain and other digital ideas including computer vision and natural language processing.

This data integration and management technique basically unifies all the data in different systems, despite the underlying technology that generated the data. These data objects are organised in such a way that data science teams can rapidly arrange data sets with machine learning algorithms that reveal new ways to enhance production.

A case study from the two firms, reports that in only 12 weeks, a program established with C3 IoT's platform, predicted successfully, low-producing wells before being drilled, leading to a potential savings of nearly $10 million. The second pilot utilised well data from more than 600 wells, all coming from progressive cavity pumps, and helped create a program that determined potential failures around 4 weeks ahead of time. This resulted to an almost 300-day pump life improvement and a 20% decrease in work-over jobs, bringing an additional $14 million in capital savings, as the companies reported.[68]

- **Marathon Oil:** IoT system to protect workers in extreme environments.

Marathon, installed Wi-Fi and location-based technologies with gas detectors to allow remote monitoring of incidents in locations previously not applicable for wireless networks. In plants around the O&G industry, the greatest challenge for safety and operations managers is how to keep their employees safe. Marathon Petroleum Company cooperated with Accenture to develop the Accenture Life Safety Solution, an IoT- enabled multi-gas detection system that helps the protection of workers in potentially extreme environments.[69]

- **Encline artificial lift technologies:** IoT for pump stroke optimization.

The optimum upstroke and downstroke speeds are different for every horizontal oil well. In addition, the optimum speeds change with time because of the dynamic nature of the fluid flow of each well. The company's IoT Pump Stroke Optimization (PSO) system automatically calculates in real time the optimum rate for upstroke speed and downstroke speed. [70]

- **Encline artificial lift technologies:** IoT to improve gas lift operations.

The IoT Phase Transition Control (PTC) system, communicates with the compressor control panel and improves gas-lift compressor operations, reduces tank vapour emissions, prevents elevation of crude vapour pressure, improves corrosion chemical effectiveness, and reduces paraffin formation. It accomplishes this by maintaining temperatures throughout the compression process in the 100% vapour region of the phase diagram, preventing any hydrocarbon condensation which is caused by over-cooling of the gas. [71]

- **WFS:** Subsea Internet of Things

WFS, is the only company who has created technology for subsea IoT. Their applications focus on asset integrity (field wide cathodic protection, pipe wall thickness, crack, vibration, impressed current, flow induced pulsation, riser fatigue, completion fatigue, mooring fatigue, leak detection) and production optimization and flow assurance (EOR water/gas injection, hydrate/wax, chemical injection, slug management).[72]

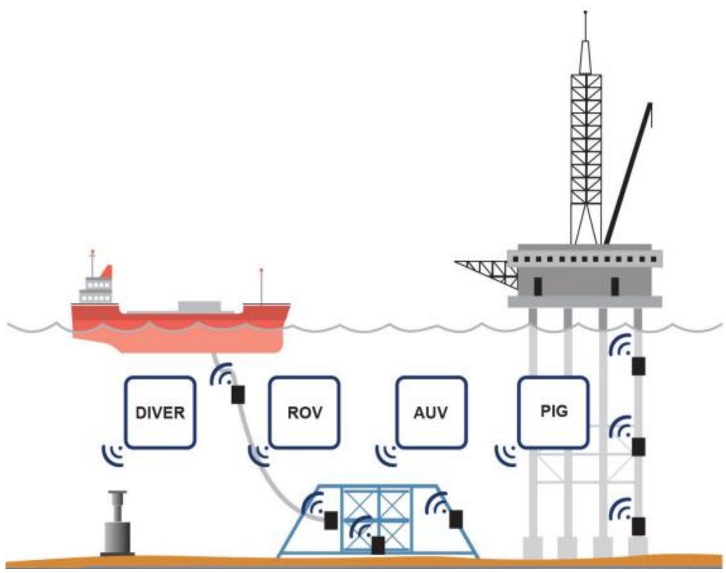

Figure 2.9: *Subsea IoT, WFS* [72]

CHAPTER 3: Benefits and Challenges of IIoT

3.1 Benefits of IIoT

The key drivers of today's IoT adoption lie on the inexpensive technology (processors, sensors), the better infrastructure (cellular technology, mesh networks), the cheaper storage (Cloud, hardware costs) and the big data analytics. In addition to reduced cost of sensors, what drives the IoT is the miniaturization of sensors, with the equivalent drop in the amount of power they require and the fact that they can be connected to wireless networks, through Bluetooth or Wi-Fi. PCs and smartphones offer the ability to control and monitor all these sensors from a developing range of apps.

IIoT permits manufacturers to smart-enable their assets to potentially save thousands in Operational Expenditure (Op-Ex) funding, and millions of dollars in Capital Expenditure (CapEx) funding. IIoT, with a combination of computing and control at the edge, connected to Cloud-based applications with analytics, makes existing systems smarter, without a rip-and-replace.

IoT applications, allow the oil and gas industry to digitize, automate and optimize processes that were previously disconnected to enhance safety and amplify earnings simultaneously, with predictive maintenance and asset tracking solutions having the biggest impact. [45] O&G IoT applications may even become necessary for a competitive edge among increasing climate change and geopolitical tensions. [23]

With IIoT technologies, the O&G industry has the ability to connect machines, sensors, devices and people with interconnectivity, that can aid firms better encounter variations in demand and pricing, face cyber-security, and minimize environmental impact.

Furthermore, the industrial internet of things can enable the advent of new business models by exploiting analytics for innovation, improving productivity and changing the workforce. [73] The potential of development by implementing IIoT is assumed to produce $15 trillion of global GDP by 2030.

<u>More specifically, the IoT can enhance each of the O&G industry sectors:</u>

- <u>Exploration:</u> Progress in seismic data acquisition (4D, micro-seismic) and computing power have already provided a better insight of subsurface geology by giving more and better data of what lies beneath. However, still significant opportunities lie in faster processing of existing seismic data and converting them into surface models. The application of smart sensors provides companies the opportunity to achieve uninterrupted production process, minimize asset failure and downtime and thus saving costs, monitoring and producing more efficiently.

- Development: Smart sensors, machine-to-machine connections and big data analytics can increase the active rig time, while a connected supply chain based on big data and network mobility can reduce cost inflation and delays in new projects.

The storing process can be improved as well with the application of IoT, by gathering and analysing real-time data to monitor temperature control and inventory levels. IoT can improve the transportation process of oil and gas by applying smart sensors and thermal detectors to receive real-time geolocation data and monitor the products for safety concerns. These smart sensors can monitor refinery processes, and improve ecological footprint and safety and reduce accident frequency. The need for products can be estimated more accurately and automatically be delivered to the refineries and production plants to accustom production levels. [45]

- Production: The opportunity to automate thousands of wells (considering that a large company manages more than 50,000 wells) and monitor numerous pieces of equipment per well (assuming that a single pump failure can cost from $100,000 to $300,000 a day in lost production), makes production the greatest potential O&G beneficiary of IoT applications. [29] Predictive maintenance can improve productivity, monitoring changes in operating conditions can enhance the process flow, and real time monitoring of assets, can increase the utilization of assets and improve the asset maintenance.[23]

3.1.1 Benefits of IIoT for small companies

There are feasible, significant advantages to be gained by gathering and analysing machine data, regardless the size of the process. IIoT and machine data monitoring technology is rewarding for large multinationals, as well as for small to medium sized enterprises but maybe the way to do it differs. [74]

According to John Rattray, senior VP marketing and business development at Memex Inc.’’If you have even just one machine, it is possible to find actionable data metrics to turn into ideas for continuous improvement and increased productivity. However, it is worth examining the level of control you preserve around your plant without the system. I’ve seen a customer with just six machines taking the data and use it effectively to create business growth”.

3.1.2 Value of sensors in IoT applications

Wireless sensors provide an important return on investment for medium to enterprise-sized businesses expecting to increase efficiency, receptivity and decrease business interference. However, even more of the value of IoT and smart sensors will derive from using that awareness from all the data collected to take better decisions. Real-time feedback and analytics can determine trends and bring better insights.

Sensors are connected to each other and the Internet, sending their data through a gateway to an IoT Platform (Cloud). There is no limit to the number of sensors and alarms. In addition, there is access to the sensors data through mobile phone, desktop and web application as well as the ability to display multi-system information simultaneously. [75]

3.2 Challenges and Solutions of IoT

While the advantages of sensors and the data they produce may be clear to achieve the digital oilfield, the industry must overcome limitations in today’s IoT infrastructure and systems to broader adoption of the technology:

1) Privacy and Security (cyber-security risks)

As the Internet of Things becomes a basic element of the future internet and the usage of the IoT for large-scale, the need to address trust and security operations is created to provide:

- Trust and quality of information in shared data models to enable re-use across many applications.
- Secure data transfer between IoT devices and consumers.

- Protection mechanisms for sensitive devices.

The conception of internet-connected devices and sensors related to IIoT technologies, combined with increased use of Cloud computing and data-as-a-service models, has further raised cyber-security worries for industrial control systems due to the fact that industrial automation systems are more sophisticated now. Meanwhile, cyber attackers are increasingly mature and well-funded. [76]

Every new device or component that connects to the IoT can become a possible liability. Gartner estimates that by 2020, more than the 25% of identified attacks on enterprises will include IoT-connected systems, in spite of its accounting for less than 10% of IT security budgets.

Eddie Habibi, founder and CEO of PAS Inc. suggested in an interview the need for petroleum companies to undertake an extensive inventory of what he calls "cyber-assets," which involves all control-system sensors, computer workstations, input-output devices, mobile devices and others. "You can't secure it if you don't know it exists," he mentioned. "If you have a complete inventory of cyber assets, you can identify vulnerabilities and determine if unauthorized changes have occurred," he noted. He also suggested that firms conduct a prioritizing exercise for the expenses and consequences of multiple types of cyber-attacks, or other incidents in which cyber-security may be at risk unintentionally. This can better ensure that resources are committed to cyber-security in a thoughtful way. Additionally, attention must be paid to how cyber assets are backed up, and how recovery from a cyber-attack can be achieved.

One of the complications in providing security solutions in IIoT applications is the fragmented type of the hardware. As a consequence, security architectures are turning towards designs that are software-based or device-agnostic.

2) The eagerness of IoT devices for the O&G environment which can vary from friendly to extremely harsh environments.

3) The lack of standardization in how the IoT devices produce and transmit data.

4) The lack of mature integrated data and information management platforms.

Lack of data integration technologies and slow adoption of Big Data technologies to store and analyse selected data can also slow information potential down.

5) The lack of skillful talent.

6) Organizational constraints.

Leadership related to the adoption and deployment of IIoT and restrictions on managing personalized data, or general lack of trust in predictive models, and even absent capabilities in the areas of analytics, statistics and modelling.

7) IT/OT convergence

The interoperability of the industrial communication protocols and security concerns arising from the need for Information Technology (IT) and Operational Technology (OT) convergence is an issue that might make companies hesitant to invest in IIoT. To overcome this, it is significant for the industry to invest in their personnel. [4]

CHAPTER 4: Future Forecasts and Statistics of IIoT

4.1 Future Forecasts

Research, from the McKinsey Global Institute, suggests that by 2025, the impact of the IoT on the global economy could be as high as $6.2 trillion. According to Oxford Economics, industry-wide adoption of IoT technology can influence global GDP by increasing it by as much as 0.8 percent, or $816 billion within the next decade. Research from Markets & Markets suggests that spending on IoT solutions in the energy market is expected to climb to $22 billion by 2020. [48], [77]

The evolution of enabling technologies like embedded systems, electronics, communications, sensors, smart phones, Cloud networking, network virtualization and software will be fundamental to allow physical devices to function in changing environments and to be connected everywhere and all the time. In addition, with sensor technology available at lower price, the amount of sensors utilised will rise quickly.

According to Gartner, by 2020, 25 billion assets will be connected-working smarter, faster and more accurately than ever before. [32]. Several developments led to that adoption:

- Expenses have dropped sharply, leaving little financial risk for implementation.
- Sensors offer a low barrier to entry — an easy first step to greater supply chain visibility.
- Visibility supply chain products with global geo-fencing of ports and transport hubs eases more use cases and ways to make profit for organizations.
- Device capabilities have broadened — better durability, bigger data storage, and longer battery life.

The Future of IoT in Oil and Gas industry

The future of IIoT has the potential to be bottomless. Progress in the industrial internet will be accelerated through integrated AI, increased network agility and the capacity to deploy, automate and secure a variety of use cases at hyper—scale. Service providers will edge additionally into IT and web scale markets, bringing new ways of income. [78]

Berg Insight forecasts a 6.8% rise in the amount of IoT devices deployed in the oil and gas industry from 2018 to 2023. The main key for a growth in the IoT devices installations is the need for remote monitoring of tanks and industrial equipment in the midstream and downstream sections. Moreover, for IoT adoption to develop, the cost of components that are required to support capabilities like sensing, tracking and control mechanisms need to be rather cheap in the near future. [79]

Facing decreased oil prices, the O&G industry starts to understand the IoT's significance to future success. But it is not as simple as applying additional sensors: Creating and capturing value from IoT applications certainly requires the identification of primary business objectives prior to implementing IoT technology, confirming new sources of information. (Figure 4.1) [80]

- Upstream section, focused on optimization can gain new operational insights by normalising the data and running integrated analytics across the functions (exploration, development, and production).

- Midstream players aiming for higher network integrity and new commercial opportunities can benefit by investing in sensors that address to every part of their facilities and analysing volume data more extensively across their network.

- Downstream players operating at an ecosystem level can build new value by widening their visibility into the entire hydrocarbon supply chain to improve core refining economics and aiming at new digital consumers through new ways of connected marketing.

O&G segment	Primary IoT-enabled business objective	Dominant value drivers	Likeliest value loop bottleneck	Potential solution
Upstream	Optimization	Scope and latency	Aggregate	Standards
Midstream	Reliability	Scale, accuracy, and timeliness	Create	Sensors
Downstream	New value creation	Scope, timeliness, and security	Act	Ecosystem management

Figure 4.1: *Analysis of IoT value by O&G segment* [25]

4.2 Statistics of IoT in O&G

According to McKinsey, by 2025, IoT has a total likely economic impact of $3.9T to $11.1T with a possible economic impact of $930B from mining and O&G companies within the next ten years. This market growth is predicted to be mainly driven by shortage of skilled labour, ageing infrastructure, increasing amount of cyber-attacks and the need to increase operational efficiency, which will act as main drivers for the adoption of IoT solutions.[23]

Over the next three to five years, 80% of upstream O&G companies schedule to invest the same, more or much more (30%, 36%, and 14%, respectively) on digital technologies as they currently do, according to a survey by Accenture and Microsoft titled"2016 Upstream Oil and Gas Digital Trends Survey". This continuous investment in digital is due to respondents' confidence that digital technologies can continue to assist them lead smarter organizations, according to Accenture. There have been notable increases in IoT investment within upstream oil and gas with 44% investing in the internet of things in 2016 compared to just 25% in 2015. [30] The Cloud gained 38%, up 8% from 2015. Until 2020, these investments are expected to address more to big data and analytics (38%), IoT (36%) and mobile (31%), according to Accenture.[48]

Analysts at Nomura, say that by fully optimizing the IoT solutions available and as more and more machinery gets filled with sensors and connected to the internet, could make O&G companies more profitable at $70pb than they were previously at $100pb and an oil and gas company with $50 billion as annual revenue could increase its profits by almost $1 billion, according to a Cisco study.[81]

For E&P companies, the analysis of normalised data will potentially mostly affect production, followed by development and exploration. By some estimations, IoT applications could decrease production and lifting expenses by more than $500 million of a large O&G integrated company with annual production of 270 million barrels. [82]

At the moment, traditional systems continue to be utilised, however, they will be integrated with new IoT systems. Eventually, in nearly 5 to 10 years' time, the industry will achieve full IoT adoption. The pace at which this happens will highly relate on factors like the speed of academic research and the progress of international standards and compliance on the part of vendors. There will need to be improvements in the safety, security, speed and reliability of the internet in order for IoT technology to become the standard.[83]

CHAPTER 5: Implementation of IIoT in a real case company project

5.1 Design Process of an IIoT Project

An IIoT project is barely completed. The first stage may come to an end, but one stage is usually not completed before the next stage starts. A design methodology is critical. Below, the steps for the development of such a project are described, with an example from O&G industry: [10]

1) Address the objective. Why is a company starting and IIoT project of any scale and complexity? When finished, what benefit will it give?

- Example: Review the needs of a problem in O&G Industry, e.g. Accidents

Figure 5.1: *Accidents caused by explosion of Refineries, (Left) Explosion of Abadan Refinery (4 Jul 2017, 11 people were killed and wounded), (Right) Explosion and fire in Tehran's oil refinery (27 Oct 2017, 10 people were killed and wounded)* [10]

2) Determine specific near-term, small and doable milestones.

- What was the cause of the incident? Gas leak and explosion.
- What is the solution? Using Gas Detection Systems.
- Common Oil & Gas Detection Systems: Limitation in Number of Sensors and Alarms / Most of them do not have remote accessibility / Unable to display multi-system information simultaneously / Additional features like Low/High Pressure Oxygen Bank Monitoring.
- Define the necessary required priority proposal: An IoT based Gas Detection System is needed.

3) Ensure the IoT components are robust. In extreme conditions, deployment or wire-wrapped demonstrator devices will tend to fail, at the most inappropriate time. Install individual IoT sensors, points, actuators, processors, gateways, etc.

- Selection of an IoT platform
- Design of the required hardware

Figure 5.2: *Hardware device of an IIoT project* [84]

4) Address signal quality. The signal to noise ratio should be of adequate distinction to provide dependable data (usually an S/N ratio of 3 or more is favoured). In addition, ensure to prevent spurious data, but not so filtered to prevent outliers.

5) Consider the end user. Too much data and not enough information will sink a project.

- Design and Implementation of Mobile & Desktop Application, to visualise the results.

Figure 5.3: *IIoT applications to visualise results* [85]

6) Is the solution robust, functional, and autonomous?

- Testing the System

Figure 5.4: *Testing of the system's functionality* [10]

5.2 Infrastructure required for IIoT Projects

- Field personnel to deploy, use and calibrate the system.
- Reliable and flexible communication system including the ability to back-fill data gaps after communication outage.
- Data retention involving short-term raw volume, long-term decimated volume and behaviour modeling.
- Streaming data processing in four approaches: Real-time monitoring, after-action analysis, pre-action planning analysis, and large-field analytics and machine learning.
- Geographic dispersion of IIoT devices, users, and systems.[7]

5.3 Engineering Skill-sets required for IIoT Projects

An IIoT Engineer must be qualified in:

- Sensors: Sensor integration, technology and specifications.
- User interfaces: Mobile devices and operations centres.
- Install-ability, serviceability, maintainability, reliability, and security.
- Data organization, storage, retrieval, and flow.
- Units of Measure, calibration, sampling rates, filtering (hardware and software filters). [7]

5.4 Hydrafact Company:

Hydrafact ltd, is a consulting and technical company offering services in gas hydrates, flow assurance and PVT and in-house technology development for hydrate inhibition monitoring. [86]

5.4.1 Hydrafact's Technical Services:

The company gives solutions to various flow assurance issues, from locating the plug, to safe and fast removal, dealing with hydrate blockages, ensuring a company is producing again in the shortest possible time. More specifically:

- Flow Assurance (In particular, Gas Hydrate, Wax, Asphaltene, Salt/Scale, Emulsion/Foaming, Corrosion) Services
- PVT Phase Behaviour and Properties Reservoir Fluids
- H_2S/CO_2-rich Systems
- Enhanced Oil Recovery (EOR)
- Commercialisation of novel technologies (e.g., HydraCHEK, HydraSENS, KHI removal/recovery/reuse, etc)

5.4.2 Hydrafact's Software:

- HydraFLASH

It is the company's advanced thermodynamic hydrate and PVT prediction software. It is designed to model the phase behaviour of petroleum systems and to measure the phase equilibria and physical properties of petroleum reservoir fluids (including: oil, gas, water, salt, alcohols, glycols, hydrates & ice) over a wide range of pressure and temperature conditions. More specifically, HydraFLASH provides:

- Hydrate Phase Modelling
- Electrolyte Solution Modelling
- PVT Options
- Hydrate Options
- Inhibitors in HydraFLASH
- Salts in HydraFLASH

HydraFLASH Interface:

HydraFLASH is available as an improved and modern GUI interface. This allows systems to be set up and calculations to be made quickly and easily. It provides an intuitive user interface with access to all HydraFLASH facilities, outputs as text files, graphics or Excel worksheets. The figures below, show the composition set up interface, and the result interface of a phase envelope.

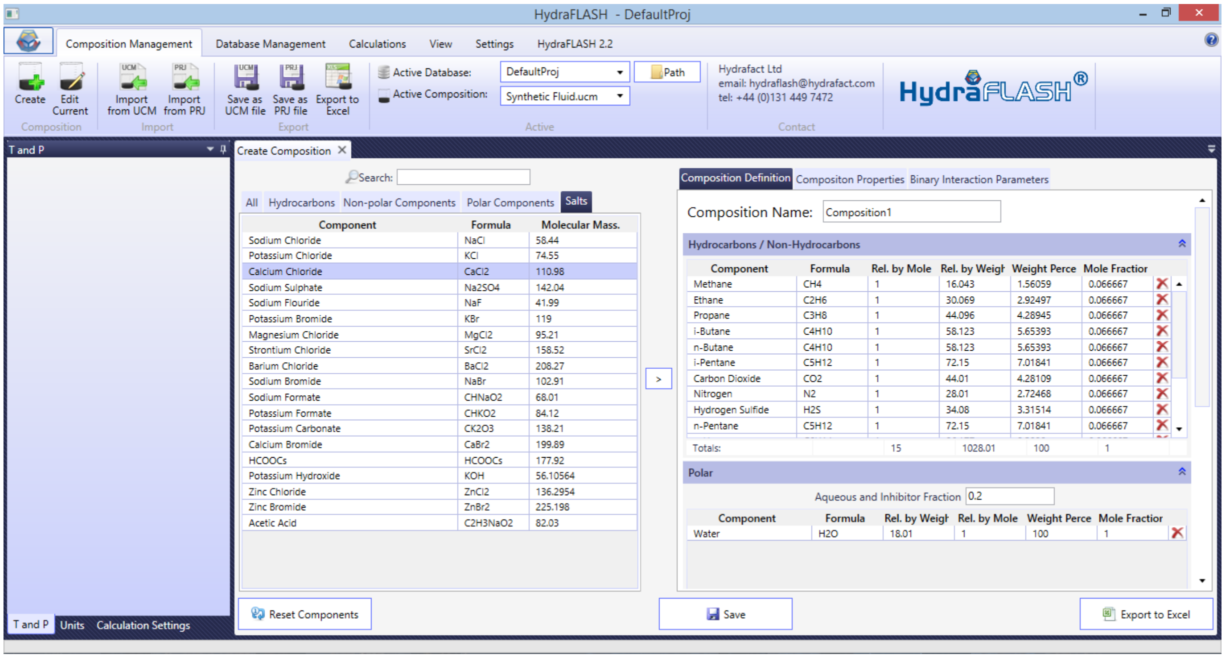

Figure 5.5: *Hydrafact's software, HydraFLASH Composition set up Interface* [87]

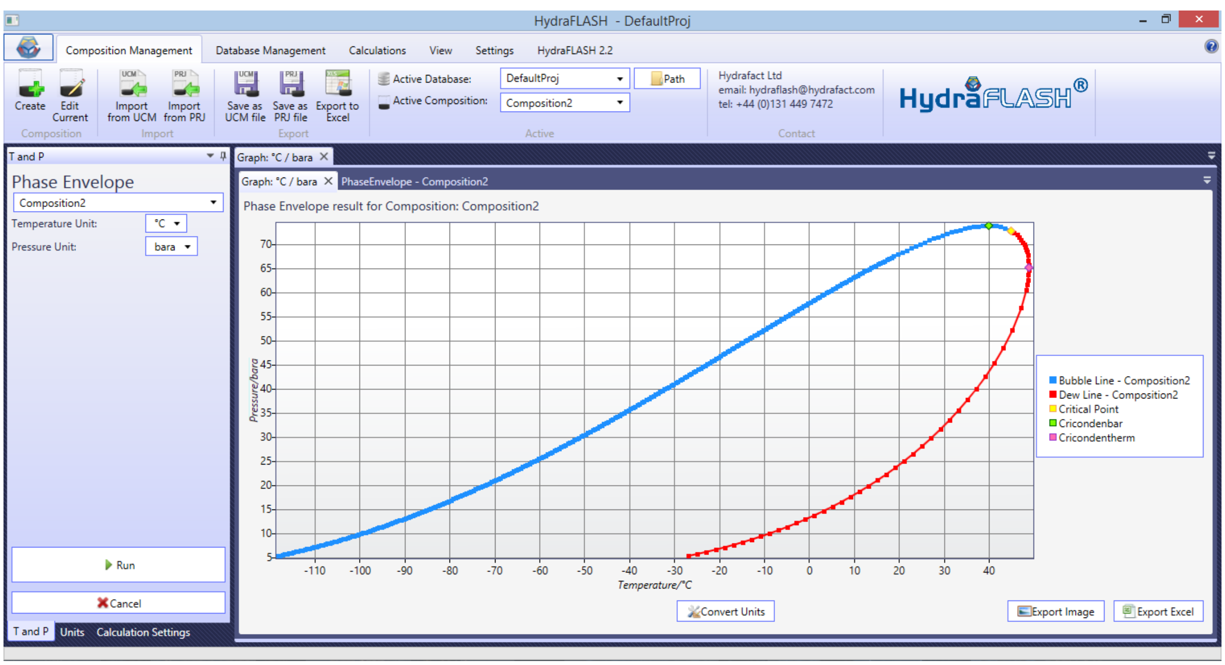

Figure 5.6: *Hydrafact's software, HydraFLASH phase envelop interface* [87]

5.4.3 Hydrafact’s Technology:

- HydraCHEK:

It is the company’s Hydrate Inhibition Monitoring System. It provides a solution to monitor the hydrate inhibition of a production system in order to prevent the significant expenses of hydrate inhibitor over use. Moreover, it determines the risk of hydrate and defines the safety margin, compared to the hydrate dissociation curve for the field.

HydraCHEK offers a quick and user-friendly analytical solution. It measures temperature and two independent physical parameters of a produced water sample: The speed of sound and the electrical conductivity to define two unknown parameters: Hydrate inhibitor and salt concentration. The calculated speed of sound and electrical conductivity of a sample are input into an artificial neural network correlation which allows both the salt and inhibitor concentration to be defined. [88]

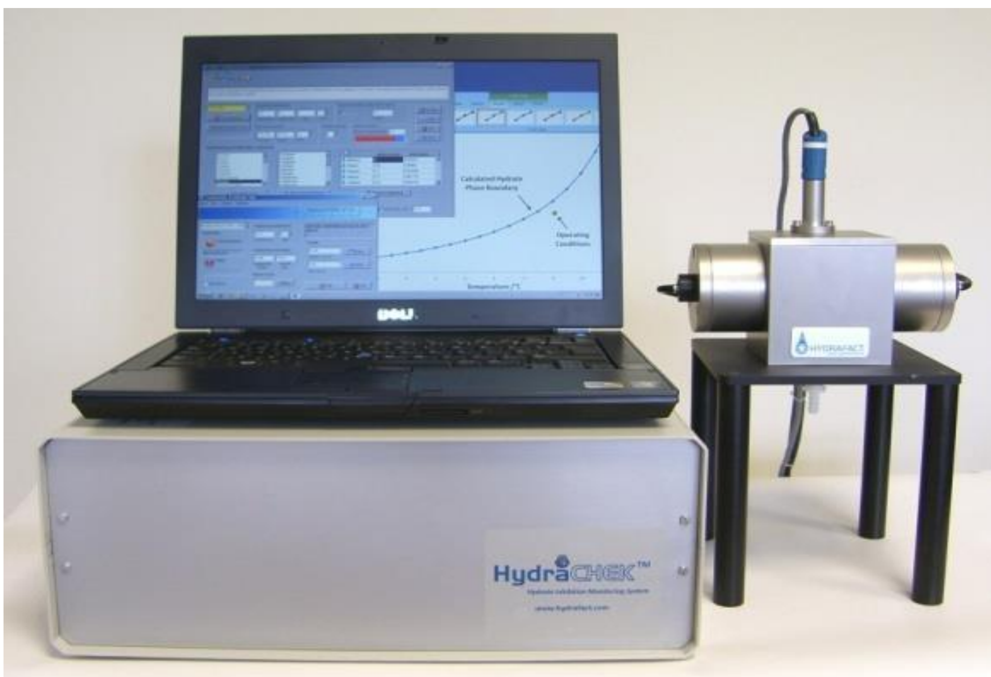

Figure 5.7: *HydraCHEK device* [88]

HydraCHEK Applications:

- Defining hydrate safety margin
- Determining the amount of water converted into hydrate
- Detecting formation water breakthrough
- Monitoring the performance of thermodynamic inhibitor regeneration units
- Improving the accuracy of Multi-Phase Flow Meters (MPFM)
- Monitoring the quality of water for disposal
- Determining the rate and amount of water production

HydraCHEK Advantages:

- Benefit from hydrate safety margin monitoring

The hydrate phase boundary can be detected for a system during operation when using thermodynamic hydrate inhibitors. The hydrate inhibitor and salt concentration in the produced water, along with the hydrocarbon fluid composition can be input into HydraFLASH to provide the hydrate phase boundary. The operating conditions can then be used to determine the hydrate safety margin indicating how well protected a system is from the risk of hydrate formation.[89]

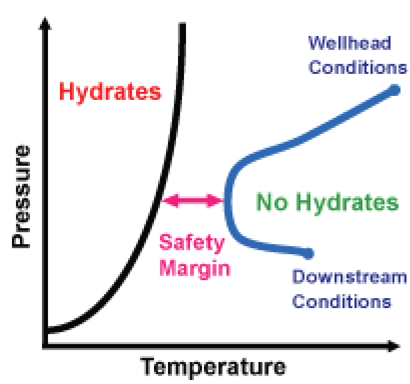

Figure 5.8: *Hydrate Phase Boundary / Safety Margins* [89]

➢ Lower inhibitor Capital Expenditure and Operating Expenditure costs

Hydrate remediation schemes usually include excessive hydrate inhibitor dosage, which results in unnecessarily high CAPEX and OPEX costs. HydraCHEK can be utilised to optimise inhibitor injection rates by providing a quick and easy way of calculating the degree of inhibition of a system and a way to monitor the effect of lowering the dosage with time.

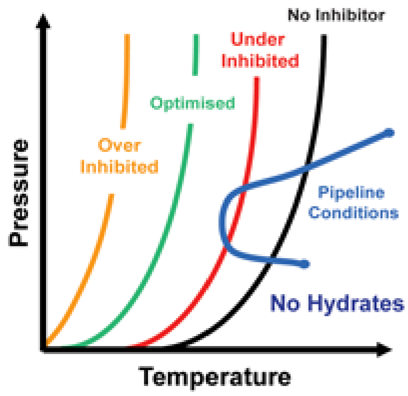

Figure 5.9: *Monitor of the dosage of hydrate inhibitors* [89]

➢ HydraSENS:

HydraSENS provides the detection (and potentially location of hydrate formation) of early signs of hydrate formation risk in real-time by monitoring the composition of produced gas from the pipelines. The device an alert at first sight of hydrate formation, and gives the operator plenty of time to react and avoid the blockage. HydraSENS exists as lab and as on-line device version. [88]

Figure 5.10: *HydraSENS device* [88]

5.4.4 HydraCHEK and HydraSENS as IoT devices

Both HydraCHEK and HydraSENS can be used as IoT devices.

All is needed is internet connection. With the implementation of IoT on Hydrafact's products, the company aims to achieve further automation, dynamic operation and optimization, delivering a simplified automation process with remote monitoring to their clients.

In addition, the company using this technology will gain the following benefits:

- Elimination of all uncertainties related to process parameters (water cut, pump rate, inhibitor purity)
- Reduced OPEX & CAPEX costs
- Increased production
- Reduced hydrate risk

5.5 Implementation process of IIoT on Hydrafact's products

Aim of the project was to create double-duplex communication between Hydrafact's sensor, HydraCHEK and a Historian (Cloud) in order to control the devices remotely and achieve predictive forecasting.

Specifically, HydraCHEK's data (temperature, electrical conductivity, acoustic velocity) and as a result, the useful information (salt and inhibitors concentration) and field data (time, temperature, pressure) needed to be extracted and sent to a Cloud (Historian), where the data would be stored and processed.

For that purpose, an IoT infrastructure needed to be created and the following things were required:

- A Raspberry Pi micro-computer as IoT device where the sensor (HydraCHEK) would be connected.
- An IoT Cloud platform (IBM) as a Historian to store and process data.
- Programming tools to connect all parts of the IoT system together.

The general IoT process designed and implemented for the current project, is described in the Figure 5.11 below:

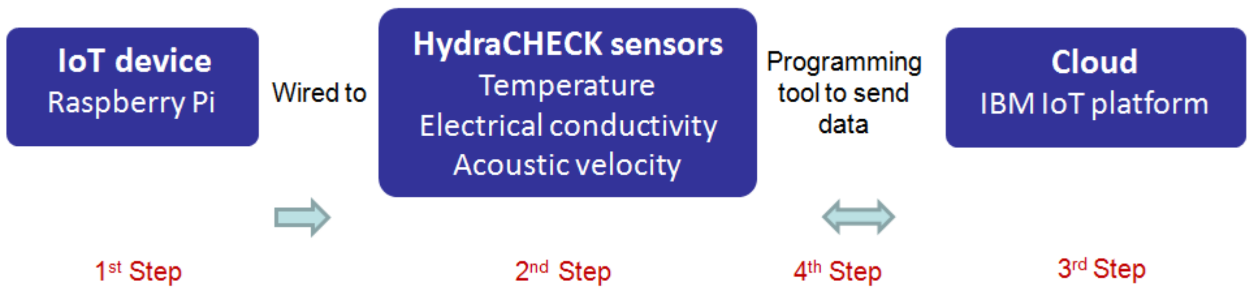

Figure 5.11: *General IoT process implemented*

The first target of this project was to create a code to connect the IoT device meaning the Raspberry Pi, to the Cloud. Among the options for IoT device, the Raspberry Pi was selected. In addition, there are many available companies offering Cloud services, but the Cloud chosen for this thesis, was from IBM Bluemix Company. For this first stage of the process, HydraCHEK was not connected to the IoT device, and so, random data were generated through the program / code, for the ease of the project.

The second stage of the project after that connection would be made, and data could be easily transferred from the IoT device to the Cloud for further processing and analysis, would be to connect HydraCHEK sensor to the so far IoT infrastructure, in order to send specific data.

The first and most significant and difficult stage was successfully implemented. The second one, due to limited time of my work at the company's office, and the width of the project, is not implemented yet, but it is planned to be completed.

5.5.1 Basic IoT infrastructure used:

- Raspberry Pi

The Raspberry Pi is a single-board micro-computer, used as the main gateway device in the IoT infrastructure.

While IoT devices are often low-powered with a microcontroller as the core processor and a Wi-Fi module as the communications interface, they don't have to be. For instance, a mainstream PC can be used as an IoT device, but doing so would prove to be difficult as PCs require mains power of many hundreds of watts. However, the Raspberry Pi, a computer far more powerful than many IoT devices, was a good candidate for IoT processing.

Figure 5.12: *Raspberry Pi hardware [90]*

The Raspberry Pi, was chosen among other similar available IoT devices, due to the following benefits it offers:

- Cost is minimal and depending on the model it can vary from £5 to £55. The specific one used, costed specifically £35. That means that starting a pilot project can be less risky for companies who are looking to implement a new technology into their workflow.

- Combining a Pi with other sensors can make getting an Industrial IoT project a much easier task since obtaining a return on investment is much easier with a $35 device versus a $100,000 piece of equipment.

- Availability of the device. It is the 3rd best-selling computer brand in the world and it's easy and fast to obtain one.

➢ It comes with lots of documentation and other resources, crucial to guide during implementation or problem-facing.

To set up the Raspberry Pi, specific hardware was required apart from the main device, and software suitable for the Pi.

a) Hardware:

➢ A Raspberry Pi computer with an SD card or micro SD card
➢ A monitor with a cable (and, if needed, an HDMI adaptor)
➢ A USB keyboard and mouse
➢ A power supply
➢ An Ethernet cable (If required)

b) Software:

➢ Raspbian language , installed via NOOBS: (Raspbian is part of LINUX)

➢ <u>IBM Cloud</u>

IBM Cloud is a set of Cloud computing services for business. It was selected among other available similar services due to the fact that it is a cost-effective solution with easy and straightforward setup and the ability to create a free Cloud account for a monthly trial.

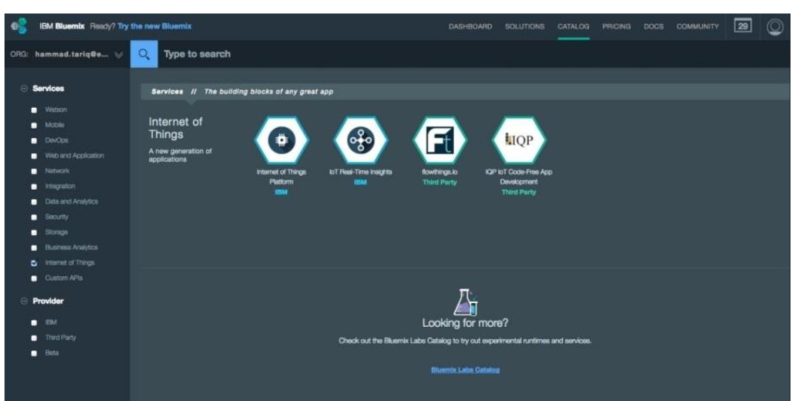

Figure 5.13: *IBM Bluemix Cloud Interface* [91]

➢ Watson IoT platform

The Watson IoT platform can handle IoT devices and make better decisions using secure, globally distributed data, analytics and Cloud. It is part of the IBM Cloud account and the ability to create a 30-days trial version of the IoT platform, was given for the completion of the project.

➢ Software Programming

For that thesis, two different kind of programming tools were trialed and used for the main purpose, due to the fact, that they were both supported to work within the IBM Cloud environment and the Raspberry Pi. Both were able to work successfully, but in the end, out of the two, the Python appeared to be more feasible and suitable for the completion of the project.

a) Node-RED:

It is a flow-based development tool for visual programming, created by IBM for wiring together hardware devices and online services as part of the Internet of Things. It is used to build software applications and is supported by Raspberry Pi IoT device. It is built on Node.js and includes a browser-based flow editor. It can work on Windows, Linux, OS X Operating Systems. [92]

b) Python:

It is an interpreted, high-level programming language. It is easy to learn with simple syntax and is supported by Raspberry Pi IoT device as well as the IBM Cloud.

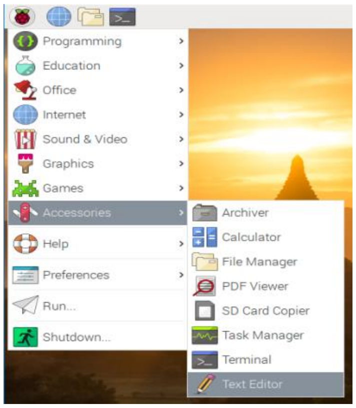

Figure 5.14: Raspberry PI Desktop [93]

5.5.2 Detailed IoT implementation process designed

The detailed IoT implementation process used is described below:

➢ **1st STEP: Install an IoT device:**

The hardware (Raspberry Pi) configuration, as shown in the following Figure 5.12, consists of:

- USB ports — Used to connect a mouse and keyboard. Other components, such as USB drive can also be connected
- SD card slot — SD card is slotted there. It is where the operating system, software and all files are stored
- Ethernet port — Used to connect the Raspberry Pi to a network with a wire. It can also connect to a network via wireless LAN
- Audio jack — Headphones or speakers can be connected here
- HDMI port — Monitor (or projector) used to interpret the result from the Raspberry Pi is connected here. If monitor has speakers, they can also be used to hear sound
- Micro USB power connector — It is where a power supply is connected
- GPIO ports — Electronic components such as LEDs and buttons can be connected here to Raspberry Pi. [94]

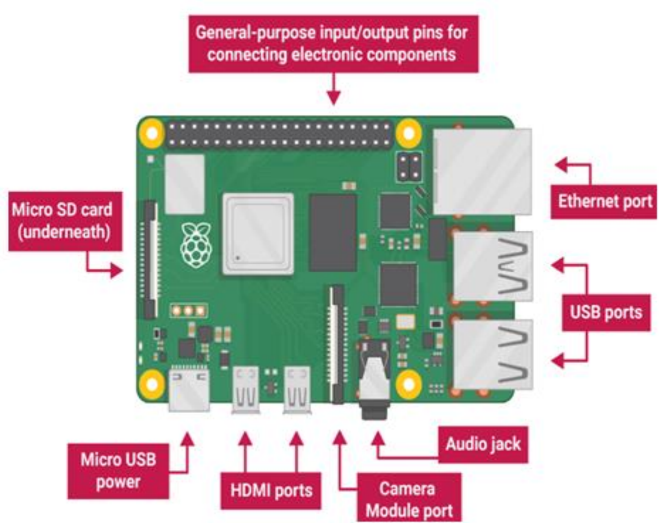

Figure 5.15*: The hardware (Raspberry Pi) configuration* [94]

To setup and connect the Raspberry Pi the following steps were done:

1) An SD card with Raspbian operating system was deployed.

The Raspbian operating system was pre-installed in the Raspberry Pi.

2) A mouse and keyboard were connected to the USB ports on the Raspberry Pi (it does not matter which of the two ports to use).

3) A screen was plugged into a wall socket and switched on. A cable was used to connect the screen to the Raspberry Pi's HDMI port.

Nothing appeared on the screen so far, because the Raspberry Pi was not running yet.

4) The Raspberry Pi was connected to the internet via Ethernet, using an Ethernet cable to connect the Ethernet port on the Raspberry Pi, to an Ethernet socket on the wall or on the internet router. There was no need to do that if we wanted to use wireless connectivity, or if we didn't want to connect to the internet.

5) Headphones or speakers were connected to the audio port to play sound on Raspberry Pi.

6) The power supply was plugged into a socket and then connected to the Raspberry Pi's USB power port.

7) Red light appeared on the Raspberry Pi and raspberries on the monitor. The device then did a boot up into a graphical desktop.[95]

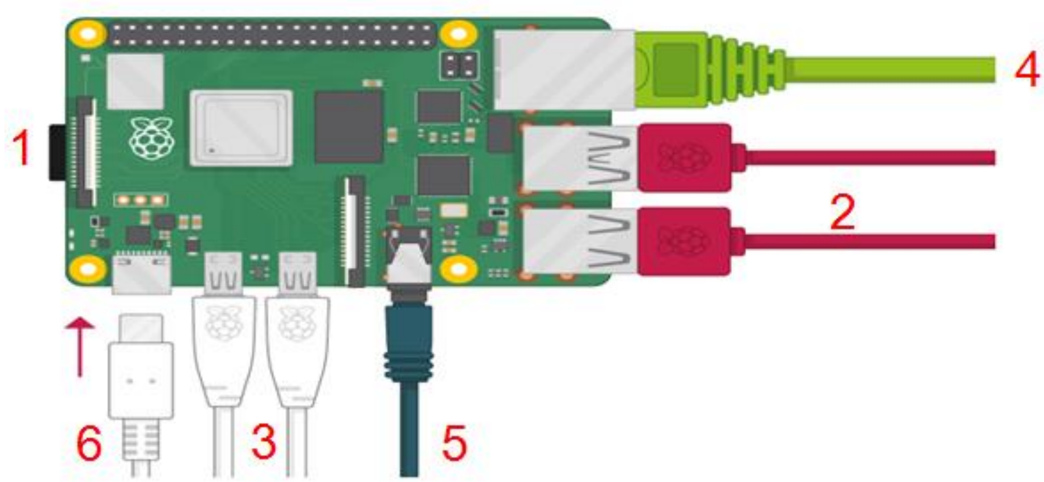

Figure 5.16: *Raspberry Pi Set up connection* [95]

➢ 2nd STEP: Bond Sensor to IoT Device:

Bond HydraCHEK sensor to Raspberry Pi:

GPIO pins (General-Purpose Input/Output). It is used to connect the Raspberry Pi to electronic circuits (HydraCHEK sensor), which allow it to control and monitor data, in this case (temperature, electrical conductivity, acoustic velocity). This step of the process is not completed yet as it was designed to be the last stage, after the whole IoT system would be made to work successfully. It is an easy step though, which only requires cable connections on the hardware devices. [96]

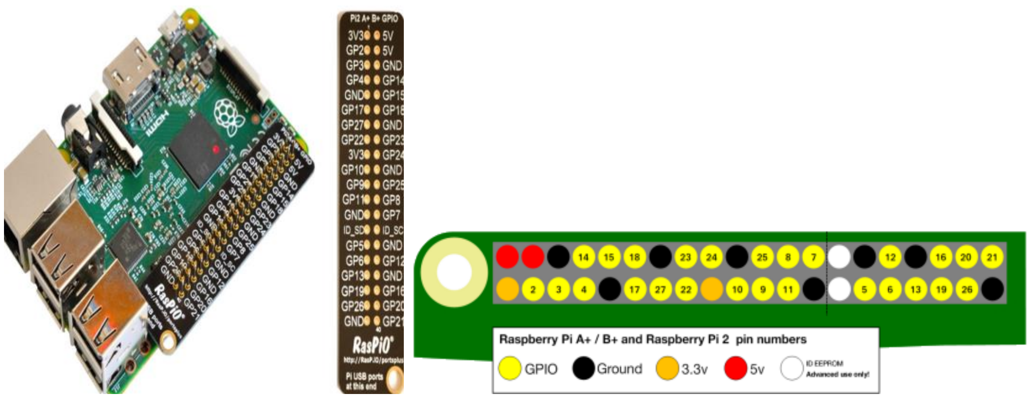

Figure 5.17: *GPIO pins on Raspberry Pi* [96]

A breadboard was needed to wire up HydraCHEK Sensor to a GPIO pin on Raspberry Pi.

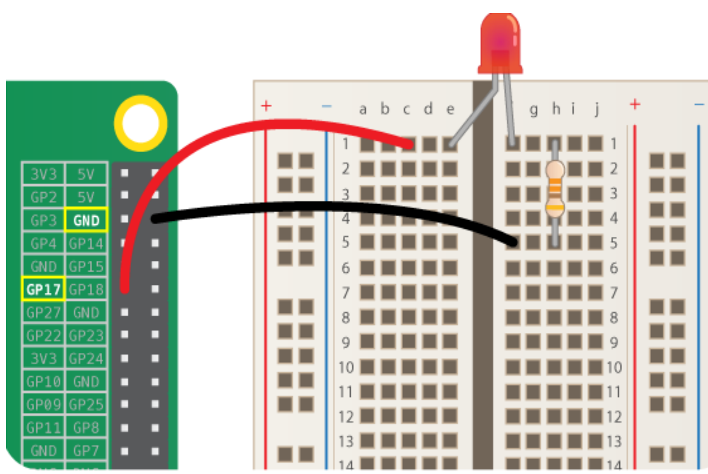

Figure 5.18: *Breadboard* [96]

- **3rd STEP: Setup Cloud account for an IoT Platform:**

As part of the creation of the IBM Cloud, the MQTT had to be installed.

MQTT: It stands for Message Queuing Telemetry Transport. It is a machine-to-machine connectivity protocol used for communication in IoT connected devices. It is useful for connections with remote locations where, is it needed, to send just a few bytes of data or the sensor values.

Specifically, the Raspberry Pi needed to be connected to the MQTT in order to enable communication between the IoT device and the Cloud.

The whole MQTT system consists of many clients and one broker. It is a system which enables publishing and receiving messages (data) as a client (e.g send commands to control outputs, read and publish data from sensors).

The devices (Raspberry Pi) act as clients while the broker (Cloud platform) receives all messages, filters the messages, determines who is subscribed to each message, and sends the message to these subscribed clients. [97]

To setup the connection, the MQTT library needed to be deployed in Raspberry Pi using the following python code:

```
sudo pip install paho-mqtt
```

***Figure* 5.19:** MQTT installation code [98]

Then, after the MQTT was successfully installed, the IBM Cloud account was created by following the steps below:

- Create and email and a password to sign up to the Cloud.

- Create resource (on dashboard): That option enables to use any service on the platform.

- Select ‘Internet of Things’ Service from resource list.

- Create and Launch IBM Watson IoT platform: That step, provides the ability to setup and manage all connected devices.

- Add device: It gives the possibility to register the Raspberry Pi to the IoT platform that was created. The following options on that tab were selected:

‘’Identify’’ a Device Type: Test, Device ID: The MAC address of Raspberry Pi was input.

‘’Device information and Security’’: That was left unfilled

‘’Finish’’: Save device credentials as they will be used later

Raspberry Pi was created in the IBM Cloud, but not connected yet!

- Connect Raspberry Pi with IoT platform by creating/writing a suitable program / code.

- Visualization of sensor data. The following options on that tab were selected:

Create a template by going into ‘’devices’’ tab, ‘’usage overview board’’ option. Add a new card and choose a graph.

Select the device previously created and ‘’ connect new data set’’.

Input the data to be displayed on the graph (event=status1, used in code later on)

- Enable communication between IBM Cloud and the Raspberry Pi.

Select from Resource list ‘’security’’ and ‘’connection security’’ tabs.

- Create program / code to transfer data values from device to the IoT platform. [99]

a) Using Node-RED

b) Using Python

- **4th STEP: Programming Tools:**

A) Using Node-RED

- Open the application on Raspberry Pi: Node-RED is already available on Raspberry Pi IoT device.
- Create a ''device flow'': Send sensor data from IoT device to the previously created Watson IoT device.
- Create an ''application flow'': IoT platform receives the data and processes it.
- Create an application in Bluemix account to receive the data: Node-RED is already available on IBM IoT Cloud.
- Create the flow on the device to manage the commands sent to it. [100]

At the current project, although the whole flow was designed, only the first stage (Device flow) was implemented in Node-RED as Python appeared to be a faster way to complete the task in the limited time available. However, the main task was achieved in Node-RED and random data (as sensors values) were generated, and sent from the IoT device to the Cloud. All the devices managed to get connected and deliver the desired result. The next step would be to create an application in order to visualize the data and then process them.

<u>The flow used in the Node-RED environment:</u>

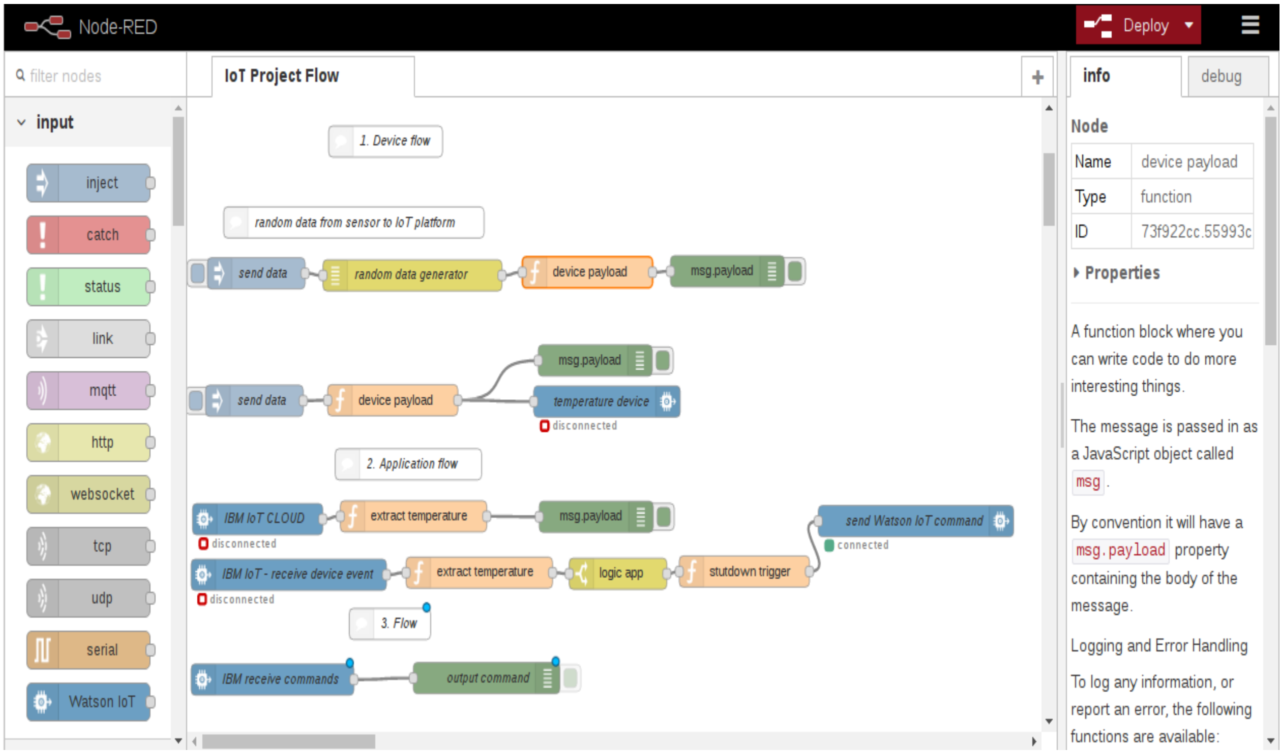

Figure 5.20: *Node-Red Flow used*

Node-Red flow, as it is shown in the Figure 5.21 below, consists of several nodes. The nodes used for the current flow are:

- Inject node (light blue): This node allows to inject messages into a flow (trigger the flow), either by clicking the button on the node, or by introducing a time interval between injects. It is the first node of the flow, dragged onto the workspace.

- Debug node (green): This node causes any message to be displayed in the Debug sidebar on the right side of the screen. By default, it just displays the payload of the message, but it is possible to display the entire message object. It is the last node of the flow and it shows the expected output. Along with each message, the debug sidebar includes information about the time the message was received, and which debug node sent it.

- Function node (orange): This node allows to send each message through a JavaScript function. The function node is wired between the inject and debug nodes. To write the desired code, it is required to double click on the function node to bring up the edit dialog. For the purpose of this project, the following code was created in order to generate some random data, as values of the HydraCHEK sensors. [101]

```
//Returns a random integer between min (inclusive) and max (inclusive)
function randomNr(min, max){
 return Math.floor(Math.random() * (max - min + 1)) + min;
}
//Test
var nr_al = randomNr(1, 25);
var nr_al1 = randomNr(0, 100);
var nr_al2 = randomNr(0, 1000);
//document.write(nr_al); //78 /355 /7098
// Create MQTT message in JSON
msg = {
 payload: JSON.stringify(
 {
 //d:{
 "temperature" : nr_al ,
 "acoustic velocity" : nr_al1,
 "electrical conductivity" : nr_al2
 //}
 }
 )
};
return msg;
```

Figure 5.21: *The Node-RED function created*

- Wiring the nodes together: The nodes, are connected together by dragging between the output port of one to the input port of the other.
- Deploy: Before the deployment of the flow, the nodes only exist in the editor and should be deployed to the server after the flow is completed. The deploy button is clicked. With the Debug sidebar tab selected, when the inject node is clicked, the numbers appear in the sidebar. [102]

<u>B) Using Python</u>

- Open the application on Raspberry Pi: Python is already available on Raspberry Pi IoT device.
- Create a code to:

1) Import wired sensor/device: Generate random sensor data.

2) Setup MQTT.

3) Send data (sensor values) from Raspberry Pi to IBM Cloud (IoT platform) and dashboard.[103]

<u>The Python code used:</u>

```
from time import sleep
import paho.mqtt.client as mqtt    # import MQTT client
ORG = "*******"          # define all the credentials that you have copied while
DEVICE_TYPE = "raspi"      # adding a device on Watson platform
TOKEN = "********"
DEVICE_ID = "************"
# provide server link and topics on which data will be published. We have 1 topic for temperature
give name as status1. Give AuthMethod as "use-token-auth" and then define clientID
server = ORG + ".messaging.internetofthings.ibmcloud.com";
pubTopic1 = "iot-2/evt/status1/fmt/json";
authMethod = "use-token-auth";
token = TOKEN;
clientId = "d:" + ORG + ":" + DEVICE_TYPE + ":" + DEVICE_ID;
# generate random data in python
import random
temperature=random.randint(1,10)
# if I want to connect Hydrafact's sensor, I have to add the sensor data on raspberry pi
import sensor # sensornamelibrary
gpio=17         # pin in hardware that sensor is connected
sensor=sensor #sensorname
temperature = sensorname.read_retry(sensor, gpio)
# Initialize a variable for MQTT client for using functionalities of MQTT. S
et port number and Server name in connect function.
mqttc = mqtt.Client(client_id=clientId)
mqttc.username_pw_set(authMethod, token)
mqttc.connect(server, 1883, 60)
# in a while loop we will continuously send temperature and humidity data to IBM cloud
after every 5 sec.
while True:
mqttc.publish(pubTopic1, temperature)
print ("Published")
sleep(5);
mqttc.loop_forever()
```

Figure 5.22: *The Python Code created*

➢ The data are uploaded on the IBM Watson platform. As soon as the module is connected with the Wi-Fi, a ''connected'' status is appeared on IBM Watson platform. That means, that the code worked successfully.

5th STEP: IoT data visualisation Techniques and Tools:

Visualization is the first step to give an insight of the data. To transcript and display data and correlations in a simple way, data analysts use a big range of techniques like diagrams, charts, maps, etc. Selecting the right technique is often the best way to make data understandable. And vice versa, false strategies may fail to present the full potential of data or even make it irrelevant.[104]

For the current project, the visualisation tools of the IBM Watson IoT platform were used, after the data were successfully sent through the Python code to the Cloud.

At the IBM Watson IoT platform, in the dashboard, there is a tab called ''Boards'' and after it is clicked, another tab called '' Usage Overview ''.

Values can be shown in different format like chart form or Gauge meter by choosing the proper options in the dashboard. One graph was created to see the values of the generated data updating every second.

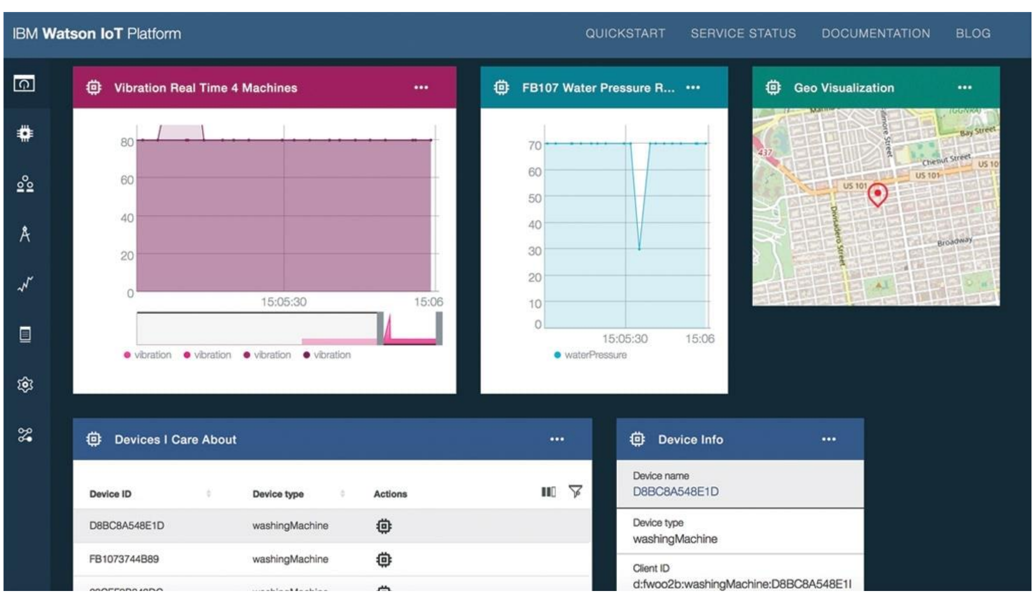

Figure 5.23: *IBM Watson IoT visualisation dashboard* [85]

CHAPTER 6: Conclusions and future recommendations

6.1 Conclusions

Digitalization of Oil and gas Industry is believed to have started a decade ago. Digital oil fields and Smart fields were the latest transformation that the industry witnessed. However, such the digitalization benefits were restricted to only optimization of oil wells and reservoir management. The new core stones in IIoT and enabling integrated platforms add a new view in the industry. Advanced data analytics and machine learning are leveraging the efforts of the operators to adopt to innovative methods. With all sensors and devices connected, none of the system parameter goes unnoticed, thus capturing the complete production performance in real time. In addition, Cloud technology is making the data easily accessible, getting in a huge visibility across the value chain.

The main benefits of IIoT in production operations could be summarized into:

- Maximizing the well production
- Minimizing the manpower leading to elimination of human errors
- Fast and accurate decision making
- Safe guarding and ensuring the operations are HSE compliant
- The data is consistent and historical without any fragmentation

However, IIoT still requires few advances to become broadly used. The technical challenges that IoT now faces, include:

- The Cloud computing requires a huge capital investment and requires to be extremely agile to befit the existing IT infrastructure. It should also possess enough bandwidth.
- Constant connectivity is challenged by the security and connectivity issues. The data science now faces a big challenge with the data variety, as many conditions in the reservoir are unique and difficult to fit into cognitive patterns and possible data loss and limitations might occur.
- Complete dependency on AI and Machine learning to solve some of the production problems still remains a challenge as with each new well, there is a new learning.

As far as the Implementation of IIoT on Hydrafact's product is concerned, the present research proves the goal of the feasibility study.

- The first target of this project was to create a code to connect the IoT device, Raspberry Pi and the Cloud. For this first stage HydraCHEK sensor was not connected to the IoT device, and so, random data were generated through coding, for the ease of the project.
- The second stage of the project after data transfer between the IoT device to the Cloud was achieved, would be to connect HydraCHEK to the IoT infrastructure, in order to send specific sensor data.
- The first and most significant stage was successfully implemented. The second one, due to limited time of my work at the company's office, and the width of the project, is not implemented yet, but it is planned for future work and only consists of cable connection of the hardware system.

6.2 Future recommendations:

Future work consists of the last part of the project which was not fully completed due to limitation of time at the company's office.

At the last and easiest part, HydraCHEK sensor should be wired to the IoT device, the Raspberry Pi. More specifically, HydraCHEK will need to connect to the GPIO pins (add 3 input raspberry nodes, of the 3 sensors: temperature, acoustic velocity and electrical conductivity) if a wired solution is chosen, or else it can connect wirelessly.

Future recommendations and improvements of the IoT in the industry, include:

- New standards for Connectivity and Networking
- New solutions for Cyber Security
- Big amounts of Data (Big Data)
- Enhanced standards for devices Integration
- Sea change advances in power and automation that will allow an entire Oil and Gas production facility to be built on the seabed.

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