DEVELOPMENT OF PHYSICAL ERGONOMICS DESIGN GUIDELINES FOR PROCESSING EQUIPMENT IN MALAYSIAN OFFSHORE OIL AND GAS PLATFORM

MOHD HAFIZUL HILMI BIN MOHD NOOR

FACULTY OF ENGINEERING
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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

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DEVELOPMENT OF PHYSICAL ERGONOMICS DESIGN GUIDELINES FOR PROCESSING EQUIPMENT IN MALAYSIAN OFFSHORE OIL AND GAS PLATFORM

ABSTRACT

The oil and gas industry in Malaysia contributes a significant portion of the local gross domestic product (GDP). The development of offshore oil and gas technologies and facilities design, in particular on operation and maintenance are critical issues during engineering design stages to ensure its efficiency and reliability. Since human physical intervention is inevitable in performing operation and maintenance tasks, physical ergonomics issues (PEI) are very crucial to be managed and mitigated through a careful consideration at early stages of the design process. This study aims to improve the implementation of physical ergonomics requirements during the early design stages of offshore processing equipment development. This is carried out through three objectives, which are to evaluate the effects of operator's concerns and operational tasks towards the physical ergonomics requirements in an offshore processing equipment design, develop physical ergonomics design guidelines (PEDG) for mitigating the PEI during the early design stages, and validate the proposed PEDG. The study was conducted in three phases. Firstly, the respondents among local oil and gas practitioners with random backgrounds were required to evaluate three sections of a questionnaire survey: the relevancy of design criteria in an offshore workplace with the physical ergonomics domain, effects of physical ergonomics implementation in design, and criticality of PEI in an offshore workplace. Secondly, operational tasks for the maintenance of offshore processing equipment were classified based on three selected case studies: Fuel Gas Package, Air Dryer Package, and Nitrogen Generation Package. Hierarchical Task Analysis (HTA) was utilized to explore the physical tasks involved during maintenance activities. As a result, four common maintenance components were established: filtering, heating, membrane, and vessel components. Thirdly, all the physical tasks were assessed against the 15 predetermined PEI through a face-to-face interview session with five industry experts, then the consequences of the PEI towards an operator were evaluated. Ergonomics principles of workplace design—body dimension and body posture, muscular strength, and body movement—were applied to recommend the mitigation plans that could be applied as a basis for ergonomics design guidelines for the common maintenance components. The results showed that the operator's concerns contributed towards the criticality rating of the PEI, which simultaneously had justified the proposed PEDG. Meanwhile, the assessment results on the operational tasks had influenced the ergonomic design requirement within a processing equipment through nine design themes: access space and reaching area, bolting, tripping and slipping hazards, materials handling, personal protection, valves and controls configuration, working at height, confined space, and others. In conclusion, this study had provided a significant understanding on the perception of stakeholders with respect to the physical ergonomics issues within a processing equipment, coupled with the combination of operational design requirements factors in developing the PEDG. This combination was found to be the best approach in ensuring the effective implementation of physical ergonomics during the early design stage of offshore processing equipment, consequently reducing the potential ergonomics risks within the facilities design.

Keywords: Oil and gas, offshore, processing equipment, physical ergonomics, Malaysia

MEMBANGUNKAN GARIS PANDUAN REKA BENTUK ERGONOMIK FIZIKAL UNTUK PERALATAN PEMPROSESAN DI PELANTAR MINYAK DAN GAS LUAR PESISIR DI MALAYSIA

ABSTRAK

Industri minyak dan gas di Malaysia memberi sumbangan yang signifikan kepada keluaran dalam negara kasar (KDNK) negara. Pembangunan reka bentuk teknologi dan kemudahan pelantar minyak dan gas luar pesisir, khususnya berkaitan dengan operasi dan penyelenggaraan adalah merupakan isu-isu kritikal semasa fasa reka bentuk kejuruteraan bagi memastikan kecekapan dan kebolehpercayaan sesuatu teknologi. Oleh kerana penglibatan aktiviti fizikal oleh manusia tidak dapat dielakkan bagi menyempurnakan sesuatu tugasan operasi, isu-isu ergonomik fizikal (PEI) sangat penting untuk diurus dan dikawal melalui pertimbangan yang teliti semasa fasa awal proses reka bentuk sesuatu projek. Kajian ini bertujuan untuk menambah baik pelaksanaan keperluan reka bentuk ergonomik fizikal dalam fasa awal reka bentuk peralatan pemprosesan di pelantar minyak luar pesisir. Tiga objektif telah digariskan, iaitu untuk menilai kesan kebimbangan pekerja dan juga tugas-tugas operasi terhadap keperluan ergonomik fizikal dalam reka bentuk peralatan pemprosesan, membangunkan satu garis panduan reka bentuk ergonomik fizikal (PEDG) bagi mengawal isu-isu ergonomik fizikal melalui fasa awal proses reka bentuk kejuruteraan, dan mengujisahkan PEDG yang dicadangkan. Kajian ini dijalankan dalam tiga fasa. Pertama, responden dalam kalangan pengamal bidang minyak dan gas tempatan dengan latar belakang yang rawak telah diminta untuk menilai tiga bahagian soalan dalam borang kaji selidik: kaitan antara kriteria reka bentuk tempat kerja di pelantar minyak dengan domain ergonomik fizikal, kesan pelaksanaan ergonomik fizikal dalam reka bentuk, dan tahap kritikal sesuatu isu ergonomik fizikal di sekitar tempat kerja di pelantar minyak. Kedua, kerja-kerja operasi untuk peralatan pemprosesan di pelantar minyak luar pesisir telah diklasifikasi berasaskan kepada tiga kajian kes: Fuel

Gas Package, Air Dryer Package dan Nitrogen Generation Package. Hierarchical Task Analysis (HTA) telah digunakan untuk mencerakinkan tugas-tugas fizikal yang terlibat dalam aktiviti penyelenggaraan tersebut. Empat jenis komponen penyelengaraan sepunya telah dikenal pasti, iaitu komponen penapisan, pemanasan, membran, dan dandang. Ketiga, 15 PEI yang telah disenaraikan lebih awal telah dinilai pada setiap tugasan fizikal melalui sesi temuramah bersemuka dengan lima orang pakar dalam industri, seterusnya kesan dan akibat untuk setiap PEI terhadap para pekerja telah dinilai. Prinsip-prinsip ergonomik untuk reka bentuk tempat kerja—saiz dan postur tubuh, kekuatan otot, dan pergerakan tubuh—telah diaplikasi untuk mencadangkan pelan mitigasi yang boleh diaplikasi sebagai garis panduan reka bentuk ergonomik untuk komponen-komponen penyelenggaraan sepunya di dalam peralatan pemprosesan. Keputusan kajian ini menunjukkan bahawa kembimbangan pekerja telah menyumbang kepada maklumat tentang tahap kritikal sesuatu PEI, dan dalam masa yang sama telah menjustifikasi PEDG yang telah dicadangkan. Sementara itu, keputusan penilaian terhadap tugas-tugas operasi didapati telah mempengaruhi keperluan ergonomik dalam sesuatu peralatan pemprosesan melalui sembilan tema reka bentuk: ruang akses dan kawasan capaian, risiko tersadung dan tergelincir, pengendalian bahan, konfigurasi injap dan kawalan, bekerja di tempat tinggi, ruang terkurung dan lain-lain. Kesimpulannya, kajian ini telah memberi kefahaman yang penting berkenaan persepsi pihak-pihak yang berkepentingan terhadap isu-isu ergonomik fizikal di pelantar minyak, ditambah pula dengan kombinasi faktor keperluan kerja-kerja pengoperasian dalam membangunkan PEDG. Kombinasi ini didapati menjadi pendekatan yang baik dalam memastikan keberkesanan pelaksanaan ergonomik fizikal semasa proses awal reka bentuk peralatan pemprosesan, seterusnya mengawal risiko-risiko ergonomik yang berpotensi wujud pada reka bentuk peralatan itu.

Kata kunci: Minyak dan gas, luar pesisir, peralatan pemprosesan, ergonomik fizikal, Malaysia

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ABS	:	American Bureau of Shipping
ANSI	:	American National Standards Institute
BCM	:	Bid clarification meeting
CAD	:	Computer-aided Design
CAPEX	:	Capital expenditure
CO_2	:	Carbon dioxide
CPP	:	Central Processing Platform
DED	:	Detailed engineering design
DOSH	:	Department of Occupational Safety and Health
EIA	:	U.S. Energy Information Administration
EPCC	:	Engineering, procurement, construction and commissioning
EWA	:	Ergonomics Workplace Assessment
EX1	:	Experience in engineering design
EX2	:	Experience in operation/ maintenance
FEED	:	Front-end engineering design
FMA	:	Factories and Machinery Act
FPS	:	Floating Production Storage
FPSO	:	Floating, Production, Storage and Offloading
FSO	:	Floating Storage and Offloading
FSU	:	Floating Storage Unit
GA	:	General arrangement
GDP	:	Gross Domestic Product
H_0	:	Null hypothesis
H_1	:	Alternative hypothesis

HC	:	Hydrocarbon
HF	:	Human factors
HFE	:	Human factors engineering
HFEM	:	Human Factors and Ergonomics Society of Malaysia
HSE	:	Health, safety and environment
HSEMS	:	Health, Safety and Environment Management System
HTA	:	Hierarchical Task Analysis
IEA	:	International Ergonomics Association
IOGP	:	International Association of Oil & Gas Producers
IQR	:	Interquartile range
ISO	:	International Standards
KDNK	:	Keluaran Dalam Negara Kasar
kg	:	Kilogram
KO	:	Knock-out
KOM	:	Kick-off meeting
MH	:	Materials handling
mm	:	Millimetre
MMH	:	Manual materials handling
MOPU	:	Mobile Offshore Production Unit
MR	:	Material Requisition
MS	:	Malaysian Standards
MSD	:	Musculoskeletal disorder
NIOSH	:	National Institute of Occupational Safety and Health
O_2	:	Oxygen
O&G	:	Oil and gas
O&M	:	Operation and maintenance

OPE	:	Offshore processing equipment
OPEX	:	Operation expenditure
OSHA	:	Occupational Safety and Health Act
P&ID	:	Process and instrument diagram
PE	:	Processing equipment
PEDG	:	Physical ergonomics design guidelines
PEI	:	Physical ergonomics issue
PFLNG	:	PETRONAS Floating Liquefied Natural Gas
PLIBEL	:	Identification of ergonomics hazards and risk factors for MSD
PO	:	Purchase order
PPE	:	Personal protective equipment
PTS	:	PETRONAS Technical Standard
Q1	:	First quartile
Q3	:	Third quartile
RFQ	:	Request for quotation
SCADA	:	Supervisory control and data acquisition
SIRIM	:	Standard and Industrial Research Institute of Malaysia
SME	:	Small and medium enterprise
SPSS	:	Statistical Package for the Social Science
TBT	:	Technical bid tabulation
UC	:	Utility connection
VDR	:	Vendor data review
ρ	:	Probability value

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Introduction

This chapter introduces the basic understanding on ergonomics and human factors engineering subject, and how it relates to the oil and gas design facilities. This chapter also provides an overview of the research such as a problem statement, objectives and scope of the study, and outline of this dissertation.

1.1.1 Ergonomics and Human Factors Engineering

Ergonomics, Human Factors Engineering (HFE), and Human Factors (HF) generally refer to a combination of various fields such as anthropometrics, biomechanics, psychology, physiology, management, including multiple engineering disciplines in industrial design practice. Ergonomics initiates a linkage between a deep understanding of human behaviours and adaption into their sociotechnical interfaces system such as in technological, organizational, or social contexts (Wilson, 2000). International Ergonomics Association (IEA) has outlined that the *ergonomics* and *human factors* terms could be used interchangeably, which are defined as an "*understanding of interactions among humans and other elements of a system, and a profession that applies theories, principles, data, and methods to design in order to optimize human well-being and overall system performance*" (IEA, 2017).

In aligning the terms used in this dissertation, the *ergonomics* and *human factors engineering* terms refer to an adaption of human characteristics, behaviours, limitations, and capabilities into a workplace design, system, and task-related activity. Both terms are used interchangeably which corresponded with the context of the discussion.

A human-workplace interface involves various influencing factors. IEA has categorized ergonomics into three key areas which are physical, cognitive, and organizational domains, albeit without classifying environmental aspects such as temperature, vibration, noise, illumination, and radiation directly into any domain (IEA, 2017). Hendrick (2008) classified these environmental aspects under the physical domain through a more comprehensive elaboration of physical ergonomics that includes hardware ergonomics (human-machine interface) and environmental ergonomics (human-environment interface).

Throughout the ergonomics research history, exploration of human behaviours against technology advancement had progressively evolved. In explaining the revolutions of ergonomics subject, Boff (2006) has categorized the advancement of ergonomics knowledge into four generations. The physical aspect was classified as a basic ergonomics principle under Generation 1, whereby physical human characteristics need to be adapted into a workplace design by firstly understanding the human physical capabilities and limitations. This corresponded with the definition of physical ergonomics by IEA (2017), which correlated with physical body activities in a workplace, mainly involving the anthropometrics and movement of the human body. In an industrial facility design, the suitability of design configuration with characteristics of the intended user population should simultaneously support the predicted physical tasks and human-equipment interfaces (McLeod, 2015). Niven and McLeod (2009) for instance, have differentiated physical and ergonomics hazards into a separate category where physical hazard covers environmental conditions in a workplace such as noise, vibration, thermal, and radiation, and ergonomics hazard comprised human-equipment interaction such as body postures and applying force during the completion of tasks. In this study, physical ergonomics is defined as the human-workplace interface in terms of associated physical tasks with human body measurements, postures, and movement, excluding the environmental aspect in offshore workplaces.

1.1.2 Overview of Malaysian oil and gas industry

In Malaysia, the O&G industry which is managed by the national custodian of the industry–PETRONAS–generally covers the holistic business chains; from an upstream operation for exploration, development, and production of resources, to midstream and downstream operations for transportation, refining, and trading of petrochemical products (ETP, 2016). To date, the upstream operation comprises 349 units of offshore platform, 7 units of floating production, offloading and storage (FPSO), 8 units of floating storage and offloading (FSO), 2 units of mobile offshore production unit (MOPU), 1 unit of Petronas Floating Liquefied Natural Gas (PFLNG), 1 unit of floating production storage (FPS), and 1 unit of floating storage unit (FSU) (Petronas Activity Outlook, 2017). These facilities are developed for Peninsular Malaysia, Sabah, Sarawak, and the Malaysia-Thailand Joint Development Area.

The downstream operation plants are developed in strategic onshore locations such as Kerteh (Terengganu), Bintulu (Sarawak), Labuan, Lumut (Perak), Gebeng (Pahang), Gurun (Kedah), and newly constructed refinery complex at Pengerang (Johor). In recent years, Malaysia has consistently produced around 600,000 to 700,000 barrels of oil per day, which catapults Malaysia to be ranked as the fourth-highest reserves in the Asia Pacific behind China, India, and Vietnam (U.S. Energy Information Administration, 2017). Since 2011, BMI Research (2015) has reported that 23 fields have been discovered in different areas of offshore Peninsular Malaysia including offshore Sabah and Sarawak, which contain multi-billions cubic meter of oil and gas reserve that is envisaged for future production plan. Deepwater and shallow water offshore facility types are required to be developed in accordance with the production and processing prospects, with an application of advanced offshore technologies.

The upstream operation might consist of several independent offshore facilities such as a wellhead platform, riser platform, processing platform, accommodation platform (Devold, 2010), as well as floating, production, storage and offloading (FPSO). Different types of offshore facility are developed based on essential factors that lead to a concept selection, such as reservoir and fluid characteristics, location of field, financial planning, and technology development (Karsan, 2005). For a standard process flow, the source of crude oil and natural gas would emanate from a wellhead platform or riser platform which is attached to subsea facilities, subsequently streaming through pipelines to a processing platform for production phases.

Basically, the offshore processing platform supports multiple integrated systems, mainly separating the crude oil, gas, condensate, and water before being transported to onshore refinery and petrochemical plants. The overall facility may consist of two major systems which are process and utility systems. The process system may consist of separation, filtration, chemicals injection, heating and cooling, gas compression and dehydration, and produced water treatment, while the utility system may consist of power generation, fuel gas, utility and instrument air, potable water maker, sewage treatment, accommodation facilities, and materials handling system (ABS, 2014). All systems are equipped with various critical components such as pumps, motors, filters, vessels, compressors, heaters, coolers, heat exchangers, and other specific components that complement a packaged equipment design. Furthermore, most of the systems are also equipped with electrical and instrument components, safety devices, and pipe fittings. These facilities require continuous monitoring, inspection, and must adhere to maintenance regime throughout its lifetime. Therefore, human intervention and physical tasks within the equipment and overall platform are inevitable. The tasks may include a series of actions to achieve the specific goal or sub-goal, partly in completing main maintenance objectives. In a real situation, it could be driven by specific intentions, perceptions, analysis, or decisions (McLeod, 2015), which should be accomplished within the workspace limitations and human capabilities constraints. As these facilities are normally designed for 20 to 25 years of lifespan, the equipment and components provisions shall deal with maintainability issues to secure its highest efficiency.

Figure 1.1: Example of a central processing platform (CPP)—SK316 Gas Development Project in offshore Sarawak, Malaysia owned by PETRONAS. Photo by MHB Engineering Solution (2018).

In tandem with the rapid development of the Malaysian oil and gas industry which requires significant human tasks involvement, integration of ergonomics requirements in the facilities design has started to crystallize. This is also supported by the sophisticated oil and gas workplace design and hazardous environment, with safety and health concerns being the top business priority. Furthermore, PETRONAS had seriously been considering the improvement of human factors element in a workplace design since 2010, as part of the HSE Management System (HSEMS) enhancement program (2010 Sustainability Report, 2018). Hence, it is noteworthy to extend a study on the implementation of physical ergonomics into the offshore processing equipment design for mitigating any potential ergonomics hazards towards operators, simultaneously enhancing the understanding of physical ergonomics requirements within an offshore processing platform.

1.2 Problem Statement

One of the important goals in applying physical ergonomics in design is to assimilate characteristics and expectations of the targeted users into a workplace design. In the oil and gas industry practice, there is a great concern that inadequate consideration of ergonomics into a processing equipment design could aggravate accident and occupational injuries rate. Current ergonomics integration approaches in the early design stage of offshore processing equipment may not be effective and conducted in a comprehensive manner. Thus, a more effective approach that considers the local industry practitioners' perspective, as well as the operation and maintenance needs of each equipment component, should be further investigated and developed to ensure any potential ergonomics issues are well mitigated during the design process.

Thus, the problem statement of this study is to focus on how the Malaysian operators' concerns and operational tasks could influence the physical ergonomics design requirements in an offshore processing equipment, which is part of the operating systems in an offshore processing platform. The operators' concerns refer to their current physical ergonomics awareness and concern towards the criticality of physical ergonomics issues within an offshore workplace, while the operational tasks refer to the needs of operation and maintenance activities of a particular component throughout its lifespan. Additionally, an operator in this study is defined as a worker who carries out operational tasks within an offshore oil and gas platform.

1.3 Objectives of the study

This research mainly aims to improve the implementation of physical ergonomics requirements within an offshore processing equipment during the early design stages, in the Malaysian oil and gas industry context. To achieve the main objective, the research methodology plan is governed by the following sub-objectives:

(a) To assess the effects of Malaysian operators' concerns and operational tasks on the physical ergonomics requirements in an offshore processing equipment design

(b) To develop the physical ergonomics design guidelines for the offshore processing equipment's maintenance component

(c) To validate the effectiveness of the proposed physical ergonomics design guidelines from technical and project management perspectives

These objectives are outlined to address the main problem statement, concurrently answering the following research questions:

(a) What are the concerns of Malaysian operators and operational tasks that influence the physical ergonomics requirements within an offshore processing equipment design?

(b) How to effectively incorporate the physical ergonomics requirements within an offshore processing equipment during the early design stage while sustaining its technical configurations?

(c) How effective is the newly proposed approach in considering the physical ergonomics factors in an offshore processing equipment design, through an engineering design process?

1.4 Scope of the study

The offshore processing equipment, which is selected as a focused subject of this study is defined as an equipment that is commonly installed within an offshore processing platform, to complement the overall process and utility systems of the facility. The targeted respondents for data collection of this study are confined to the Malaysian oil and gas operators, who are engineering experts in the local region and have relevant hands-on experience in the Malaysian offshore workplaces. This limitation is deliberately stipulated to confine the scope of the study within the offshore processing equipment design process and from the Malaysian oil and gas environment perspective.

1.5 Outline of the dissertation

This dissertation is divided into six chapters. Chapter 1 describes the definition of ergonomics as a focused study field and how it relates to an offshore oil and gas facility design. This chapter also explains the main problem statement and research questions that formed the basis of this study, as well as the objectives that governed the research methodology and the scope of this study.

Chapter 2 discusses the literature review of the scope of this study. Several topics encompassing the published application of physical ergonomics principles and issues within offshore facilities design, effects of the HFE implementation program and its development in recent years, and an overview of ergonomics studies in the Malaysian region are included. This chapter also highlights the significant gap from the previous studies and what would be further investigated in this study, as outlined in Chapter 1.

Chapter 3 elaborates the flow of research methodology that has been applied in this study, which is separated into five parts. This chapter explains the aim of each part and justifies the sampling methods, tools selection, and analysis approaches. While the methodology in Part 1 assessed the ergonomics awareness and concerns among the Malaysian oil and gas operators, Part 2 classified the maintenance tasks of offshore processing equipment's case studies by using a task analysis tool. Part 3 evaluated the physical ergonomics issues (PEI) and its consequences based on inputs from the industry experts, while Part 4 focused on the development of physical ergonomics design guidelines (PEDG) for maintenance components of offshore processing equipment. Finally, Part 5 validated the proposed PEDG during the design process.

Chapter 4 presents the results and discussions for Part 1, Part 2, and Part 3 of this study. A better understanding of the physical ergonomics issues within an offshore processing equipment from the operators' concerns and operational tasks perspectives is elaborated for preparing inputs for the PEDG development process.

Chapter 5 presents the outcomes of methodology in Part 4, which are the derived key physical ergonomics design themes within an offshore processing equipment design. This chapter also explains the results of multiple inputs combination in developing the PEDG specifications for common maintenance components that are available within an offshore processing equipment, namely filtering, heating, membrane, and vessel components.

Chapter 6 explains the validation results of the proposed PEDG based on the technical and project management criteria, covering feedback from end users when adapting the PEDG in their design process. In addition, this chapter also discusses which design phases the proposed PEDG should be embedded in and how it should be utilized to ensure the physical ergonomics issues are well mitigated during the early design process stage.

Lastly, Chapter 7 aligns all findings with the research objectives, emphasizing contributions of the study to the body of knowledge and the significance of the PEDG in an industry practice. This chapter also outlines limitations of the study and recommendations for future works.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter discusses the literature review of the issues and benefits of the HFE integration program within an offshore workplace design, and also the physical ergonomics principles and common physical ergonomics issues within the facility design. Relevant topics from previous studies and industry standards in worldwide offshore facilities design are referred. Since the cognitive and organizational ergonomics domains are not considered in the research scope, the literature review would not cover these topics thoroughly. Besides that, this chapter also explains how ergonomics requirements are currently integrated into a project execution plan, and where improvement area could be further investigated in offshore processing equipment design. At the end of this chapter, the limitations of previous studies and the significant gap are elucidated to justify the objectives and scope of this study.

2.2 Issues and benefits of HFE implementation in offshore workplace design

Applying physical ergonomics in an offshore workplace design could influence how operators work in terms of body posture, physical movement, applying force, and reading method during the operational tasks (Niven & McLeod, 2009). Poor workplaces design could lead to three ergonomics risk factors, namely awkward working condition in lifting and using heavy tools (force), risky body movement (posture), and long-term exposure to bad posture and excessive load (fatigue). Gallagher and Heberger (2013) stressed that an interaction between force exposure and repetition task supports the development of musculoskeletal disorder (MSD) risk, based on the 10 cases of evidence that were identified from 12 case studies. A comprehensive review from past studies that examined the root cause of low-back MSD have categorized five-associated physical work-related risks: physical ergonomics issue that relates to a heavy physical work, lifting and forceful movement, body bending and twisting, whole body vibration, and static working posture (Bernard, 1997). In addition, by using the Ergonomics Bayesian network analysis, Garcia-Herrero et al. (2012) concluded that physical demands in a workplace, especially applying an excessive force during tasks execution has strongly influenced the increasing rate of accidents and MSD disease among workers.

In the early days, accident reports in United Kingdom (UK) offshore oil industry have demonstrated that human factors were the significant causes of accidents. Gordon (1998) classified the causes of human error relating to workplace design and direct human intervention into two categories, namely the immediate cause and underlying cause. The immediate cause may involve human and technical factors such as improper lifting and handling method, wrong equipment selection, and the present of environmental and ergonomics hazards at a workplace. The underlying cause may be contributed by personal factors–physical capability, inadequate orientation, fatigue and health hazards; and system factors–lack of safety system, confusing direction, equipment selection, and incompatible individual with the job task. Among other types of human error that contribute to the accident, a design-induced error was one of the classifications which referred to a contradictory between workplace design specifications and end users' characteristics, including the provision of maintenance space within an equipment design (Thomas et al., 2002). Hence, reducing the human errors through ergonomics implementation in design could partly mitigate the cause of accidents, thus reducing the occupational injury rate at a workplace.

Non-ergonomics compliance in design may cause sequel effects after the facility has been commissioned in an oil field. A conflict between safety issue and processing performance would become a liability, in which costly site modifications on existing offshore facilities design at a later stage are required to mitigate safety and ergonomics issues (Satrun, 1998; Pray et al., 2014). The ergonomics implementation during the early stage of design could prevent modifications at later stages. In a broader perspective, as part of the operating expenditure (OPEX), the eliminated costs may cover three things. Firstly, the cost of acquiring equipment, materials, and labour for the existing offshore site modification. Secondly, the lost-revenue of production and manpower during a plant shutdown for the modification campaign, and thirdly compensation to workers involved in ergonomics occupational injuries (Son et al., 2017). Therefore, the non-ergonomics compliance in design must be enhanced during the early design stage through a proper project implementation plan.

In the oil and gas industry practice, a continuous improvement of HFE implementation approach for offshore facilities design should be explored as there are a few notations from past studies regarding the inefficient HFE implementation in a design process. For example, during a 3D model design exercise, an engineer or designer may not be of maintenance procedures of packaged equipment and lack of insight into human error factors (Wulff et al., 1999b). The engineer tends to ignore thick and general ergonomics specifications document, where it needs further interpretation process when applying it into the specific equipment design. As a result, the ergonomics requirements will not be implemented if there is no HFE specialist assistance (Wulff et al., 1999b). Besides that, past site observations on existing oil and gas facilities design always found discrepancies in the ergonomics specifications (Skepper et al., 2000; Passero et al., 2012), which required modification works at a later stage.

A study on the root cause of 126 manual handling incidents at the UK offshore facilities found that existing workplaces design and poor equipment design were the common root cause of the events (Randle & Smith, 2006). Improper plan of operational tasks which offshore operators are involved in, would result in common MSD injuries such as upper limb disorders (Niven & McLeod, 2009), sprains and strains, muscle spasms in the lower back, tendonitis in hands and forearms, tear of ligaments and cartilages in shoulders and knees, and nerves entrapment (Blaho & Button, 2013). A review on the occupational injury reports in the Norwegian oil industry from 1992 to 2003 showed that 40% of the 3,131 musculoskeletal disorder cases were related to maintenance workers. In the study, physical exertion and repetitive works were identified as the most reported causes that affected upper and lower limbs, back pain, and neck disorder MSD injuries (Morken et al., 2007). It was also emphasized by Gallagher and Heberger (2013) that one of the MSD risk controlling factors a repetitive task. The latest statistics for the year 2017 showed that physical ergonomics related risks were recorded as among the causes of offshore accidents in the UK region. For instance, 37% of all reported injuries were caused by slips, trips, or falls on the same level, while 11% of the accidents were caused by handling, lifting, or carrying a load (Health and Safety Executive, 2018). These circumstances may also affect Malaysian oil and gas operators since the offshore facilities normally involve similar operational tasks and its associated hazards across the globe.

Generally, the HFE implementation in oil and gas facilities design were beneficial for the betterment of operators' working postures, occupational risks control, operability improvement, as well as reduction of modification cost at a later stage. Nevertheless, the HFE implementation approach must be driven by a comprehensive understanding of the physical ergonomics principles that are applicable in the offshore oil and gas facilities.

2.3 Physical ergonomics principles

The reliability of process and utility systems within the offshore facilities partly rely on its efficiency and safety conditions, which could be achieved by ensuring the operability and maintainability of the systems throughout its lifetime. Routine cleaning and inspection, as well as replacement of damaged or deficient components might occur on every offshore processing equipment. These anticipated maintenance tasks involve personnel access and physical contact with a limited workplace design, which directly determine the level of operational risks and occupational hazards during maintenance activities (Sheikhalishahi et al., 2016). The ergonomic workplace condition played a vital role in supporting these tasks, especially the physical ergonomics design factors which deserved critical attention as described in many studies (Skepper et al., 2000; Lind & Nenonen, 2008; Passero et al., 2012; Garotti & Mascia, 2012; McLeod, 2015; Sheikhalishahi et al., 2016).

The physical human-workplace interaction within an offshore platform could be categorized into two types, namely *activity* and *relations among material elements*, which would predetermine technical recommendations in a facility design (Duarte & Silva, 2010). *Activity* is a situation which is initiated by a specific goal of operational tasks such as maintenance and inspection, while the *relations among material elements*—simplified as *design elements*—refers to workplace design configurations that support human-workplace interface such as the requirements of access space design according to workers' anthropometric data (McLeod, 2015), while in certain circumstances the access space should consider the use of survival suit (Stewart et al., 2015), maintenance space (Sheikhalishahi et al., 2016), as well as design specification of stairs, ladders, and access platforms for working at high elevation (Passero et al., 2012).

Basically, the physical ergonomics design refers to an equipment design that suits body measurements of the intended user population. It should support human tasks and human-technology interfaces that are predicted during the early design process (McLeod, 2015). Working space and valves operating area are the examples of critical issues that are present in many heavy engineering workplaces (McLeod, 2015; Skepper et al., 2000). In a study of five production units of oil refinery plant, Passero et al. (2012) found that almost all of the accumulated 256 ergonomics constraints were associated with physical ergonomics design, namely personnel access to valve handles (high point), personnel circulation (access around the equipment), and access to instrument controls (monitoring, gauging, and sampling).

McLeod (2015) has outlined five important parameters that govern the physical ergonomics principles in an industrial workplace design, particularly with respect to the interface between operators and processing system facilities. The parameters are:

(a) Permit for human variability

(b) Sufficient access and working area

(c) Clear and consistent design of workplace and equipment interfaces based on the common practice and design standards

(d) Design of work environment to suit the capabilities and limitations of a human body in terms of seeing, hearing, reaching, and applying force.

(e) Workplace layout design should circumvent the exposure of excessive forces and energy in terms of capacity and duration.

The body size of end users is one of the determining factors in the physical ergonomics domain; workplace design specifications should be driven by an anthropometric data of the specific end-user population. All human characteristic such as maximum and minimum height, shoulder breadth (bideltoid), reaching parameter, and eyes level should be considered as baselines of the HFE specifications, and guidelines for designing the offshore facility and processing equipment. This is to ensure that any operation and maintenance activities comply with human capabilities and limitations. The facility design should accommodate variability of body measurements according to the region of the installed workplace, and consider the limitations and capabilities of the human body such as reading level, hearing level, and reaching parameter (McLeod, 2015). A mismatch between design specifications and end users' body dimensions is also among the critical issues in heavy engineering workplaces (Skepper et al., 2000; Zunjic et al., 2015). Besides that, Skepper et al. (2000) suggested that other physical-related workplace issues such as valve operating area, poor positioning of instruments, and inadequate workspace provision must be accorded due attention during the design phase.

In addition to the standard offshore platform, the development of FPSO installation has progressively taken place within the Malaysian region in recent and upcoming years. An FPSO unit is built by a combination of modularized platform structures with vertically stacked decks, thus creating additional physical ergonomics concern for operators. For instance, personnel access occasionally involves more movements between different modules (horizontal movement), and between upper and lower decks within the same module (vertical movement). This design configuration could exacerbate the ergonomics problem if improper design configurations such as extreme valves location and disorganized materials handling system occur in the design of the modules (Garotti & Mascia, 2012).

2.3.1 Materials handling system

Lind and Nenonen (2008) observed that workers at industrial maintenance workplaces are often exposed to high-risk activities such as materials handling tasks—heavy lifting, holding a load, poor work tool design, and working method, while the working environment condition could initiate tripping and slipping hazards. In addition, the authors also remarked that these conditions might potentially put the workers at risk of sustaining injuries, particularly with the awkward postures due to non-ergonomics design. Materials handling tasks that involve excessive load are also considered as one of the crucial ergonomics issues in an offshore facility design (IOGP, 2011). This would normally occur in manual materials handling (MMH) activities such as lifting, lowering, pushing, pulling, carrying and holding a load by single, combined, or complex type of MMH arrangement (Rajesh, 2016). Some of the MMH tasks may require excessive force and energy in terms of its capacity and working duration, which could reduce the effectiveness of human sensory, physiological, and biomechanical systems (McLeod, 2015).

Other than MMH risk, the overall materials handling system design for executing the maintenance tasks is also considered as a physical ergonomics related issue within the offshore platforms and FPSO installations. The system design includes materials handling provision for vertical (lifting) and horizontal (transportation) transfers from one point to another, as well as the selection of materials handling devices. Rossi et al. (2013) have categorized the multiple indicators under the ergonomics and safety performance domain for selecting the materials handling device that can be manually operated by workers. The listed criteria encompassed accessibility and reach zones, comfort for use, lifting and carrying, mechanical hazards, posture issue, pushing and pulling, required space, visual requirement, and repetitive handling at high frequency, which could be adapted in the design of offshore materials handling devices. A comprehensive design process is required for aligning the outlined criteria with other design specifications that identified by a technical standard such as ABS (2013).

2.3.2 Personal protective equipment

Generally, the usage of a personal protective equipment (PPE) is specifically for protecting a worker against various hazards, as the existing gazetted regulation by all offshore facilities owners. A high-visibility coverall, safety helmet, gloves, eye protection, safety footwear, safety harnesses (Health and Safety Executive, 2013), and life jacket are among the typical safety measures to ensure the safety and health of the operators. Instead of making the workers wear the PPE during performing physical tasks, workplace design studies often consider the undressed body measurements as a basis for incorporating the relevant end users' characteristics into the workplace design. To clarify this issue, Stewart et al. (2015) have explored the potential ergonomics hazards if the workers are wearing a survival suit and other safety apparatus for accessing a restricted space within an offshore platform, such as a manhole and emergency escape route. The UK population-based study discovered that wearing a survival suit would reduce the probability of one worker passing another worker within a limited working space. More critical conditions would occur for the emergency egress event from hazardous points to a central muster area when operators are carrying a load. The space requirement in a workplace which only consider the body measurements directly from an anthropometric data might not satisfy the actual needs of offshore workers with supplementary PPE measures.

2.3.3 Accommodation and control room

Other common facilities within offshore platforms are office and control rooms for a managerial purpose. Although such workplaces have less critical physical ergonomics issues as compared to the processing equipment facilities, there are common ergonomics factors expected in an office workplace design. The factors include a selection of office furniture that supports prolonged use and suited user population, training for good ergonomics working posture, and late HFE implementation in control room and workstation (Halimahtun & Helander, 2012). The international standards such as ANSI/HFES 100 – 2007 and ISO 11064-7 are in place for the design process guidance, adaptable in various control centre concepts within an oil and gas installation (Duarte et al., 2012). However, for the application of control room design in the oil and gas industry, adapting a goal-based design approach rather than strictly applying the extensive technical standards would improve the maintainability and flexibility of the designed technology (Aas & Skramstad, 2010).

Control panels and monitoring systems in a control room would require more cognitive and organisational ergonomics design approach as these interface systems relate directly to the reliability and operability of main process systems. Several human factor issues are observed in a control room of oil and gas pipeline systems, with regards to alarm and control interfaces configuration at the workstation and also those related to mental workloads which are the data processing and arrangement, routine communication, and personnel-workload mismatch. These human-related working conditions are considered as the critical factors for any potential accidents. To mitigate such issues, (Meshkati, 2006) for example, proposed some improvement ideas which are simplifying working procedures, and improving the physical design and control panels interfaces.

A study of workplace environment had been done at 25 different offshore control rooms in the North Sea region through a survey method, by analysing the offshore workers' live experience. The study found that non-compliance specifications of the thermal condition, noise, air quality, lighting, system usability, and alarm parameters were occurred compared to the SCADA design standard. The analysis from the survey by Walker et al. (2014) presumed that the result might be influenced by the co-evolved factors between the level of ergonomics knowledge among workers and the current nature of control rooms that were equipped by automation technologies with less requirement of human intervention.

Among the highlighted physical ergonomics principles and its related issues in oil and gas facilities design, the most reported literature review explains the general ergonomics design guidelines such as the anthropometric accommodation, manual handling tasks, PPE, valves and controls accessibility, including access and working area. Some of the studies focused on the ergonomics assessment of existing facilities without exploring the front-end design approach, which would be difficult for engineers or designers to turn the inputs into engineering design practices. Furthermore, there was lack of exploration concerning the specific ergonomics issues and design needs within an offshore processing equipment design.

To get a clear overview of how these ergonomics principles were applied throughout the oil and gas project execution phases, subsequent section would discuss the existing HFE implementation program in greater detail.

2.4 HFE implementation program

It is important to ensure that the ergonomics design requirements are considered in an overall project execution plan. HFE implementation program for the oil and gas industry had been transformed for 20 years ago in order to improve the consistency of application in an engineering design process (Robb & Miller, 2012). Robb and Miller (2012) reported that one of the earlier HFE implementation programs in design and construction stages was implemented on the Auger Tension Leg Platform (Gulf of Mexico) back in 1990, followed by the improvement of its control room configuration in 2001.

A literature search found that most of the HFE implementation programs in offshore installations design were established according to the industry practitioners' experience. Among other previous studies, general HFE implementation programs for the oil and gas industry had been presented by McCafferty et al. (2002), McSweeney et al. (2008), Kenefake et al. (2009), Seet and McLeod (2012), Pray et al. (2014), and Chandrasegaran et al. (2016). The systematic approaches were established to ensure the ergonomics principles are properly integrated into the whole facility design throughout the project development phases. In aligning the effectiveness of worldwide HFE implementation programs, the International Association of Oil and Gas Producers has recommended five key HFE design steps namely HFE screening, design analysis, design validation, support to start-up, and operational feedback (IOGP, 2011). In the design analysis and design validation periods, adherence to ergonomics design specifications from a local regulatory, industry, and company standard are examined and confirmed.

It must be highlighted that during the integration process, operational tasks and design configuration requirements for offshore facilities could be assessed by experienced personnel or random observers (Hendrick, 2008). However, different assessors could distinguish the output of variables that was needed in operational tasks, which might affect the predetermined ergonomic design recommendations. Non-ergonomics compliance in offshore facilities design occurred due to lack of ergonomics awareness and knowledge among engineers and designers during a design process. It is triggered by insufficient ergonomics guidelines and standard working procedures by ergonomics experts in the design process (Skepper et al., 2000). Furthermore, Cordeiro et al. (2015) clarified that designers might have not been in an offshore platform. Hence, lack of operational experience and information might trigger ergonomics issues in a workplace design. Similar concern was raised by Halimahtun and Helander (2012) by adding that an ergonomist, also known as HFE Specialist should get a technical support from clients as a custodian of offshore facilities, for assessing the engineering design process and technical information. It is part of the HFE Specialist's role to analyse maintenance related activities of critical processing equipment and suggest the necessary ergonomics design solutions (McCafferty et al., 2002). Besides that, during an equipment supply bidding stage, the HFE Specialist should also assist in reviewing the equipment's bid proposal from a vendor and ensure conformity to ergonomics specifications (McCafferty et al., 2002; McSweeney et al., 2008; Pray et al., 2014).

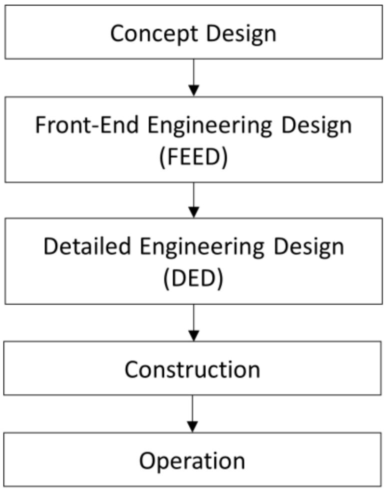

Figure 2.1: Engineering design stages flowchart (Chandrasegaran et al., 2016)

Generally, engineering design procedures of oil and gas facility projects that involve the HFE implementation plan is divided into five stages, as shown in Figure 2.1. The most appropriate design stage where the HFE implementation program should be integrated into an equipment design process is basically determined by the two major procedures. As explained previously, the procedures involve an integration of ergonomics requirements into a packaged equipment design specification and an evaluation of its compliance. Since the equipment specification document is normally developed during FEED stage for bidding purpose, HFE specifications shall be incorporated accordingly (McCafferty at al., 2002; Pray et al., 2014). It could be included in general HFE specifications or detailed design checklist form. The HFE design checklist shall be prepared by the HFE Specialist and cascaded to all engineers or designers who are involved in equipment design job scope (Son et al., 2017). This approach could also reduce their time and effort to explore the full HFE general specifications document (Pray at al., 2014). With a specific design formulation, they could also avoid inaccurate interpretation of the HFE specifications. During DED stage, explicit design documents of equipment from the awarded vendor such as equipment layouts, general arrangement drawings, 3D model, as well as operation and maintenance procedures are prepared and further refined for construction stage. This is the appropriate phase where the HFE design validation through a 2D drawing or 3D CAD model shall take place (McCafferty et al., 2002; McSweeney et al., 2008; Chandrasegaran et al., 2016), which non-compliance against ergonomics requirements will be aligned with the specified HFE codes, standards, and specifications.

The idea of predetermining the potential ergonomics issue through the early design process is due to human factors have a significant contribution in reducing physical and health performance during the operational period (Kim, 2016). To overcome this challenge, a comprehensive HFE implementation program should systematically facilitate the multidisciplinary involvement for evaluating and discussing alternative design, to eliminate ergonomics issues at the early stage of projects (Passero et al., 2012).

2.5 Ergonomics studies in Malaysian region

Ergonomics research activities in this region are progressing in various sectors including automotive, manufacturing plant, small and medium enterprise (SME) industry, and building development. Generally, local ergonomics implementation within the machinery and workplace design is regulated by the Act 514 Occupational Safety and Health Act 1994 under the section 4(c), section 15(2)(b) and section 15(2)(e), as well as the Factory and Machinery Act 1967 under the Section 12. Ergonomics hazards at a workplace such as lighting, noise, temperature (heat stress), workspace, posture and movement, as well as the MMH task are discussed in the context of safety and health issues (Roslina et al., 2011). Under the purview of Standard and Industrial Research Institute of Malaysia (SIRIM), the Malaysian Standard (MS) for ergonomics application which covers nine aspects of workplace design is developed by adopting the International Standards (ISO). However, the non-obligatory of MS implementation in industries and no specific guidelines for each industry sector contributed to minimal awareness and application of the standard in workplace design (Rosnah et al., 2016).

In the recent years, Department of Occupational Safety and Health Malaysia (DOSH) in collaboration with Human Factors and Ergonomics Society of Malaysia (HFEM) and Ergonomics Excellence Centre, NIOSH Malaysia has established the Guidelines on Ergonomics Risk Assessment at Workplace (DOSH, 2017) and Guidelines for Manual Handling at Workplace (DOSH, 2018). These guidelines explain in detail the ergonomics risks assessment approaches to analyse existing job tasks or workplaces. However, the national standards and guidelines do not outline any explicit ergonomics design specifications for the front-end engineering design standard of the Malaysian offshore facilities, except for the restricted-public access Petronas Technical Standard (PTS) that has been established for internal design recommendation only.

A study on the Malaysian manufacturing industries found that an ergonomics program was rarely implemented due to insufficient information, education and training factors. Additionally, lack of pressure from top management to initiate ergonomics program also contributed to the leading factors (Mustafa et al., 2009). Reviews of various local industries found that ergonomics subject in the Malaysia region was considered new and its development in education, research, or application was relatively slow, while industry workers were reported to be rarely responsive to non-ergonomics workplace design (Loo & Richardson, 2012). These circumstances reflected a low level of awareness towards the correlation between an improper workplace design with a long-term health risk. Unfortunately, Loo and Richardson (2012) have not included the highlight of the O&G industry in their review, which left an assumption of inadequate information access in the mainstream resources (Halimahtun & Helander, 2012). This is supported by findings from the literature search, showing that a small number of ergonomics awareness study and a processing equipment design assessment regarding the Malaysian oil and gas industry have been carried out, either from physical, cognitive, or organizational ergonomics perspectives.

2.6 Summary

The physical ergonomics principles and issues that are relevant in the offshore oil and gas facilities design have been discussed earlier. Based on past studies, various offshore installations including an offshore processing platform might have shared identical ergonomics issues within the common processing design systems. Integration of safety measures for mitigating safety and health hazards in technology development nowadays would become more challenging due to the concurrent technology advancement for oil and gas exploration and processing systems, as well as growing demands of the safety and health precautions (Niven & McLeod, 2009).

However, there is a dearth of extensive exploration of the physical ergonomics issues within an offshore processing equipment with regards to operation and maintenance needs, from the Malaysian operators' perspective. The lack of this study provides a significant gap regarding the stance of local industry practitioners towards the mentioned subject, which consequently creates a void in outlook towards the priority of operational needs. This condition also leaves a strong necessity of assessing the actual physical ergonomics issues that might arise within the processing equipment to improve the equipment design and optimize the HFE implementation approach. Thus, the first objective that has been outlined in Chapter 1 would provide sufficient insight in resolving the stated gap.

Besides that, the growing challenges in offshore facilities design are also related to the HFE implementation approach at the early design stage and involvement of an HFE Specialist during the design process. Most of the previous literature review focused more on the top-view perspective of HFE implementation program, especially form the project execution management perspective, stakeholders' responsibilities, and appropriate project phases for the ergonomics design integration. This included the application of general ergonomics specifications and standards which did not address specific and comprehensive guidelines for a processing equipment design. A further investigation would be required to develop detailed ergonomics design guidelines for a particular processing equipment, which might help an engineer or designer to improve the strategy in considering operators' concerns and operational tasks factors when designing an offshore processing equipment. Hence, the second and third objectives of this study would resolve the significant gap and enhance the body of knowledge.

Figure 2.2 illustrates the summary of the literature review and the significant gaps that will be explored in this study.

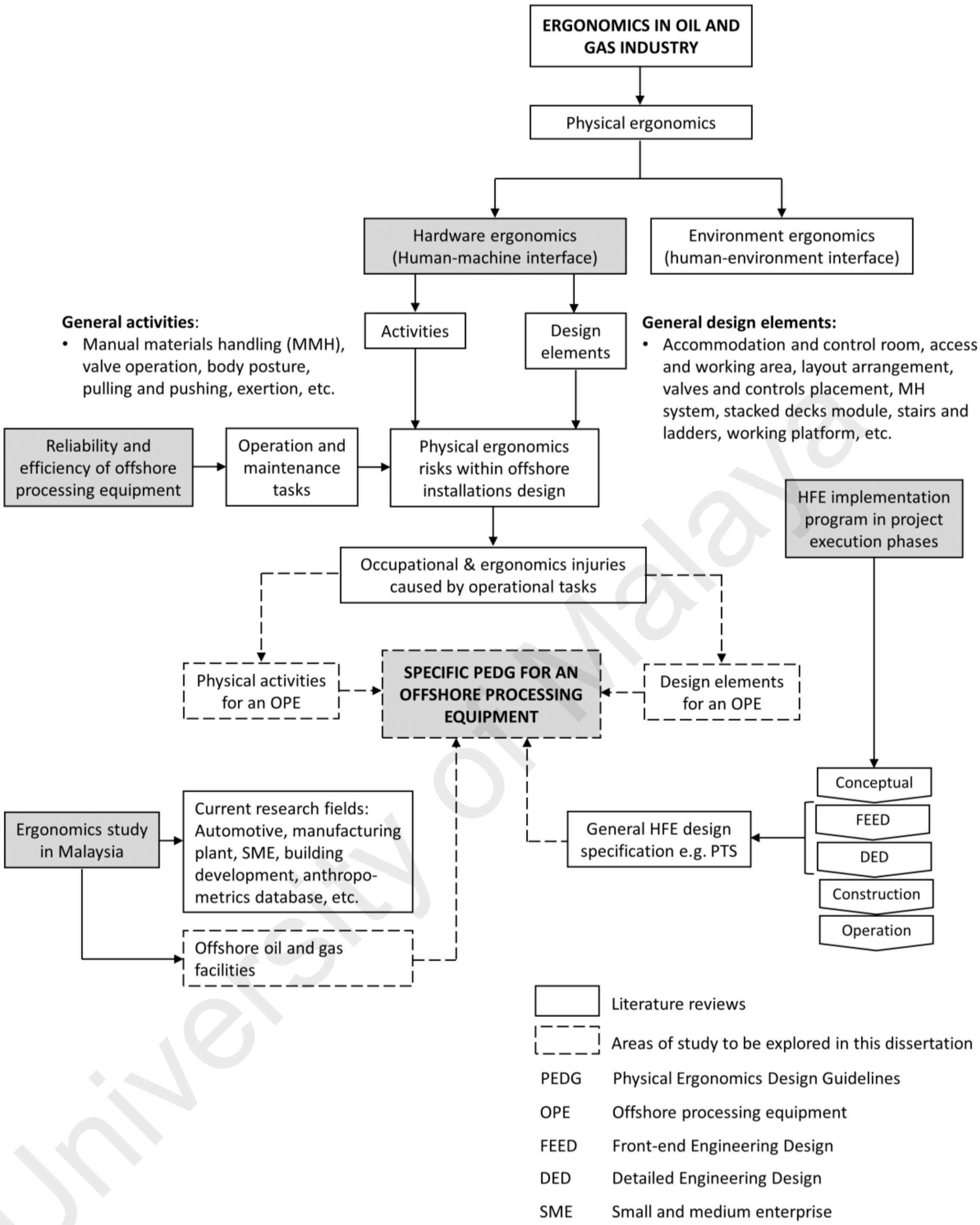

Figure 2.2: Summary of literature review

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter presents the research methodology of this study, which was designed according to the sequence of research questions and consisting of five sequential parts as illustrated in Figure 3.1. The sequence shown in the flowchart explains that outcomes from Part 1 would be direct inputs for Part 4, while outcomes from Part 2 would be inputs for Part 3, and subsequently would be inputs for Part 4. Finally, outcomes from Part 4 would be validated in Part 5. This chapter also explains the objectives of each part, the characteristics of respondents and case studies, instruments for data collection, and analysis methods.

3.2 Part 1: Assessing operators' physical ergonomics awareness and concerns towards criticality of physical ergonomics issues

This methodology part aimed to evaluate the current state of physical ergonomics awareness among the Malaysian oil and gas operators and their concerns towards the physical ergonomics issues within an offshore workplace. The respondents were characterized by several criteria such as job classifications, ranges of experience in an offshore platform, and types of experience in the industry. The data was collected based on three dependent variables namely respondents' perception towards relevancy of design criteria within an offshore workplace with the physical ergonomics domain, effects of physical ergonomics implementation in an offshore processing equipment design, and criticality of physical ergonomics issues within an offshore processing equipment. A questionnaire tool was used to collect data, where the construction of the questionnaire leveraged upon hands-on experiences among the respondents. It was envisaged that the findings could provide an understanding of local operators' outlook towards the physical ergonomics issues in an offshore workplace and assess their physical ergonomics concerns within an offshore processing equipment design. This methodology part would answer the first research question of this study.

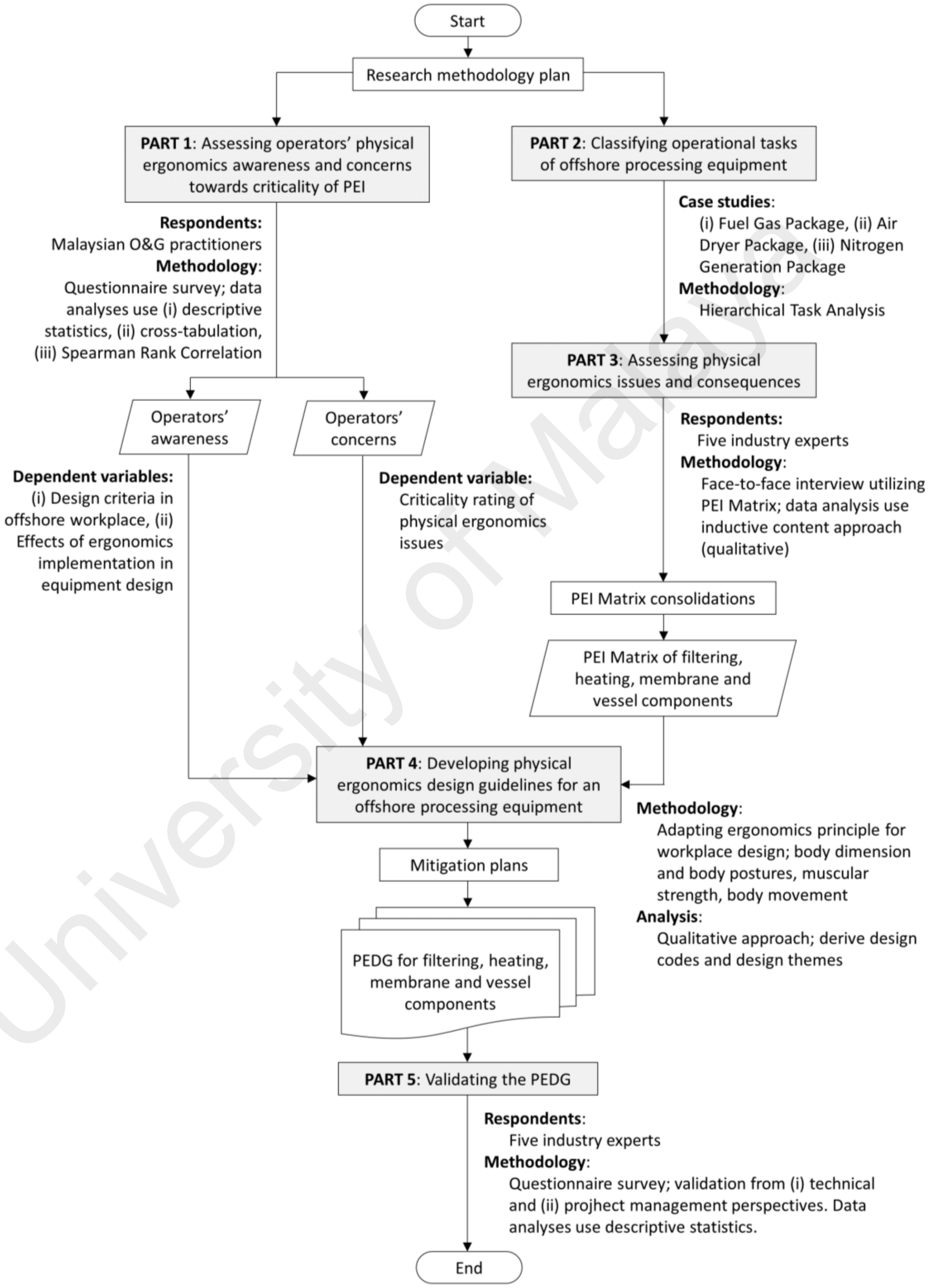

Figure 3.1: Research methodology flowchart

3.2.1 Questionnaire design

There were three sections in the questionnaire. Section 1 consisted of demographic information surveys such as age, current job classification, and range of experience in an offshore platform by using multiple choice question, and type of experience among the respondents (*engineering design* or *operation/maintenance*) by using dichotomous question. Section 2 contained a series of questions that assessed the physical ergonomics awareness among the respondents, comprising two sub-sections which were design criteria in an offshore workplace design that was related to physical ergonomics domain (a list of nine design criteria using multiple choice question; *yes*, *no* and *maybe*), and effects of physical ergonomics implementation in an offshore processing equipment design (a list of four potential effects using a 5-point scale question; from 1—*strongly disagree* to 5—*strongly agree*). Section 3 assessed the respondents' concern towards the physical ergonomics issues, containing a list of 17 different issues. A 5-point rating scale question was used; from 1—*not critical at all* to 5—*very critical*. All the tested physical ergonomics cases in the questionnaire were based on the consolidation of inputs from past studies and the author's industrial experiences. The questionnaire template can be referred in Appendix A.

3.2.2 Sample of population

The targeted respondents were characterized according to the following criteria: Malaysian citizens who are engineering practitioners in the oil and gas sector regardless of their job classification, type of experience, and range of experience. These criteria were deliberately included to ensure that the collected data broadly covered the outlook of Malaysian oil and gas operators from various backgrounds. The questionnaire was distributed to 131 samples of the population by using an online survey platform through e-mail and other online communications. 54 of them returned the completed questionnaire, reflecting a return rate of 41.2%.

3.2.3 Data analysis

Statistical analysis software, SPSS version 19.0 was used to analyse the accumulated data. The following three dependent data groups were recorded from the questionnaire and the data was analysed using three methods as described in subsequent sections.

(a) Respondents' perception towards relevancy of the nine design criteria in an offshore workplace with the physical ergonomics domain

(b) Respondents' perception towards the four effects of physical ergonomics implementation in an offshore processing equipment design

(c) Respondents' concern towards the 17 physical ergonomics issues within an offshore processing equipment design

3.2.3.1 Descriptive analysis

Percentage calculations and bar charts were generated to review a demographic data of the respondents. The same method was used to analyse data for the first and second dependent data groups to understand the trend of responses. For the third dependent data group, quartile analysis was carried out where the first quarter (Q1), third quarter (Q3), and interquartile range (IQR = Q3 - Q1) of the data were determined to understand a tendency of the respondents' thought towards the tested variable. In this analysis, a small IQR score indicated a consensus of agreement among the respondents.

3.2.3.2 Cross-tabulation

A cross-tabulation analysis method offers an effective way to analyse more than two categorical data, which provides a comprehensive information within the same frame for concluding overall trends and comparing a relationship between the tested variables. This study used the cross-tabulation method not only to compare percentages of the overall respondents' feedback towards the three dependent data groups, but also to analyse the trend of responses between two types of working experience, namely engineering design and operation/maintenance.

3.2.3.3 Spearman Rank Correlation analysis

Extensive analyses, comprising three different tests were carried out to examine how the range of experience factor among the respondents affected their state of physical ergonomics awareness and ergonomics concern in an offshore workplace. The Spearman Rank Correlation analysis was used to analyse the non-parametric data that acquired through the questionnaire survey. The tests were:

Test 1: Correlation between the respondents' range of experience and their perception towards the relevancy of nine design criteria in an offshore workplace with the physical ergonomics domain

Test 2: Correlation between the respondents' range of experience and their perception towards the four effects of physical ergonomics implementation within an offshore processing equipment design

Test 3: Correlation between the respondents' range of experience and their concern towards the 17 physical ergonomics issues within an offshore processing equipment design

Prior to the tests, null (H_0) and alternative (H_1) hypotheses were established and applicable for all tests, whereby the Spearman Correlation Coefficient (ρ) and probability value (Sig. 2-tailed) would interpret a state of correlation between the tested variables.

H_0: There is no correlation between the range of experience and the respondents' feedback

H_1: There is a correlation between the range of experience and the respondents' feedback

3.3 Part 2: Classifying operational tasks of offshore processing equipment

This part aimed to assess common operational tasks required for various types of offshore processing equipment. This could be achieved by breaking down every physical task and subtask that might be involved in completing the maintenance goals for the chosen case studies. Basically, an equipment design and maintenance manuals were reviewed, and a task analysis was implemented on maintenance procedures of the case studies. The methodology Part 2 outcomes would provide inputs for the methodology Part 3, which would also address the first research question of this study.

3.3.1 Case studies sample

To accommodate this methodology, three types of offshore processing equipment from Project A – Fuel Gas Package, Air Dryer Package, and Nitrogen Generation Package were selected as case studies, in accordance with the following bases: the equipment is commonly available in process and utility systems of processing platform, involves frequent maintenance activities with inevitable physical human intervention, and consists of common maintenance components that are also available in other processing equipment within the platform. Several detailed design references namely piping and instrumentation diagram (P&ID), operation and maintenance manuals (O&M), and general arrangement (GA) drawings were studied carefully to perceive the technical knowledge of each case study. The details include the processing philosophy, main and auxiliary components details, equipment layout arrangement, and recommended maintenance procedures. A typical schematic flow diagram of all case studies are shown in Figure 3.2, Figure 3.3, and Figure 3.4, providing an overview of available maintenance components within the equipment skid boundary.

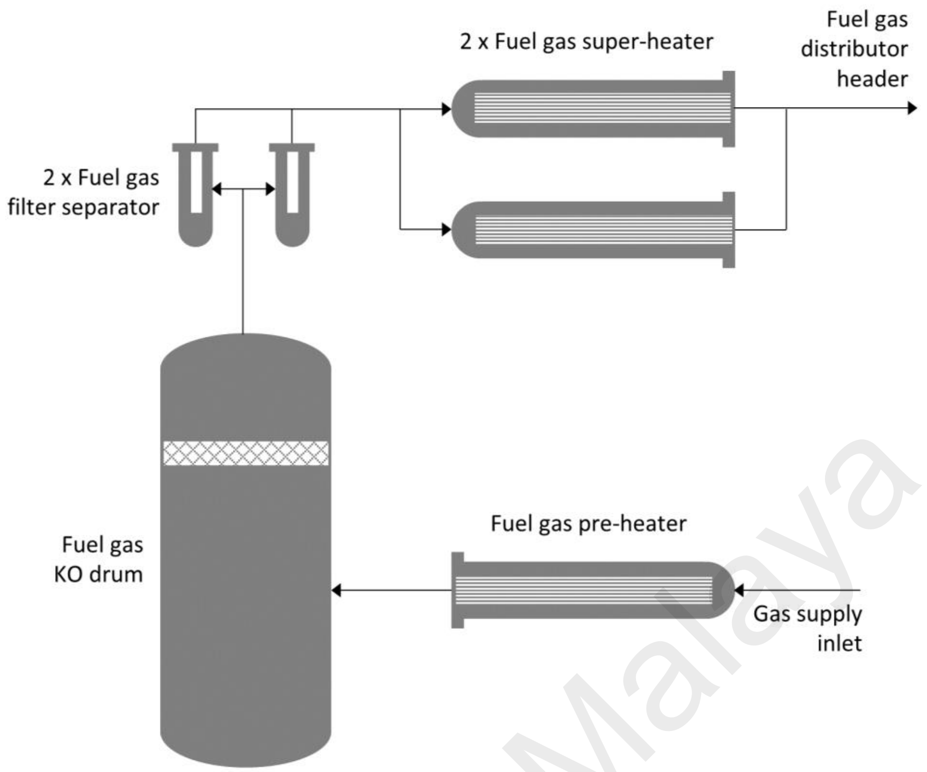

Figure 3.2: Typical schematic flow diagram of the Fuel Gas Package

The Fuel Gas Package is often connected from dehydrated gas, export gas, and other raw gas supply lines at the upstream of equipment, streaming through heating, demisting, and filtering processes for producing clean and compatible fuel gas. The end product will be used for fuelling a power generation equipment at offshore installation (Devold, 2010). The produced fuel gas is directed to the fuel gas distribution header at the downstream of the equipment for various utilization. Based on the schematic diagram, the fuel gas filter separator and fuel gas super-heater consist of 2×100% configuration where both components work for 100% performance, but one will be a spare to the other in case of failure of the running component.

Referring to Figure 3.3, high-pressure utility air that is produced by an air compressor and stored in utility air vessel is streamed to the Air Dryer Package for filtering undesired particles and eliminating moisture (Jeong et al., 2013). The high-pressure utility air is converted to instrument air through a series of pre-filter medium, a filled vessel with a drying agent and after-filter medium, and subsequently stored in a separate instrument air vessel at downstream of the Air Dryer Package. Based on the typical schematic flow diagram, the pre-filter and after-filter consist of 2×100% configuration with an additional spare component for the running component. The instrument air dryer involves 4×50% configuration, where two vessels work concurrently at one time to form 100% performance and two other vessels work as standby components.

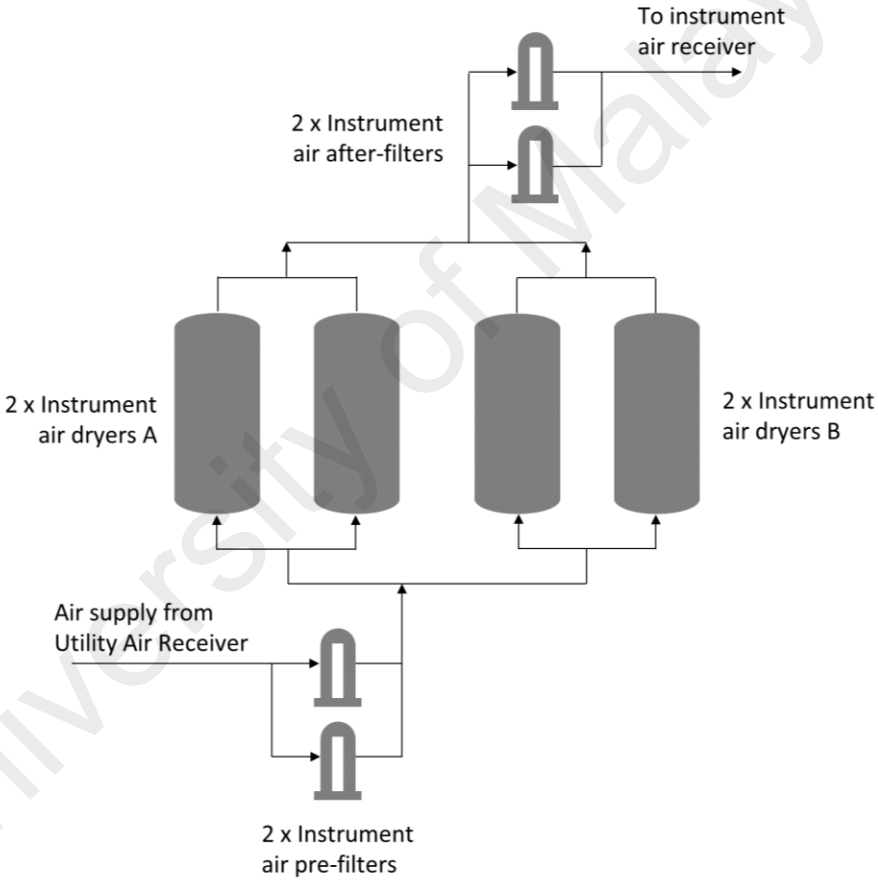

Figure 3.3: Typical schematic flow diagram of the Air Dryer Package

Nitrogen Generation Package is a conversion system of instrument air to nitrogen gas. As an inert gas with non-flammable characteristic and does not chemically react with other substance under certain conditions, nitrogen is often used for blanketing and purging operations within processing lines or closed vessels (Jeong et al., 2013). While maintaining the pressurized gas supply, the Nitrogen Generation Package guarantees a continuous nitrogen gas supply for various uses during operation and maintenance activities. To produce the nitrogen gas, instrument air is streamed through a filtering medium, heating, and a series of membrane modules for removing other gas mixtures. A typical Nitrogen Generation Package may consist of 2×100% configuration for coarse coalescer filters, fine coalescer filters, and generator pre-heaters, respectively. While the number of membrane modules is determined by the process flow and conversion capacities of the equipment.

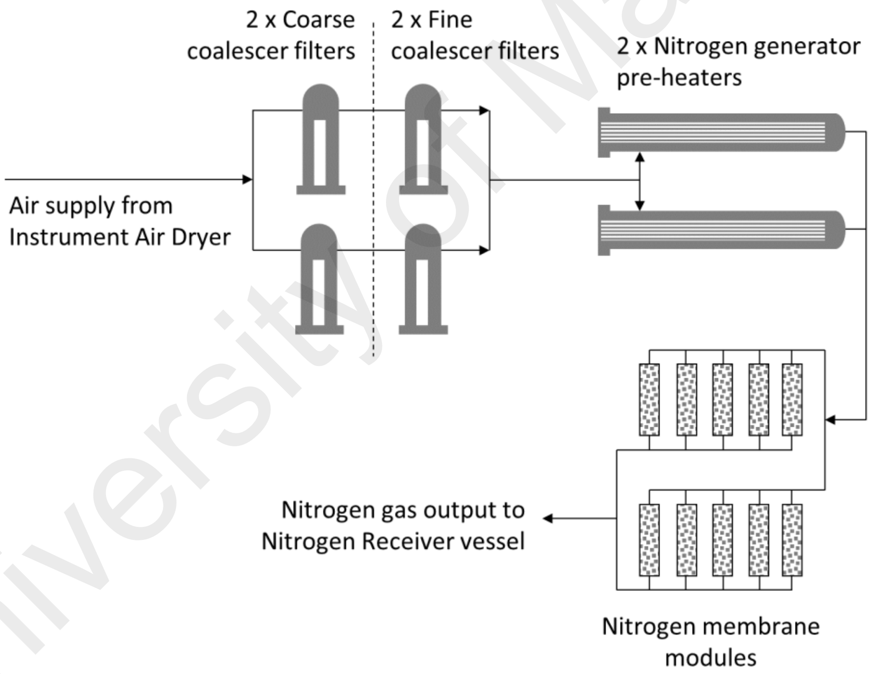

Figure 3.4: Typical schematic flow diagram of the Nitrogen Generation Package

3.3.2 Hierarchical Task Analysis

The Hierarchical Task Analysis (HTA) tool was selected as an ergonomics assessment tool to analyse tasks and subtasks of the three case studies. HTA is a well-known tool that could be manipulated to break down the goal and sub-goal of a job task, and compatible for analysing a complex system especially in the chemical processing industry where some of its equipment has an advanced automation system. The function of the HTA tool is dependent on the goals and operations of the system, regardless of the human tasks involvement (Annett, 2005). This feature could possibly prevent any oversight towards potential physical ergonomics hazards and human errors that might arise during operation and maintenance activities of the processing equipment. Moreover, Shepherd (1998) has successfully explored the mapping of cognitive tasks element within the HTA framework. During the maintenance activities, it is hypothetically expected that multiple physical tasks could be carried out simultaneously within the same limited working space. The possibility of interconnected or integrated different tasks are envisaged and this condition would also affect the physical ergonomics requirement in a workplace design. The nature of complex tasks emphasizes the requirement of systematic and holistic task analysis method, which could be fulfilled by the HTA.

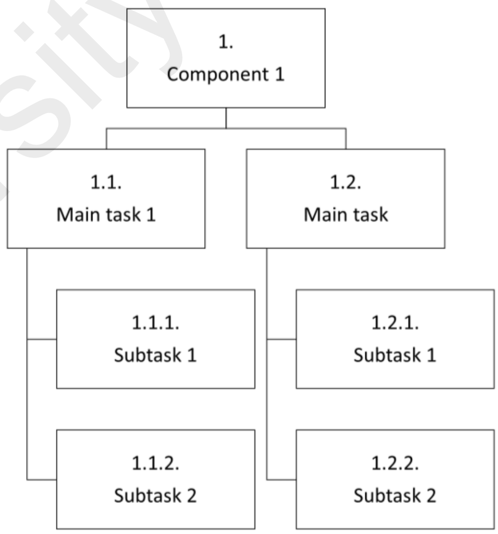

Figure 3.5: Example of HTA flowchart

All maintenance components of the case studies were identified, and related job sequences were scrutinized up to the main tasks and subtasks only, to delimit the physical task boundary. A flowchart format that was used to present the HTA results is shown in

Figure 3.5. Numbers of components, tasks, and subtasks that obtained from this study were accumulated and common maintenance components among the case studies were identified.

3.3.3 Categorization of maintenance components

To simplify the process of subsequent methodology parts, all maintenance components that were inferred from the case studies were categorized into similar component types, based on the following criteria:

(a) Process function of each maintenance component. For instance, a filtering component commonly contains removable filtering elements that were installed inside a pressurized shelve or vessel

(b) Components that consist of identical tasks and subtasks in maintenance procedures, based on results of the HTA exercise

It was envisaged that similar types of maintenance components might raise comparable physical ergonomics issues due to similar physical tasks requirement.

3.4 Part 3: Assessing physical ergonomics issues and its consequences

This part aimed to assess physical ergonomics issues that might potentially arise during the completion of each main task and subtask in all the case studies. A face-to-face interview method was applied to acquire Malaysian oil and gas operators' experience, opinion, and technical know-how towards normal maintenance practices and the physical ergonomics issues within an offshore processing equipment. Basically, the HTA results from Part 2 could ease the subsequent assessment and analysis procedure (Stanton, 2006). In this study, the HTA outputs were utilized as a basis for designing the interview method and acquiring pertinent data to completely answer the first research question of this study.

3.4.1 Design and method of interview

A closed and fixed-response interview (Patton, 2002) was carried out where all the respondents were asked to evaluate physical tasks of the case studies against a list of predetermined physical ergonomics issues (PEI). A dichotomous response (answer: *yes* or *no*) was expected from the respondents through this interview session. This approach was used to optimize the interview session timeframe, ensure the data consistency, and simplify the data analysis.

15 predetermined PEI which could potentially cause an occupational injury to operators were developed in advance based on a combination of two content components. The first component was based on an adaption of the PLIBEL (*Plan för Identifiering av. Belastningsfaktorer*) tool and the second component was based on the author's industrial experience. PLIBEL (Kemmlert, 1995) is a simple screening checklist tool that has been utilized for identification of ergonomics hazards and risk factors for musculoskeletal disorder (MSD) injuries with regards to five body regions. The body regions are the upper back (neck and shoulder), elbow-forearms-hands, feet, knees and hips, and lower back (Kemmlert, 2005), as shown in Figure 3.6. This approach was selected since the assessment for larger body regions during maintenance activities are more appropriate with a face-to-face interaction during the interview session, where any physical task risks are easily linked to the five main body regions. The PLIBEL checklists that were identified as irrelevant to physical tasks within an offshore processing equipment were withdrawn to ensure the predetermined PEI were compact and fit the assessment purpose.

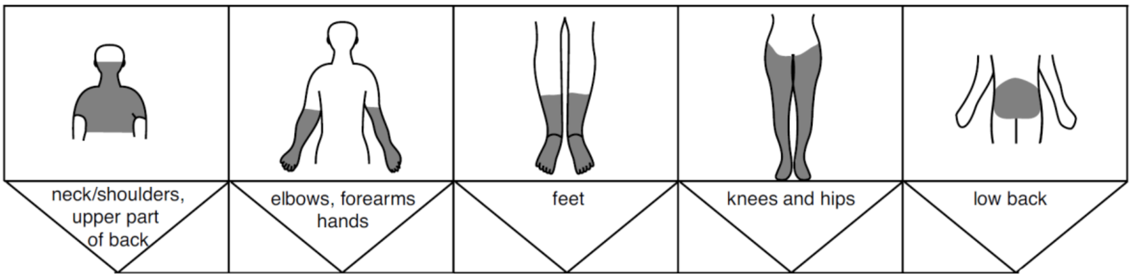

Figure 3.6: Focused body regions in PLIBEL screening tool. Photo by Kemmlert (2005)

The predetermined PEI—as outlined in Table 3.1—were employed during the face-to-face interview sessions with industry experts to ensure the scope of discussion was kept within context. Besides that, the respondents were also encouraged to share additional physical ergonomics issues based on their hands-on experience within an offshore platform. In aligning the potential PEI with the category of physical human-workplace interactions (Duarte & Silva, 2010), each potential PEI was reviewed and classified into *activity* or *design elements* category as shown in Table 3.1.

Table 3.1 Potential physical ergonomics issues in an offshore processing equipment design

Reference no.	Potential physical ergonomics issue	Human-workplace interaction	
		Activity	Design element
1	Access platform requirement to complete the task?		✓
2	Step on an uneven structure to reach the critical controls and valves e.g. piping, equipment, steel frame	✓	
3	Access space requirement for personnel to work?		✓
4	Space requirement for withdrawal of maintenance components?		✓
5	Space requirement for hand tools (screwdriver, spanner, driller)?		✓

Table 3.1: Continued

Reference no.	Potential physical ergonomics issue	Human-workplace interaction	
		Activity	Design element
6	Material handling equipment or special tool requirement for lifting/pulling/pushing the maintenance component?		
6.1	Permanent or temporary		✓
6.2	Space for handling equipment		✓
7	Effective design of holding point or lifting point on maintenance component?		✓
8	Does the task involve manual handling by one or two people?		
8.1	Repetitive lifting within a short time	✓	
8.2	Handling beyond forearm length	✓	
8.3	Handling below knee height	✓	
8.4	Handling above shoulder height	✓	
9	Does the task involve pulling or pushing effort?		
9.1	Repetitive pulling/pushing within a short time	✓	
9.2	/pushing beyond forearm length	✓	
9.3	Pulling/pushing below knee height	✓	
9.4	Pulling/pushing above shoulder height	✓	
10	A possibility of awkward body posture for completing the task (e.g. operating valve, filling point)?		
10.1	Slightly flexed forward	✓	
10.2	Severely flexed forward	✓	
10.3	Severely twisted	✓	
10.4	Extended backward	✓	
11	Forearm or hand (including fingers) movement requirement for completing the task?		
11.1	Twisting movement	✓	
11.2	Forceful movement (switch)	✓	
11.3	Hold the load for a long time	✓	
12	Hot or cold surface?		✓
13	A sharp edge that possibly exists in the design of component?		✓
14	Demand for visual activity (e.g. controls, sampling point, gauge, panels, working point)?		✓
15	Piping route laying on the floor adjacent to a working area?		✓

A documentation worksheet for the interview, namely Physical Ergonomics Issue (PEI) Matrix was prepared to systematically collect the data. Outputs from HTA were firstly tabulated against the 15 potential PEI for all maintenance components of the case studies. The respondents were briefed about each of the main task and subtask, then were asked to associate the tasks with a relevant predetermined PEI. Although there might be similar types of maintenance component which may reflect the same PEI as explained in Section 3.3.3, the PEI assessment was even done on all components separately to ensure the cumulative respondents' feedback covers as much as overall design conditions and configurations among the case studies. In addition, rendered sketches and additional ergonomics issues relating to specific tasks that were provided by the respondents were recorded to enhance data collection. The PEI Matrix was used to document all the findings. Whichever potential PEI for a particular task that was raised by the respondents, was marked as a score '1', with a notation that the score did not represent a weighted value nor scale rating but reflected as an input from a respondent instead. A sample of PEI Matrix template and how it was filled is shown in Figure 3.7.

Case study: Equipment 1 (Component 1)
Data source: Respondent 1

Task	Description	Physical ergonomics issue										
		1	2	3	4	5	6	7	....	13	14	15
1.1	Main task 1											
1.1.1	Subtask 1		1	1	1					1		1
1.1.2	Subtask 2	1	1		1					1		1

Figure 3.7: A template of Physical Ergonomics Issue (PEI) Matrix

3.4.2 Sample of respondents

Five industry experts were engaged to complete required information in the PEI Matrix for further analysis. To ensure the inputs were valuable from the Malaysian perspective and workplace environment, the respondents were characterized as a practitioner in the

Malaysian oil and gas industry, who had been practicing for 10 years and above in the local industry, and also familiar with operation and maintenance works within the Malaysian offshore platforms.

3.4.3 Data analysis

A qualitative analysis with inductive content approach was carried out to evaluate how the operational perspective towards the physical ergonomics issues would affect a processing equipment design, and which ergonomics issue requires more attention in a design process. In simplifying the data analysis and initiating a comprehensive data interpretation, structured consolidations of raw data, maintenance components, and scores were established. The consolidations exercise could reduce overlapping data since a few similar categories of maintenance components were envisaged from the case studies. For clarity, the consolidations approach flowchart is illustrated in Figure 3.8.

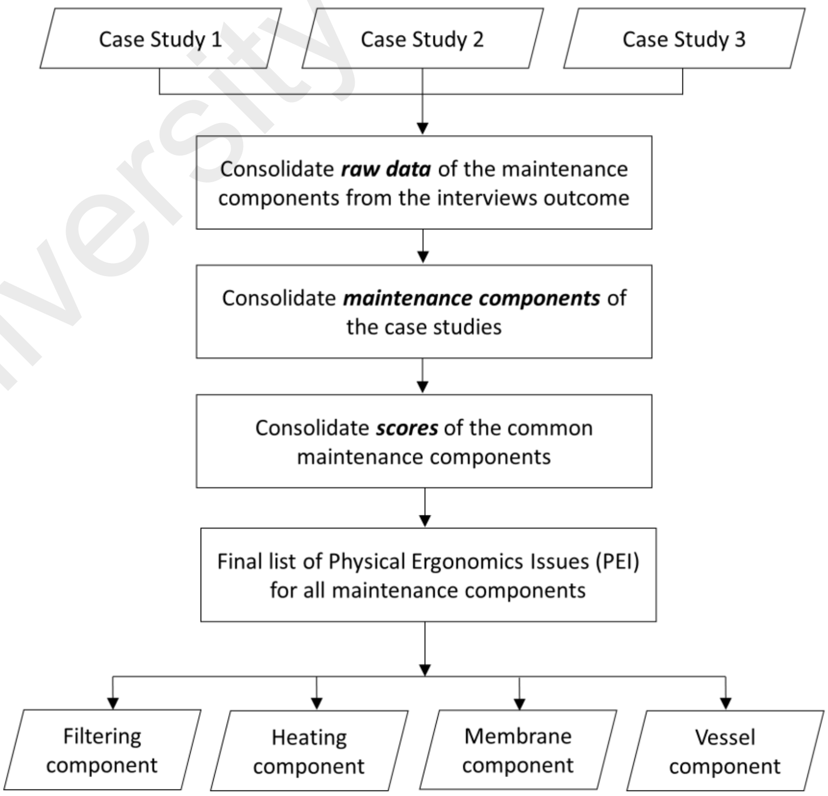

Figure 3.8: Flowchart of the consolidation approach for raw data, maintenance components, and scores.

A *raw data consolidation* is defined as the accumulation of scores and findings of each maintenance component from all the respondents into a single worksheet, which resulted in the highest score and lowest score in the main PEI Matrix. For example, if five respondents acknowledge that a task of Component 1 of the Case Study 1 has the potential PEI-1, a score in PEI Matrix would be '5' which reflects the highest score in the matrix. The lowest score would be '1' which reflects a score from one respondent only, while the PEI Matrix will be left blank if no response is recorded for a particular PEI.

As discussed in methodology Part 2 in Section 3.3.3, the maintenance components of the case studies were categorized into similar categories. Using the same procedures, the *maintenance components consolidation* together with the maintenance tasks and subtasks in the PEI Matrix were carried out according to the same basis. For instance, a list of tasks for fuel gas filter separator (Case Study 1) and a list of tasks for air dryer pre-filter (Case Study 2) would be combined into a single list of filtering component. In this consolidation process, the identified overlapping tasks were removed, and distinctive tasks remained as common maintenance tasks of the component. The final step of the consolidation procedure was a *score consolidation*, where the overlapping scores were averaged out to form a final score; within a 1– 5 range. As discussed earlier, the score would not represent a weighted value, criticality, nor importance scale rating. However, it could be interpreted as a likelihood of the physical ergonomics issue that was potentially experienced by the respondent within specific tasks, based on the justification that the scores were counted based on the number of respondents who raised the issue. From this basis, a score of 3–5 was defined as a *high likelihood*, which means that a higher number of respondents have experienced the issue along with their experience, while a score of 1–2 was defined as a *low likelihood*, reflecting a lower response from the respondents.

Raw data inputs

Case Study 1 / Component 1 (Data from **RESPONDENT 1**)					
Task	Description	Potential Ergonomic Issues			
		1	2	3	4 … 15
1.1	Main task				
1.1.1	Sub task 1		1	1	1
1.1.2	Sub task 2	1	1	1	1

Case Study 1 / Component 1 (Data from **RESPONDENTS 2 …. 5**)					
Task	Description	Potential Ergonomic Issues			
		1	2	3	4 … 15
1.1	Main task				
1.1.1	Sub task 1		1	1	1
1.1.2	Sub task 2		1	1	1

Raw data consolidation

CASE STUDY 1 / Component 1 (Consolidated data from all respondents)					
Task	Description	Potential Ergonomic Issues			
		1	2	3	4 … 15
1.1	Main task				
1.1.1	Sub task 1		5	5	5
1.1.2	Sub task 2	1	5	5	5

CASE STUDY 2 … 3 / Component 1 (Consolidated data from all respondents)					
Task	Description	Potential Ergonomic Issues			
		1	2	3	4 … 15
2.1	Main task				
2.1.1	Sub task 1		3	3	5
2.1.2	Sub task 2	1	2	4	5
2.1.3	Sub task 3	1	3	3	5

Maintenance components consolidation

COMPONENT 1 (Consolidated components)					
Task	Description	Potential Ergonomic Issues			
		1	2	3	4 … 15
1.1	Main task				
1.1.1	Sub task 1 (Case study 1)		5	5	5
2.1.1	Sub task 1 (Case study 2)		3	3	5
1.1.2	Sub task 2 (Case study 1)	1	5	5	5
2.1.2	Sub task 2 (Case study 2)	1	2	4	4
2.1.2	Sub task 3 (Case study 2)	1	3	3	5

Scores consolidation

COMPONENT 1 (Averaged out scores)				
Task	Potential Ergonomic Issues			
	1	2	3	4 … 15
Main task				
Sub task 1		4	4	5
Sub task 2	1	3.5	4.5	5
Sub task 3	1	3	3	5

Figure 3.9: Physical Ergonomics Issue (PEI) Matrix consolidation procedure

Smooth consolidations could be achieved as the acquired data was assembled through the closed and fixed-response interview by utilizing a typical frame of PEI Matrix. A template of PEI Matrix consolidation procedures is illustrated in Figure 3.9.

Outcomes from the methodology Part 3 were expected to provide sufficient bases for the development of physical ergonomics design guidelines (PEDG), as shown in the variables framework of PEDG development in the subsequent methodology part.

3.5 Part 4: Developing physical ergonomics design guidelines for an offshore processing equipment

This methodology part aimed to analyse and integrate findings from the methodology Part 1, Part 2, and Part 3, subsequently develop a PEDG for the identified maintenance components. This part would answer the second research question of this study on how to effectively incorporate the physical ergonomics requirements in an offshore processing equipment design during the early design stage. The PEDG development framework which encompassed all related variables from the earlier methodology parts is illustrated in Figure 3.10 and explained in the subsequent sections accordingly.

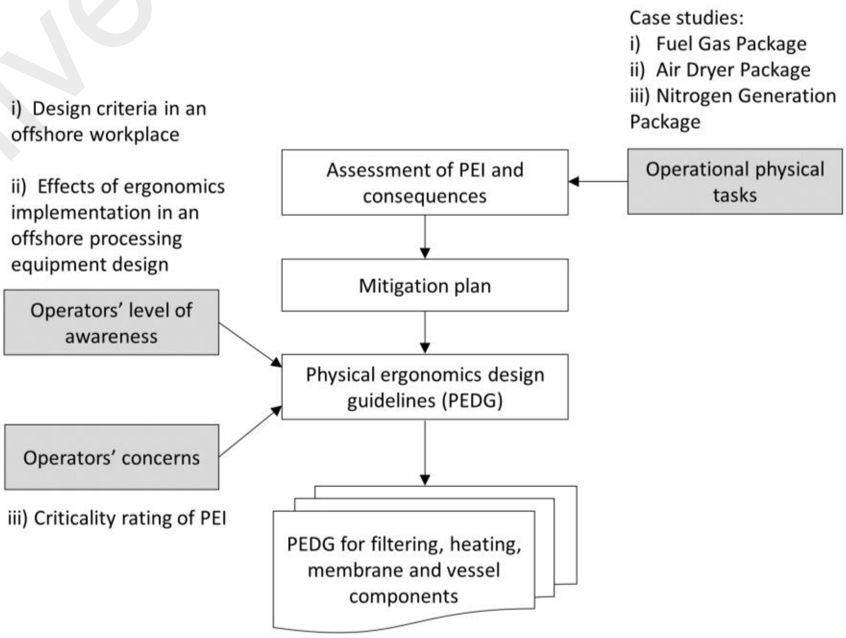

Figure 3.10: Variables framework of PEDG development process

3.5.1 Operators' level of awareness and concern (questionnaire survey)

The questionnaire results from the methodology Part 1 were manipulated in the variables framework the PEDG development in two ways. Firstly, the respondents' level of physical ergonomics awareness would determine a basis for developing the design guidelines. For example, any specific trend of awareness shown among the respondents towards a particular ergonomics issue would reflect a specific requirement in the design guidelines. Besides that, influential variables such as the type of experience and range of experience in an offshore workplace among the respondents would contribute as pertinent prerequisites in the PEDG development process. Secondly, the results of the criticality rating of all the tested physical ergonomics issues in the questionnaire survey would form a basis of how important each physical ergonomics aspect was within a processing equipment design. Finally, the questionnaire results would accumulate a consensus of opinion among the respondents who came from various technical backgrounds, which would be later converted into structured and repeatable-used design guidelines in a future engineering design process.

3.5.2 Operational physical tasks (HTA and interview)

A completed PEI Matrix with the assessment findings of physical ergonomics issues against tasks and subtasks of each maintenance component was transferred into a tabulation form. An assessment towards each PEI was carried out to assess hazards and consequences towards an operator. Each PEI and its consequence was cross-evaluated with the ergonomics principles for workplace and workstation design, which were body dimension and body posture, muscular strength, and body movement (Department of Standards Malaysia, 2005). This exercise aimed to suggest mitigation plans for eliminating the physical ergonomics issues, and eventually established a list of PEDG for an offshore processing equipment design. In aligning the assessment of PEI's consequences and mitigation plans with the related maintenance components, the analysis was carried out within a tabulation format as shown in Table 3.2.

Table 3.2: A tabulation format for PEI lists of each maintenance component

Task	Subtask	Physical ergonomics issue		Hazards / Consequences	Mitigation plan
		Activities	Design element		
Task 1	Subtask 1	PEI 1		Consequence 1	Requirement 1
			PEI 3	Consequence 2	Requirement 2
			PEI 4	Consequence 3	Requirement 3

3.5.3 Data analysis

A qualitative analysis approach was applied to the proposed mitigation plans of four maintenance components namely filtering, heating, membrane, and vessel. Each mitigation plan was assigned with relevant design codes, and several design themes were derived from the relevant group of design codes. A comparison of results among the maintenance components was established, showing which design codes were applicable for which maintenance components. A reasoning process through cross-comparison between the established design themes and the PEI criticality ratings that have been analysed from the questionnaire survey (methodology Part 1) was carried out to evaluate and justify the importance of ergonomics design requirements which need to be integrated into the proposed PEDG.

Following that, a structured and theme-based design guidelines list for all maintenance components was developed with regards to the proposed mitigation plans, by filtering overlapping items and combining relevant ergonomics design requirements. A theme-based design guidelines approach is shown in Table 3.3, where the structure of design guidelines is initiated by the established design themes, followed by applicable ergonomics design specifications. This approach was preferred due to the following criteria:

(a) A design-themes based approach would provide end users with a holistic introductory overview of the physical ergonomics needs within an offshore processing equipment design

(b) The design specifications will be tied with its design theme instead of other aspects such as a specific part of a maintenance component. Therefore, it could be adapted widely for other similar types of component despite some of the design specifications which might not be applicable due to untypical design parts

Table 3.3: Theme-based physical ergonomics design guidelines format

Design theme	**Design specification**	**Compliance**		
		Yes	**No**	**N/A**
Example 1				
Example 2				
Example 3				

*N/A: Not applicable

Since the proposed PEDG would be applied by an engineer or designer during a design process of processing equipment, a validation survey was needed to check whether it could meet end users' needs during the design process. Details of the validation exercise are presented in the subsequent section, as the methodology Part 5.

3.6 Part 5: Validating the physical ergonomics design guidelines

The proposed PEDG for filtering, heating, membrane, and vessel components were validated using a face-to-face questionnaire method, targeting a total of five engineers who were involving in an engineering design of various projects. The selected respondents were based at Company B, a company that provides front-end engineering design (FEED), detailed engineering design (DED) and procurement services in the oil and gas industry. Three of them were considered as a senior engineer level with a minimum of 10 years' experience in an engineering design practice, whilst two of them were considered as an intermediate engineer level with a minimum of 5 years of the same experience. The face-to-face method was selected to ensure the accuracy of the validation process, and simultaneously acquiring intended feedback from the targeted end users. The purpose of this validation exercise was to ensure that the proposed PEDG meet the end users' actual needs in integrating the physical ergonomics requirements within a processing equipment design, and also to ensure the proper functioning in a design process.

The complete sets of PEDG for filtering, heating, membrane, and vessel components were presented to the respondents before they were asked to provide feedback in the validation questionnaire.

3.6.1 Questionnaire design

Two validation criteria with relevant a few dependent variables were predefined through a series of questions to collect feedback from the respondents. The criteria encompassed *technical recommendation* and *project management*, which both criteria evaluated the pivotal skills among engineers in an engineering design practice.

Firstly, the *technical recommendation* criterion tested three variables namely comprehensiveness of the proposed PEDG, design improvement and technical understanding towards the design specifications. A Likert-scale question (5-point scale from 1—*strongly disagree* to 5—*strongly agree*) was utilized to evaluate the variables. Secondly, the *project management* criterion assessed the end users' feedback on the managerial approach in five project design phases, namely concept design, front-end engineering design (FEED), detailed engineering design (DED), construction, and operation. The respondents were required to rate the importance of the design guidelines during each project phase, by using a Likert-scale question (5-point scale: 1—*not important*, 2—*less important*, 3—*moderately important*, 4—*important*, 5—*very important*). Another examined element of the *project management* criterion was the needs of HFE Specialist supervision when applying the PEDG (used multiple choice question: *full supervision*, *less supervision*, *do not need supervision*). A sample of validation questionnaire can be referred in Appendix E.

3.6.2 Data analysis

A simple descriptive analysis was carried out to explore the validation data. A trend of results was analysed through the percentage calculation on the *technical recommendation* part, while a median score was analysed for the *project management* part. This analysis would provide a clear indication and tendency overview of the respondents' feedback towards the proposed PEDG.

3.7 Summary

The appropriate scope of study, respondents and case studies selection criteria, data collection methods, and analysis approaches for each methodology part have been discussed throughout this chapter to ensure the reliability of the research outcome. The methodology plan was developed to answer the specified research questions as outlined in Chapter 1. To recap, the methodology Part 1 covers the first research question on the concerns of Malaysian practitioners which influence the physical ergonomics requirements within an offshore processing equipment design. The methodology Part 2 and Part 3 would also answer the first research question on what were the operational tasks concern that influenced the physical ergonomics issues within an offshore processing equipment design. While the methodology Part 4 would explore the PEDG development process to address the second research question. Lastly, the methodology Part 5 would validate the proposed PEDG and answer the third research question.

A few notations that are worth to be highlighted from this methodology plan are:

(a) The data collection for the questionnaire survey (Part 1) and industry expert interview (Part 3) were narrowed into the scope of Malaysian respondents' perspective and the local environment. This could provide an outlook towards how the local oil and gas practitioners perceive the physical ergonomics issues within an offshore workplace

(b) The selection of the offshore processing equipment case studies would reflect the common facilities in an offshore processing equipment, where similar types of maintenance components might also be installed in other processing equipment than the case studies. The findings are envisaged to be applicable to some of the other processing equipment within offshore processing systems

(c) The variables framework of PEDG development process considers both crucial sides, from the viewpoints of operational tasks and industry practitioners concern towards specific physical ergonomics issues

CHAPTER 4: PHYSICAL ERGONOMICS ISSUES WITHIN AN OFFSHORE PROCESSING EQUIPMENT DESIGN

4.1 Introduction

This chapter which contains three sections discusses the understanding of the physical ergonomics issues within an offshore processing equipment design. The first section explains the results of the questionnaire survey, which is the current state of physical ergonomics awareness among the Malaysian operators and the critical issues that need to be considered when developing the physical ergonomics design guidelines. The second section presents the classification of maintenance components that are available within an offshore processing equipment based on the HTA results, while the third section explains the findings of physical ergonomics issues and consequences assessment towards each physical maintenance task.

4.2 Operators' physical ergonomics awareness and concern

This section discusses the results of the questionnaire survey on the level of physical ergonomics awareness in an offshore workplace and concern towards the criticality of physical ergonomics issue (PEI) within an offshore processing equipment among the stakeholders.

4.2.1 Demographic

Figure 4.1 shows the job classification of the respondents, showing that most of the respondents came from the engineering design/consultation background, followed the installation and commissioning, and maintenance and inspection, while the other five groups show a proportion of 5.6% and below. As these questionnaires were randomly distributed to the oil and gas practitioners, the top three job classifications could be generally understood as top percentages of the industry practitioners' group and play an important role during projects execution.

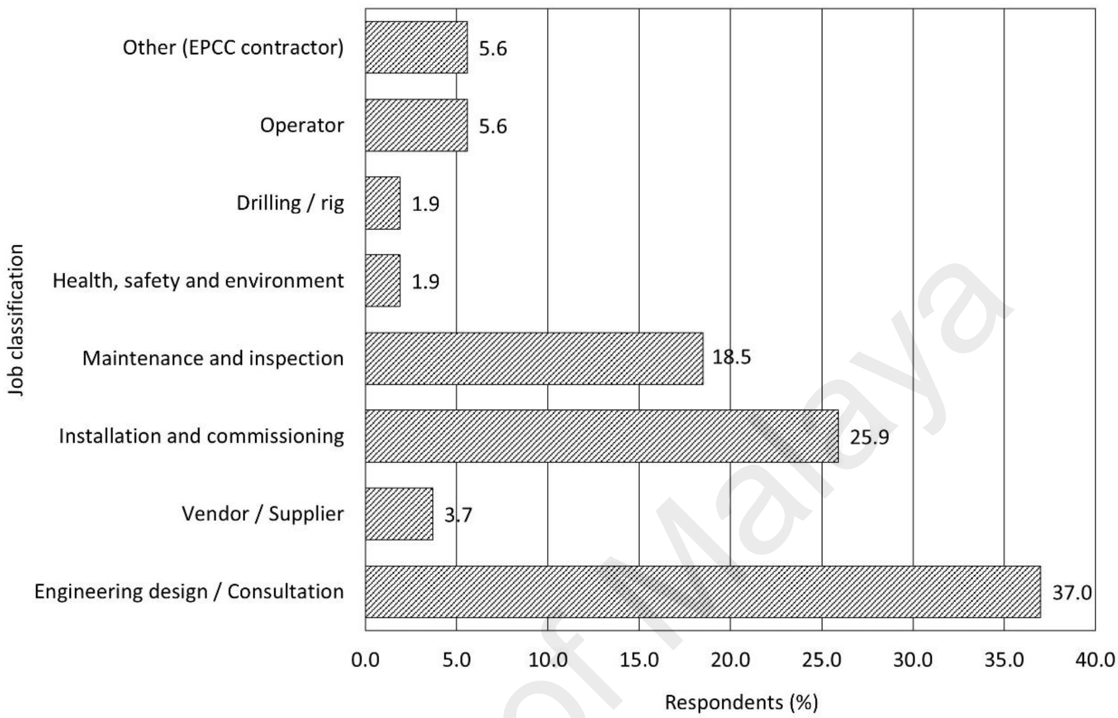

Figure 4.1: Job classifications of the respondents

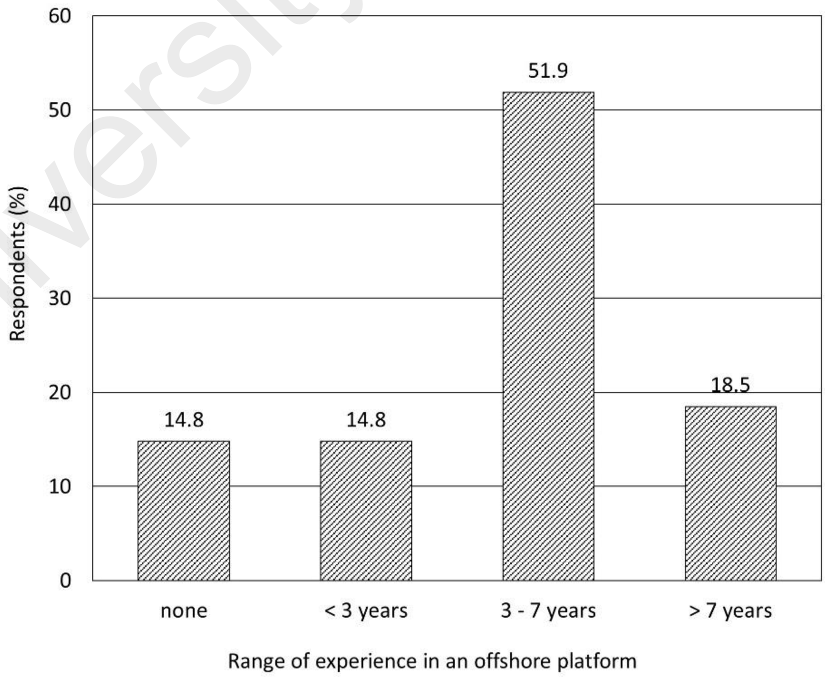

Figure 4.2: Ranges of experience of the respondents in an offshore platform

Figure 4.2 presents the respondents' characteristic based on their range of working experience in an offshore platform. Approximately half of the respondents had *3–7 years* of experience, followed by *more than 7 years* (18.5%) and *less than 3 years* (14.8%), while only 14.8% of the respondents had never experienced the offshore workplace environment. In general, it could be considered that most of the respondents (85.2%) have had the working experience within an offshore environment. Furthermore, the median value fell on *3–7 years'* range of experience, which represented the central tendency of the offshore experience period among all the respondents.

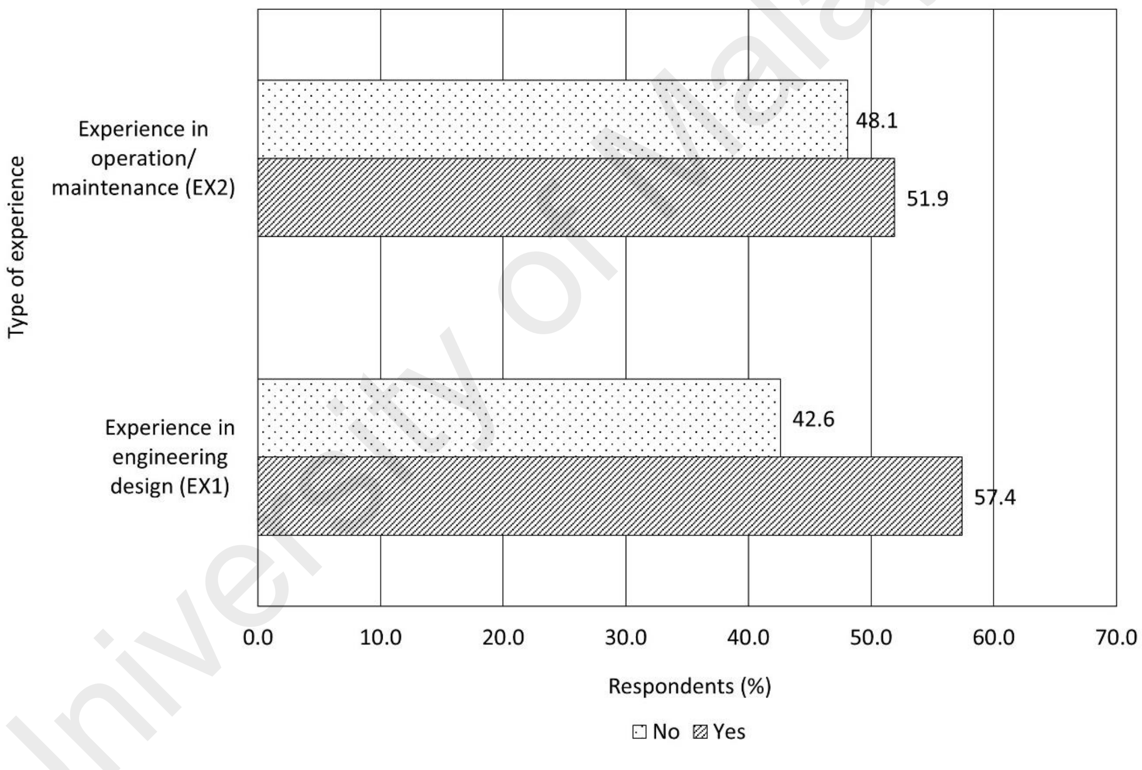

Figure 4.3: Types of experience among the respondents

Respondents were also characterized based on the type of experience they had in the O&G industry, either *experience in preparing design or specification of offshore processing equipment during engineering design stage* (simplified as Engineering Design – EX1) or *experience in monitoring, inspection, cleaning, operation and maintenance of* *offshore processing equipment* (simplified as Operation/Maintenance – EX2). The results are illustrated in Figure 4.3, showing the percentage of having or not having both types of experience, whereby the group with the experience (answer: *yes*) was slightly more than the other (answer: *no*) – for both types of experience. Nevertheless, from the individual point of view, it was acknowledged that one respondent might have either one experience only or one might have or might not have both experiences. This was supported by the findings that showed 24.1% of the respondents had both experiences while 14.8% did not have both experiences, by virtue that some of the respondents might have working experience in the O&G industry but not necessarily within the scope of designing and operating an offshore processing equipment.

Besides that, among the respondents who had an offshore workplace experience (85.2% of the overall respondents), 54.3% of them had the experience in engineering design and 54.3% of them had the experience in operation and maintenance, while only 21.7% of them had both experiences.

4.2.2 Physical ergonomics awareness

The understanding of physical ergonomics awareness among the respondents was evaluated based on two criteria, which were their evaluation towards the relevancy of the tested design criteria with the physical ergonomics domain and the effects of physical ergonomics implementation within an offshore processing equipment design. The following sections describe the results of both criteria.

4.2.2.1 Design criteria in an offshore workplace that are related to physical ergonomics domain

This subsection describes the results of the respondents' perception towards the relevancy of the design criteria in an offshore workplace with the physical ergonomics domain. The results shown in Table 4.1 explain over two-thirds of the respondents agreed that all the design criteria are related to the physical ergonomics domain, except for C3 (coaming area to avoid hydrocarbon or water spillage) and C7 (cable/piping routing across an access way) design criteria which recorded 68.5% and 70.4%, respectively. These findings explain what most of the respondents thought about the design criteria, where a good level of physical ergonomics awareness was noticed among the respondents. There were also indications shown in Table 4.1, which a higher percentage of the respondents who were inclined to disagree on the C3 and C7. Concurrently, the same design criteria also recorded a significant percentage of the respondents who were in doubt (answer: *maybe*). For a clear overview, the trends of the respondents' feedback are illustrated in Figure 4.4.

Table 4.1: Percentage of the respondents' perception towards the relevancy of the design criteria in an offshore workplace with the physical ergonomics domain

Design criteria in an offshore workplace	Percentage (%)		
	Yes	No	Maybe
C1: Withdrawal space for filter, membrane and heater elements.	81.5	1.9	16.7
C2: Personnel access area in front of a control panel	88.9	3.7	7.4
C3: Coaming area to avoid hydrocarbon or water spillage	68.5	13.0	18.5
C4: Reserved space for operation of valve's wheel/lever	87.0	9.3	3.7
C5: Location of valves, gauges, or controls is within a reachable parameter	81.5	11.1	7.4
C6: Accessibility of pedestal crane/materials handling facilities	88.9	3.7	7.4
C7: Cable/piping routing across an access way	70.4	18.5	11.1
C8: Service platform for reaching and working at height	90.7	3.7	5.6
C9: Pulling, lifting and pushing devices for removal of components	77.8	11.1	11.1

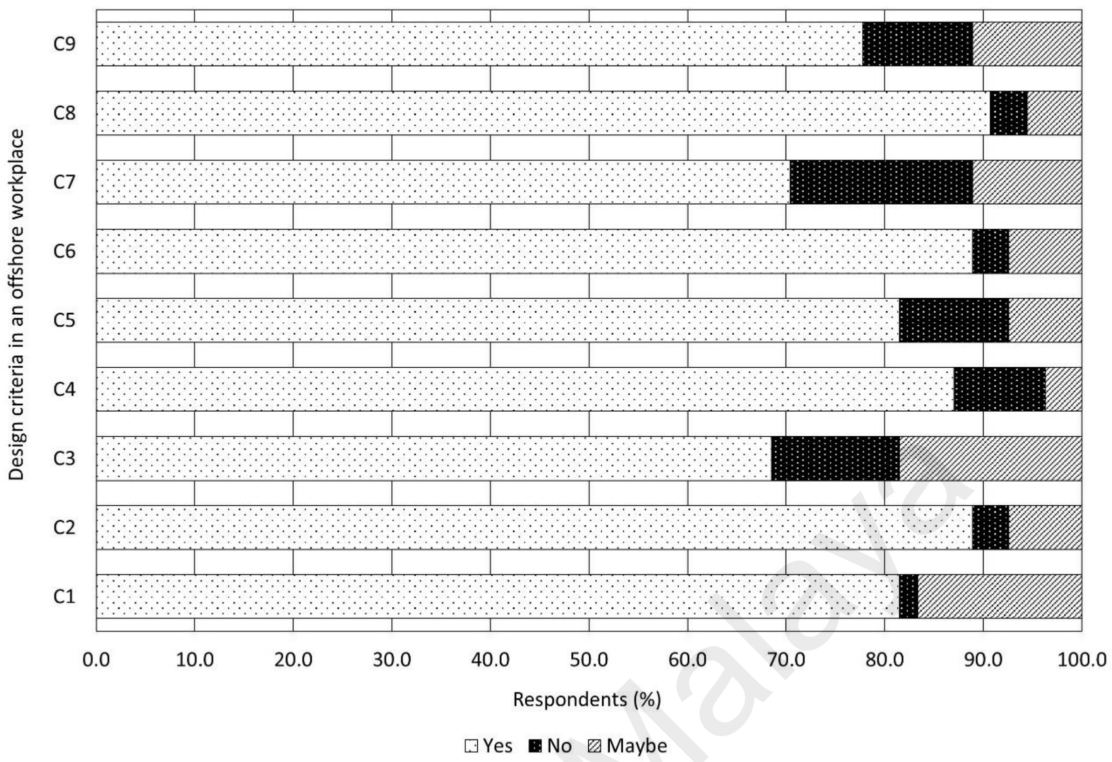

Figure 4.4: Trends of the respondents' feedback towards the design criteria in an offshore workplace

In addition, a comprehensive cross-tabulation for each design criterion was explored to provide a deeper understanding of trends regarding the respondents' perception towards the design criteria. The cross-tabulation result that presented in Table 4.2 summarizes the percentages breakdown of the respondents' feedback towards each design criterion. The table also consists of the percentage comparison of the respondents with or without EX1 experience, and with or without EX2 experience including the percentage results for overall respondents.

For further evaluation on the respondents' level of physical ergonomics awareness, the nine tested design criteria were grouped into four design categories namely working and access space (C1, C2, C8), valves operation (C4, C5), materials handling (C6, C9), and tripping hazards (C3, C7). An analysis of each category highlighted some trends from the respondents' feedback.

Table 4.2: Cross-tabulation of the respondents' perception towards the relevancy of the design criteria in an offshore workplace with the physical ergonomics domain

Design criteria in an offshore workplace	Answer	Experience in engineering design (EX1)		Experience in operation/ maintenance (EX2)		Overall (%)
		Yes (%)	No (%)	Yes (%)	No (%)	
C1: Withdrawal space for filter, membrane and heater elements	*Yes*	93.5	65.2	78.6	84.6	81.5
	No	3.2	-	-	3.8	1.9
	Maybe	3.2	34.8	21.4	11.5	16.7
C2: Personnel access area in front of a control panel	*Yes*	96.8	78.3	89.3	88.5	88.9
	No	-	8.7	7.1	-	3.7
	Maybe	3.2	13.0	3.6	11.5	7.4
C3: Coaming area to avoid hydrocarbon or water spillage	*Yes*	74.2	60.9	71.4	65.4	68.5
	No	9.7	17.4	14.3	11.5	13.0
	Maybe	16.1	21.7	14.3	23.1	18.5
C4: Reserved space for operation of valve's wheel/lever	*Yes*	87.1	87.0	85.7	88.5	87.0
	No	9.7	8.7	10.7	7.7	9.3
	Maybe	3.2	4.3	3.6	3.8	3.7
C5: Location of valves, gauges, or controls is within a reachable parameter	*Yes*	83.9	78.3	78.6	84.6	81.5
	No	9.7	13.0	14.3	7.7	11.1
	Maybe	6.5	8.7	7.1	7.7	7.4
C6: Accessibility of pedestal crane/materials handling facilities	*Yes*	90.3	87.0	89.3	88.5	88.9
	No	-	8.7	7.1	-	3.7
	Maybe	9.7	4.3	3.6	11.5	7.4
C7: Cable/piping routing across an access way	*Yes*	77.4	60.9	71.4	69.2	70.4
	No	16.1	21.7	25.0	11.5	18.5
	Maybe	6.5	17.4	3.6	19.2	11.1
C8: Service platform for reaching and working at height	*Yes*	96.8	82.6	85.7	96.2	90.7
	No	-	8.7	7.1	-	3.7
	Maybe	3.2	8.7	7.1	3.8	5.6
C9: Pulling, lifting and pushing devices for removal of components	*Yes*	83.9	69.6	75.0	80.8	77.8
	No	9.7	13.0	14.3	7.7	11.1
	Maybe	6.5	17.4	10.7	11.5	11.1

In terms of the *working and access space* category as shown by the overall percentage in Table 4.2, over 81.5% of the respondents inferred that the space requirement for personnel access and component withdrawal during maintenance activity were related to the physical ergonomics domain in an offshore workplace. However, high percentages of the respondents without EX1 experience (34.8%) and with EX2 experience (21.4%) were doubtful of the C1 design criteria, by answering *maybe*. These indications did not necessarily mean that the respondents were less aware of physical ergonomics issue, as their feedback for the C2 and C8 design criteria that were also related to the *working and access space* requirements indicated contrasting trends.

In the *valves operation* category, as demonstrated in Table 4.2, more than 81.5% of the respondents believed that placing the valves, gauges, and controls within a reaching parameter and providing space for the operation of valves were associated with the physical ergonomics domain. Generally, there was no noticeable trend of the respondents' perception against the different types of experience. Workers with or without EX1 and EX2 experience indicated the same level of physical ergonomics awareness towards this design category.

The *materials handling system* category is considered a common design factor in an offshore workplace design, in which most of the O&G operators might have an exposure either in the engineering design or operation/maintenance stage. Based on the data analysis in Table 4.2, more than 77.8% of the respondents believed that the C6 and C9 design criteria were associated with the physical ergonomics domain. The percentages comparison between the respondents with or without EX1 experience, and with or without EX2 experience did not show any noticeable trend. Like the *working and access space* category, a higher percentage of the respondents were undecided by answering *maybe,* which might be caused by different contexts of experience that were related to materials handling activities. Furthermore, the respondents' feedback which the materials handling requirement was considered as part of the physical ergonomics issue is supported by the finding from the C1 design criterion.

The last design category was *tripping and slipping hazards.* A hidden obstruction along an access way could be created due to improper design configurations, such as unavailability or insufficient structural coaming with a steel plated floor to avoid liquid spillage that could cause a wet and greasy floor, as well as electrical cables or pipes laying across the access way. These design conditions could indirectly lead to tripping and slipping hazards for offshore operators, consequently increase an injury risk. It is considered as one of the ergonomics issues in a workplace environment and happened frequently in industrial maintenance tasks (Lind & Nenonen, 2008). The slipping and tripping accidents rate would increase with additional human factors in the workplace such as lack of attention and awareness, as well as stress and fatigue among operators after completing their job (BOMEl Ltd, 2002). Despite that, only 68.5% and 70.4% of the respondents believed that the C3 and C7 design criteria were associated with the physical ergonomics domain, respectively. The trends of response showed a slight difference with other design criteria, whereby a lower percentage of the respondents agreed (answer: *yes*), and a higher percentage of the respondents disagreed (answer: *no*) and were undecided (answer: *maybe*). However, the data comparison between different types of experience for the C3 and C7 design criteria was aligned with the other design criteria, which did not indicate any different trend.

In summary, the trends of results as shown in Table 4.2 reflected the respondents' awareness towards the physical ergonomics domain contextually in an offshore workplace. According to the results of data analyses, it supports the statement that the level of physical ergonomics awareness among the Malaysian oil and gas practitioners is at a good level. Besides that, the factor of having different types of experience does not significantly influence the respondents' level of awareness.

4.2.2.2 Effects of physical ergonomics implementation in an offshore processing equipment design

This subsection discusses the results of the respondents' feedback towards the effects of physical ergonomics implementation in an offshore processing equipment design, as summarized in Table 4.3. For all potential effects that were tested in the questionnaire, more than two-thirds of the respondents agreed that the implementation of physical ergonomics could improve working postures of personnel, reducing the risk of physical hazards to personnel, improving operability and maintainability of equipment, and reducing projects cost by avoiding modifications of equipment at a later stage. However, there were negligible percentages of the respondents who disagreed, which were 1.9% for Effect A (*improve working postures of personnel*) and 3.8% for Effect D (r*educe cost by avoiding modification of equipment at a later stage*). The result also explained that the respondents had a good level of physical ergonomics awareness from the perspective of how the ergonomics design could benefit all offshore facilities' stakeholders.

Table 4.3: Scores percentage for the respondents' perception towards the effects of physical ergonomics implementation in an offshore processing equipment design

Effect of physical ergonomics implementation	Percentage (%)				
	1	2	3	4	5
A: Improve working postures of personnel	-	1.9	9.3	33.3	55.6
B: Reduce the risk of physical hazards to personnel	-	-	5.6	25.9	68.5
C: Improve operability and maintainability of equipment	-	-	14.8	33.3	51.9
D: Reduce cost by avoiding modification of equipment at a later stage	-	3.7	18.5	29.6	48.1

*Note: Scores 1 = *Strongly disagree*, 2 = *Disagree*, 3 = *Neutral*, 4 = *Agree*, 5 = *Strongly agree*

Table 4.4: Cross-tabulation of the respondents' perception towards the effects of physical ergonomics implementation in an offshore processing equipment design

Effect of physical ergonomics implementation		Experience in engineering design (EX1)		Experience in operation/ maintenance (EX2)		Overall (%)
		Yes (%)	No (%)	Yes (%)	No (%)	
A: Improve working postures of personnel	*Disagree*	3.2	-	3.6	-	1.9
	Neutral	3.2	17.4	10.7	7.7	9.3
	Agree	38.7	26.1	25.0	42.3	33.3
	Strongly Agree	54.8	56.5	60.7	50.0	55.6
B: Reduce the risk of physical hazards to personnel	*Neutral*	9.7	-	7.1	3.8	5.6
	Agree	19.4	34.8	25.0	26.9	25.9
	Strongly Agree	71.0	65.2	67.9	69.2	68.5
C: Improve operability and maintainability of equipment	*Neutral*	12.9	17.4	10.7	19.2	14.8
	Agree	29.0	39.1	42.9	23.1	33.3
	Strongly Agree	58.1	43.5	46.4	57.7	51.9
D: Reduce cost by avoiding a modification of equipment at later stage	*Disagree*	3.3	4.5	-	8.3	3.7
	Neutral	16.7	22.7	10.7	29.2	18.5
	Agree	30.0	31.8	39.3	20.8	29.6
	Strongly Agree	53.3	45.5	50.0	50.0	48.1

The cross-tabulation results shown in Table 4.4 indicated the percentages comparison between the respondents with or without EX1 experience and with or without EX2 experience. Generally, as illustrated in Figure 4.5, over 77.4% of the respondents believed (*agree* and *strongly agree*) that the ergonomics implementation in design would result in the four tested effects, reflecting most of the respondents were aware of the ergonomics subject and the potential effects of implementation in design. With 88.9% of the respondents agreed on Effect A (*improve working postures of personnel*), the finding supported the fact that integration of ergonomics in an equipment design could influence the working posture, movement, and applying force (Niven & McLeod, 2009). Moreover, an inefficient ergonomics design within a limited and congested working space such as a crane cabin could restrict the visibility during operations, consequently triggering body bending, hip twisting, and neck bending postures for a visibility adjustment (Zunjic et al., 2015).

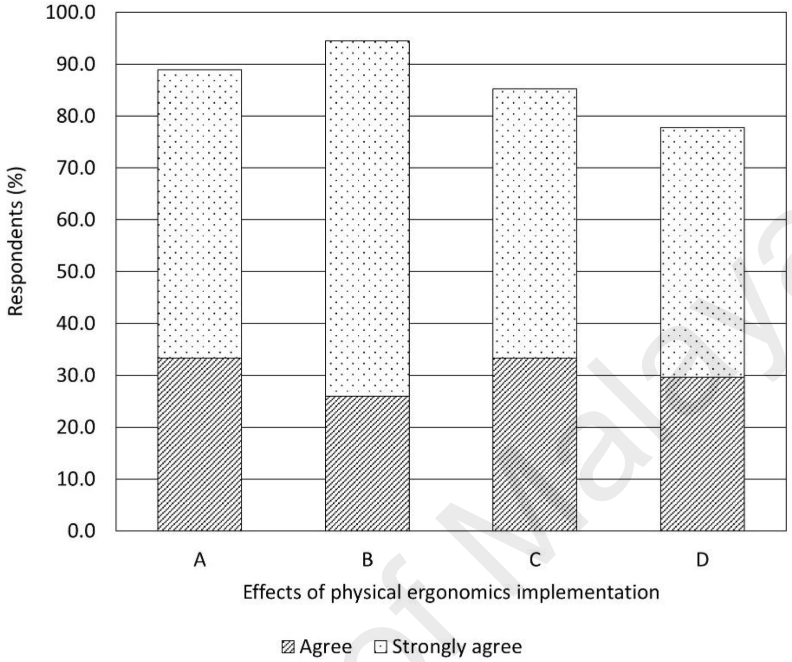

Figure 4.5: Accumulated positive responses of the respondents' perception towards the effects of physical ergonomics implementation in an offshore processing equipment design

Most of the respondents agreed (94.4%) that Effect B (*reduce the risk of physical hazards to personnel*) would be achieved if ergonomics design requirements were considered in a facility design. In industrial maintenance activities, physical hazards that could affect safety and health include heavy lifting, holding weight, work tool design, uneven walking surface, slipping and tripping hazards, and dangerous working procedures (Lind & Nenonen, 2008). These physical ergonomics-related hazards play a significant cause of occupational mishaps and it could be controlled through ergonomics consideration in a workplace design.

Furthermore, a minimum portion of capital expenditure (CAPEX) for integrating the ergonomics program in the engineering design stage would provide a significant life-cycle saving of the operating expenditure (OPEX) of an offshore platform. Modifications at a later stage would need to be considered in OPEX to resolve safety and ergonomics issues which arose during the operation phase (Satrun, 1998). In fact, establishing the ergonomics implementation program during the early design stages would only consume 1% of the engineering cost, rather than during the operational stage which could go higher than 12% of the project cost (Hendrick, 2008). Hence, what most of the respondents (77.4%) believed in Effect D (r*educe cost by avoiding a modification of equipment at a later stage*) corresponds to the cost optimization practice.

Based on the percentages comparison that was presented in Table 4.4, it was found that no noticeable trend between the different types of experience among the respondents. Respondents with or without EX1 experience and respondents with or without EX2 experience showed similar trend of good physical ergonomics awareness.

4.2.3 Physical ergonomics concerns within an offshore processing equipment design

This section discusses the respondents' perception towards the criticality of 17 physical ergonomics issues (PEI) in an offshore processing equipment design. Table 4.5 shows the first quartile (Q1), median, and third quartile (Q3) scores of the criticality rating towards each of the PEI. 10 tested issues had a median of 5 (*very critical*), while another five issues had a median of 4 (*critical*) and two issues had a median of 4.5 (between *very critical* and *critical*). The median score on each ergonomics issue indicated the central tendency of the respondents' opinion, whereby the *very critical* rating was mostly preferred by the respondents. The IQR scores of all the tested issues were 1, while only CE08 indicated a different IQR score which was 1.25. The small IQR scores indicated a consensus among the respondents where all the tested issues were acknowledged as high critical in a processing equipment design.

Table 4.5: Quartiles and interquartile range (IQR) of the respondents' evaluation towards the criticality of physical ergonomics issues in an offshore processing equipment design

Physical ergonomics issue in an offshore processing equipment design	Percentile			IQR
	25th (Q1)	50th (Median)	75th (Q3)	(Q3 - Q1)
CE01: Access platform to monitor pressure gauge, level gauge, controls, etc.	4	4	5	1
CE02: Clear space for inspection and maintenance activities within an equipment	4	5	5	1
CE03: Body posture when completing tasks e.g., manual handling, pulling, pushing, lifting	4	5	5	1
CE04: Trapped within an equipment skid during emergency cases, and require more time to escape due to unclear access way	4	5	5	1
CE05: Stepping on any structure or component to operate critical valves, due to unavailability of a proper access platform	4	5	5	1
CE06: Overhead obstruction exists along access and handling ways which could hit your head	4	5	5	1
CE07: Secondary/alternative escape route within an equipment skid especially for an elevated deck, in case of unexpected blockage along primary escape routes	4	4.5	5	1
CE08: Filling point to any tank (lube oil, diesel, etc.) should be accessible and located at the edge of a tank	3.75	4	5	1.25
CE09: Reaching a valve handle which is located beyond normal height	4	4	5	1
CE10: Standardization of valve's opening and closing direction	4	4	5	1
CE11: Materials handling equipment or lifting beam/pad eye for lifting heavy components	4	5	5	1

Table 4.5: Continued

Physical ergonomics issue in an offshore processing equipment design	Percentile			IQR
	25th (Q1)	50th (Median)	75th (Q3)	(Q3 - Q1)
CE12: Handling route with sufficient dimension and load capacity	4	4	5	1
CE13: Withdrawal space for filters or heater bundles removal	4	4.5	5	1
CE14: Tripping accident along an access way due to poor arrangement of components on the floor	4	5	5	1
CE15: Sharp edge exists within an equipment which could harm your body	4	5	5	1
CE16: Thermal insulation on the hot or cold surface e.g., pipeline, heater, etc.	4	5	5	1
CE17: Location of emergency and safety devices (e.g., safety shower, eyewash, first aid) are adjacent to a potential source of hazard/equipment	4	5	5	1

*Note: Score 1 = *Not critical at all*, 2 = *Less critical*, 3 = *Neutral*, 4 = *Critical*, 5 = *Very critical*.

Table 4.6: Cross-tabulation of the respondents' evaluation towards the criticality of physical ergonomics issues in an offshore processing equipment design

Physical ergonomics issue in an offshore processing equipment design	Answer	Experience in engineering design (EX1)		Experience in operation/ maintenance (EX2)		Overall (%)
		Yes (%)	No (%)	Yes (%)	No (%)	
CE01: Access platform to monitor pressure gauge, level gauge, controls, etc.	*Less critical*	6.5	0.0	7.1	0.0	3.7
	Neutral	9.7	21.7	10.7	19.2	14.8
	Critical	48.4	26.1	32.1	46.2	38.9
	Very critical	35.5	52.2	50.0	34.6	42.6
CE02: Clear space for inspection and maintenance activities within an equipment	*Neutral*	9.7	13.0	7.1	15.4	11.1
	Critical	32.3	30.4	35.7	26.9	31.5
	Very critical	58.1	56.5	57.1	57.7	57.4
CE03: Body posture when completing tasks e.g. manual handling, pulling, pushing, lifting	*Less critical*	3.3	0.0	3.6	0.0	1.9
	Neutral	10.0	8.7	3.6	16.0	9.4
	Critical	33.3	17.4	21.4	32.0	26.4
	Very critical	53.3	73.9	71.4	52.0	62.3
CE04: Trapped within an equipment skid during emergency cases, and require more time to escape due to unclear access way	*Less critical*	3.2	0.0	3.6	0.0	1.9
	Neutral	6.5	13.0	7.1	11.5	9.3
	Critical	25.8	21.7	28.6	19.2	24.1
	Very critical	64.5	65.2	60.7	69.2	64.8
CE05: Stepping on any structure or component to operate critical valves, due to unavailability of proper access platform	*Neutral*	16.1	13.0	7.1	23.1	14.8
	Critical	25.8	34.8	35.7	23.1	29.6
	Very critical	58.1	52.2	57.1	53.8	55.6

Table 4.6: Continued

Physical ergonomics issue in an offshore processing equipment design	Answer	Experience in engineering design (EX1)		Experience in operation/ maintenance (EX2)		Overall (%)
		Yes (%)	No (%)	Yes (%)	No (%)	
CE06: Overhead obstruction exists along access and handling ways which could hit your head	*Less critical*	0.0	4.3	0.0	4.2	1.9
	Neutral	13.8	17.4	14.3	16.7	15.4
	Critical	31.0	17.4	21.4	29.2	25.0
	Very critical	55.2	60.9	64.3	50.0	57.7
CE07: Secondary/alternative escape route within an equipment skid especially for an elevated deck, in case of unexpected blockage along primary escape routes	*Less critical*	3.2	0.0	3.6	0.0	1.9
	Neutral	12.9	17.4	7.1	23.1	14.8
	Critical	38.7	26.1	25.0	42.3	33.3
	Very critical	45.2	56.5	64.3	34.6	50.0
CE08: Filling point to any tank (lube oil, diesel, etc.) should be accessible and located at the edge of a tank	*Less critical*	3.2	0.0	0.0	3.8	1.9
	Neutral	16.1	30.4	21.4	23.1	22.2
	Critical	51.6	43.5	46.4	50.0	48.1
	Very critical	29.0	26.1	32.1	23.1	27.8
CE09: Reaching a valve handle which is located beyond the normal height	*Neutral*	12.9	17.4	17.9	11.5	14.8
	Critical	41.9	34.8	39.3	38.5	38.9
	Very critical	45.2	47.8	42.9	50.0	46.3
CE10: Standardization of valve's opening and closing direction	*Less critical*	3.2	0.0	3.6	0.0	1.9
	Neutral	12.9	21.7	17.9	15.4	16.7
	Critical	41.9	21.7	25.0	42.3	33.3
	Very critical	41.9	56.5	53.6	42.3	48.1

Table 4.6: Continued

Physical ergonomics issue in an offshore processing equipment design	Answer	Experience in engineering design (EX1)		Experience in operation/ maintenance (EX2)		Overall (%)
		Yes (%)	No (%)	Yes (%)	No (%)	
CE11: Materials handling equipment or lifting beam/pad eye for lifting heavy components	*Less critical*	3.3	0.0	0.0	4.0	1.9
	Neutral	6.7	13.0	10.7	8.0	9.4
	Critical	30.0	21.7	21.4	32.0	26.4
	Very critical	60.0	65.2	67.9	56.0	62.3
CE12: Handling route with sufficient dimension and load capacity	*Neutral*	12.9	21.7	17.9	15.4	16.7
	Critical	38.7	30.4	32.1	38.5	35.2
	Very critical	48.4	47.8	50.0	46.2	48.1
CE13: Withdrawal space for filters or heater bundles removal	*Neutral*	19.4	13.0	17.9	15.4	16.7
	Critical	25.8	43.5	35.7	30.8	33.3
	Very critical	54.8	43.5	46.4	53.8	50.0
CE14: Tripping accident along an access way due to a poor arrangement of components on the floor	*Less critical*	6.5	4.3	3.6	7.7	5.6
	Neutral	9.7	13.0	10.7	11.5	11.1
	Critical	29.0	34.8	28.6	34.6	31.5
	Very critical	54.8	47.8	57.1	46.2	51.9
CE15: Sharp edge exists within an equipment which could harm your body	*Neutral*	9.7	8.7	10.7	7.7	9.3
	Critical	25.8	34.8	25.0	34.6	29.6
	Very critical	64.5	56.5	64.3	57.7	61.1

Table 4.6: Continued

Physical ergonomics issue in an offshore processing equipment design	Answer	Experience in engineering design (EX1)		Experience in operation/ maintenance (EX2)		Overall (%)
		Yes (%)	No (%)	Yes (%)	No (%)	
CE16: Thermal insulation on the hot or cold surface e.g., pipeline, heater, etc.	*Neutral*	9.7	13.0	3.6	19.2	11.1
	Critical	29.0	30.4	32.1	26.9	29.6
	Very critical	61.3	56.5	64.3	53.8	59.3
CE17: Location of emergency and safety devices (e.g., safety shower, eyewash, first aid) are adjacent to a potential source of hazard/ equipment	*Neutral*	9.7	8.7	7.1	11.5	9.3
	Critical	32.3	30.4	32.1	30.8	31.5
	Very critical	58.1	60.9	60.7	57.7	59.3

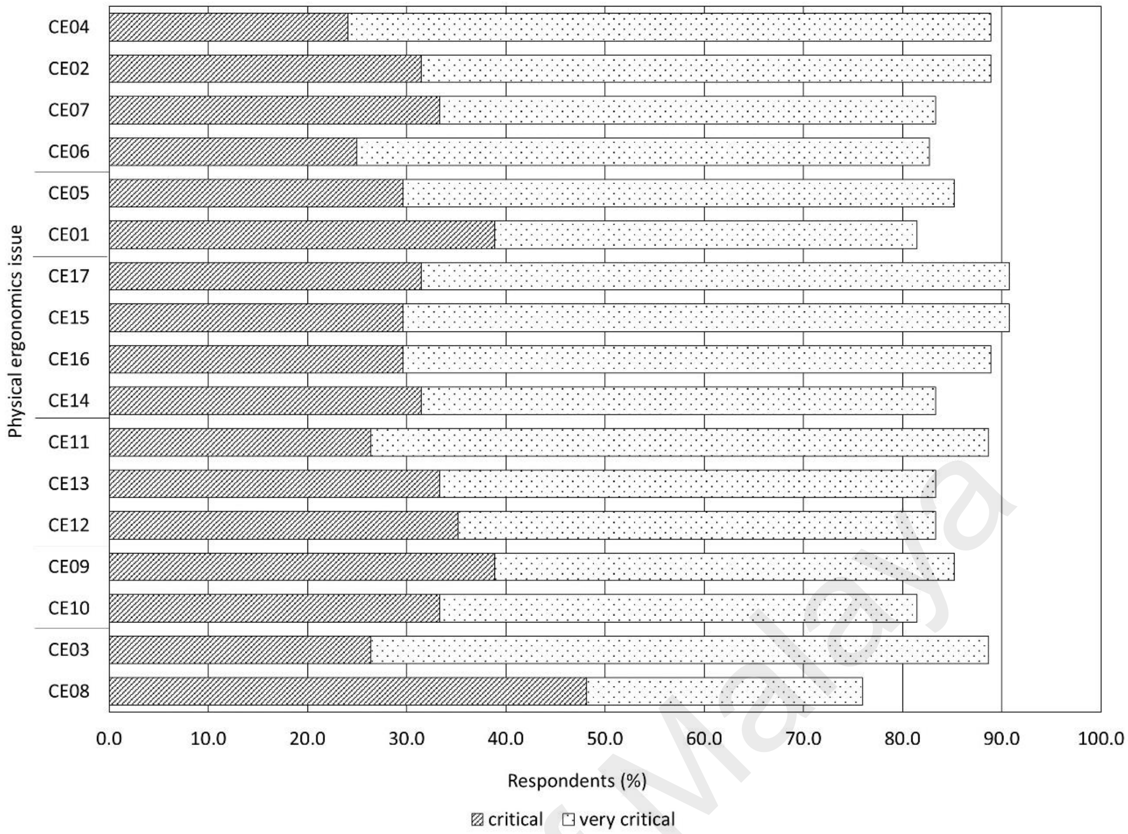

Figure 4.6: Accumulated positive responses of the respondents' evaluation towards the criticality of physical ergonomics issues - sorted by categories of design criteria

Further data exploration through a cross-tabulation method is presented in Table 4.6. The cross-tabulation consisted of the overall percentage of the respondents as well as the percentage comparison among the four types of experience; with or without EX1 and with or without EX2. From the overall outlook, more than 75.9% of the respondents believed that all of the tested physical ergonomics issues were critical in a processing equipment design, with negligible percentages of *less critical* rating were recorded for certain ergonomics issues. Note that a magnitude value of response between *critical* and *very critical* or between *less critical* and *not critical at all* could not be measured literally, given that the ordinal scale data were influenced by an individual's interpretation and approach in expressing their subjective perception, apart from the contextual experience faced by the individual. Therefore, the positive evaluation response which referred to *critical* and *very critical* ratings were accumulated and illustrated in Figure 4.6. According to the graph, the trends of criticality rating for all issues were aligned with the IQR scores which indicated a consensus among most of the respondents.

To simplify an understanding of the results, the 17 physical ergonomics issues in Figure 4.6 were classified and sorted into six categories according to common design criteria in an offshore workplace, namely workspace and access way (CE02, CE04, CE06, CE07), working at height (CE01, CE05), worker safety (CE14, CE15, CE16, CE17), materials handling system (CE11, CE12, CE13), controls and valves (CE09, CE10), and body posture (CE03, CE08).

The *workspace and access way* category is part of the design-induced error which contributes to human error in operational activities (Thomas et al., 2002). A worker would interact with a workspace design with specific characteristics, capabilities, and limitations where a human error could possibly occur if operability and maintainability factors are not considered in a workplace or equipment design. The high percentage of criticality ratings shown in Table 4.6 where 82.7% to 88.9% of the respondents believed that the workspace design issues were critical, conveying their concern in a processing equipment design. A frequent direct interaction between workers and offshore workplace or access area might hone the criticality awareness and become a crucial requirement for ergonomics compliance in the design.

There were two ergonomics issues related to the *working at height* category, mainly involving access to highly mounted valves, controls, sampling points, or monitoring gauges. Over 81.5% of the respondents believed that both issues were critical in a processing equipment design. Similar issue occurred in the *controls and valves* category, where vertical and horizontal reaching parameters were also considered as critical, as demonstrated by 85.2% of the respondents (refer to CE09 in Table 4.6). The valve accessibility factor indicated the most critical concern among other physical ergonomics issues within the oil and gas facility, where the identical problem was assessed in an onshore refinery plant design. According to Passero et al. (2012), 62% of all ergonomics requirements that were identified within the five production units were related to valves or blockages accessibility. Apart from the valve accessibility issue, workers might also deal with various types, functions, and sizes of valves within a congested offshore facility area. A series of valves position and operating direction (opening and closing) should be synchronized for mitigating a human error. Any inevitable odd valve's operating direction should be installed with a visible instruction label for operators' awareness (ABS, 2013). The operating method of hand wheel valves could also affect the operator's comforts and operational efficiency, as explained by Aghazadeh et al. (2012). These design requirements underscore the criticality of controls and valves design configuration and in line with what most of the respondents were inclined with the CE10 variable.

Integration of *materials handling system* in an offshore workplace is necessary to accommodate human limitations during handling heavy loads from one point to another. Handling of maintenance components with excessive load and size would require dedicated lifting, pushing, pulling, or transportation aid, including the facility layout configuration that complements the handling space and load-bearing capacity along the handling route. The concern was expressed by more than 83.3% of the respondents by acknowledging the *critical* and *very critical* ratings to the CE11, CE12, and CE13. Furthermore, the system should ensure the handling route is obstacles free which could damage an asset, affect the operability of materials handling system, and trigger a tripping hazard especially during performing a manual handling task. Azevedo et al. (2014) found that the heavier the load of manual handling, the higher the risk of falling incident while carrying the load through floor obstacles. In an offshore processing equipment design case, there is a possibility of overlooking the maintenance requirements during the equipment design stages. Consequently, it results in poor accessibility within and surrounding area of the equipment, at the same time operators are exposed to ergonomics-related risk while executing the material handling task within the equipment (Lind & Nenonen, 2008).

Four *worker safety* related issues which identified as CE14, CE15, CE16, and CE17 were rated as high critical issue within a processing equipment design. Among them, two issues could be considered as the direct causes of operator injury encompassing sharp edge on equipment design (CE15) and the direct contact with extremely hot or cold surface (CE16). Data analysis demonstrated that 90.7% and 88.9% of the respondents rated these as high critical issues, respectively. It was noticed that a lower percentage of the respondents (83.4%) rated the CE14 as a critical issue, with 5.6% of them considered *less critical.* Even though the percentage was still relatively high among the others, this finding could support the premise that improper design conditions at the workplace could indirectly trigger the ergonomics hazard towards workers. Hence, some of the workers might not aware of this hazard, as previously elaborated in Section 4.2.2.1 under the *tripping and slipping hazards* category.

Other than emphasizing the criticality rating of the tested ergonomics issues, the findings also reflected the respondents' good level of physical ergonomics awareness in an offshore workplace design. Since every physical ergonomics issue has its own distinctive requirement and design effect, the different percentages of the criticality ratings as shown in Figure 4.6 did not necessarily represent the priority nor criticality sequence of the issues. Moreover, the cross-tabulation presented in Table 4.6 proved that the comparison between the two types of experience did not demonstrate any noticeable trend among the criticality ratings. This evidence supported a statement that different types of experience do not necessarily influence the respondents' criticality rating evaluation and their concern on the subject matter.

4.2.4 Correlation analysis between the range of experience and the respondents' perception

In this section, the respondent's perception towards the relevancy of the design criteria in an offshore workplace with the physical ergonomics domain (Test 1) were examined, including the effects of physical ergonomics implementation in an offshore processing equipment design (Test 2) and the criticality of physical ergonomics issues in an offshore processing equipment design (Test 3).

The *Test 1* analysis found that the C3 design criterion (*coaming area to avoid hydrocarbon or water spillage*) resulted in the largest correlation coefficient, which was 0.286. However, Cohen's rule of thumb interpreted this value as a small effect size (Cohen, 2003), whereby the evidence was not strong enough to justify the correlation. A correlation coefficient for the other design criteria recorded insignificant values, thus justified a statement that the respondents' perception towards the design criteria did not correlate with the respondents' range of experience. Sig. (2 tailed) values for each tested design criterion indicated that the probability values (ρ) were larger than 0.05, except for C3 design criterion which was 0.036). These indications provided enough evidence to accept H_0 for the related design criteria, which meant the respondents' perception towards the tested variables did not correspond with the respondents' range of experience in an offshore platform. However, H_0 was rejected only for C3.

For *Test 2,* Effect A (*improve working postures of personnel*) showed the largest correlation coefficient which was 0.269. However, this could be interpreted as a small effect size, whereby the evidence was not strong enough to justify the correlation. The correlation coefficient values for the other tested effects indicated lower values, demonstrating that no correlation occurred between both variables. Furthermore, Sig. (2 tailed) values indicated that ρ for all variables were larger than 0.05, except for Effect A (*improve working postures of personnel*). These indications provided enough evidence to accept H_0 for Effects B, C, and D, which meant that the respondents' perception did not correlate with the respondents' range of experience. For Effect A (*improve working postures of personnel*), however ρ was 0.049, hence H_0 was rejected.

In *Test 3,* from the Spearman's rho test, physical ergonomics issue CE15 (*sharp edge exists within the equipment which could harm your body*) indicated the largest correlation coefficient which was 0.311. According to Cohen's rule of thumb, this value showed a medium effect size of the correlation between the tested variables. Correlation coefficients for the other physical ergonomics issues indicated below 0.3, which reflected the small correlations between the tested variables. Sig. (2-tailed) values for all variables were larger than the significant level at 0.05, except for CE15. Thus, there was enough evidence to accept H_0 for the other physical ergonomics issues, which meant that the respondents' perception of this variable did not correlate with the range of experience factor. For CE15, however ρ was 0.022, hence H_0 was rejected.

The correlation tables for all the correlation tests can be referred in Appendix B.

4.3 Classifying maintenance tasks of offshore processing equipment

This section discusses the result of Hierarchical Task Analysis (HTA) for the case studies, where the results provide an understanding on types of maintenance components that are commonly available in an offshore processing equipment. The findings also include common tasks and subtasks for maintenance activities of the equipment. Basically, the findings of Part 2 would prepare a basis for pursuing the methodology Part 3 of this study.

4.3.1 Hierarchical Task Analysis (HTA)

Through the HTA of the three case studies (labelled as S1, S2, and S3), eight main maintenance components were identified, containing 43 main tasks and 145 subtasks, as summarized in Table 4.7. Detail HTA findings for the components were illustrated in a flowchart form and the overall HTA results could be referred in Appendix C. The physical tasks level was assessed up to the second level only as this smallest task unit would sufficiently explain the requirement of physical tasks for each maintenance component. Generally, an offshore processing equipment comprises common components that complement its processing design requirement such as heating, cooling, filtering, coalescing, tank storage, mixing, drying, and separating systems. In this analysis, the eight maintenance components were categorized into filtering, membrane, heating, and vessel component groups. The same categories of component might be available in other offshore processing equipment too, but it might differ in terms of design capacity, processing medium (e.g. gas, oil, water, and chemicals), size, weight, installation method, and skid layout arrangement. Identical components might possibly involve similar physical tasks, consequently would trigger similar physical ergonomics issues during its maintenance activity, as shown in the following results.

There were similar types of component in the same case study identified from HTA exercise. For instance, a pre-heater and super-heater of Fuel Gas Package, as well as an air pre-filter and after-filter of Nitrogen Generation Package, were combined into the same component due to the similarities in design configuration.

As shown in Table 4.7, four common maintenance components that were extracted from the case studies—filtering, heating, membrane, and vessel—were established. The filtering component combined the fuel gas filter separator (S1), air dryer pre-filter and after-filter (S2), and coarse/fine coalescer filter (S3). The heating component combined the nitrogen generation pre-heater (S3) and fuel gas pre-heater/super-heater (S1). The membrane component only consisted of the nitrogen membrane modules (S3), while the vessel component combined the air dryer desiccant (S2) and KO drum (S1).

Table 4.7: Hierarchical Task Analysis results

Case study	Description	Maintenance component	Component category	Main task	Sub-task
S1	Fuel Gas Package	Filter separator	Filtering	6	22
		Pre-heater / super-heater	Heating	7	18
		KO Drum (demister)	Vessel	6	25
S2	Air Dryer Package	Air pre-filter /after-filter	Filtering	7	20
		Air Dryer (desiccant)	Vessel	4	13
S3	Nitrogen Generation Package	Coarse / fine coalescer filter	Filtering	4	15
		Pre-heater	Heating	4	17
		Membrane module	Membrane	5	15
Total		8	4	43	145

4.3.1.1 Filtering component

Based on the physical task steps needed for the maintenance of filter separator (S1), air pre-filter/after-filter (S2), and coarse/fine coalescer filter (S3), two common major tasks were identified for the filtering component. Firstly, *taking out a filter element* task which referred to the subtask 1.4.2 (S1), subtask 1.3.2 (S2), and subtask 1.3.1 (S3). Secondly, *installing a new filter element* task which referred to the subtask 1.4.3 (S1), subtask 1.5.2 (S2), and subtask 1.3.2 (S3). However, different equipment configurations might be distinguished by the processing capacity of equipment which determined dissimilar length, height, or weight of the filter element, filter vessel mounting elevation, and also vessel orientation. Normally, these criteria would stipulate handling approaches in terms of withdrawal mechanism and direction. For example, an upward removal type was designed for the S1 case while a downward removal for the S2 and S3 cases, and possibly a horizontal removal type for other cases. A 2D sketch overview of typical filtering component is illustrated in Figure 4.7.

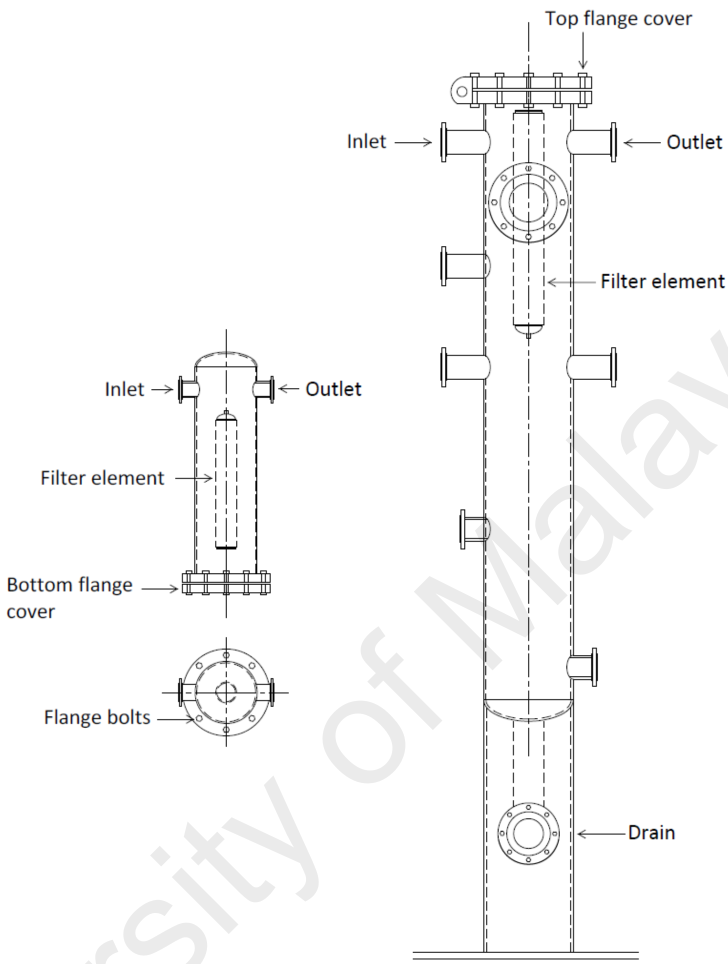

Figure 4.7: Typical 2D sketch of a filtering component: bottom flange type (left) and top flange type (right)

4.3.1.2 Heating component

The HTA exercise for the maintenance of heating components which were pre-heater/super-heater (S1) and pre-heater (S2) resulted in three common major tasks. Firstly, *pulling out a heater bundle* task which referred to the subtask 2.3.2 (S1) and subtask 2.2.2 (S3). Secondly, *transferring a heater bundle* task which involved the subtask 2.4.2 (S1) and subtask 2.3.2 (S3), while the third task was *inserting a heater bundle into its housing* which referred to the subtask 2.5.3 (S1) and subtask 2.4.4 (S3).

The design configuration and handling procedure of heating component might differ according to its design capacity which would determine its length, diameter, and weight, as well as mounting location and elevation within a processing equipment skid. An overview of a typical filtering component is illustrated in Figure 4.8.

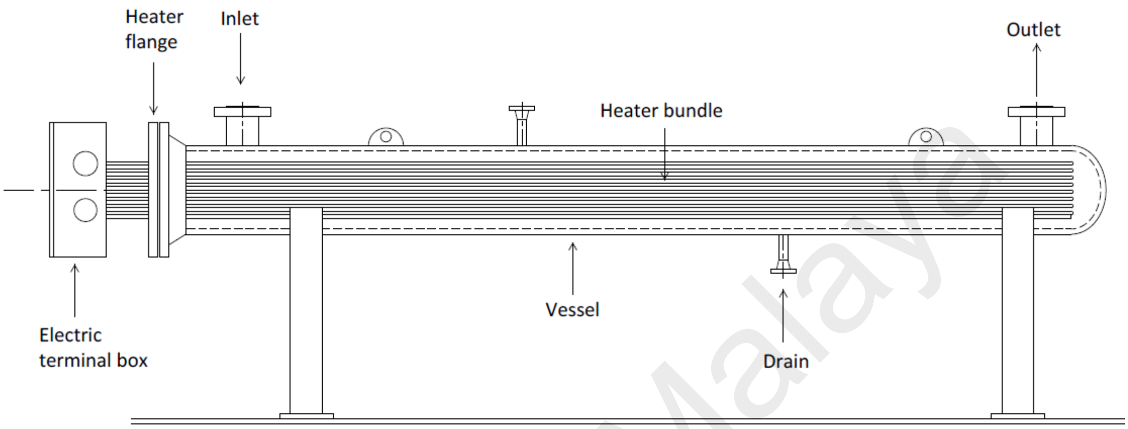

Figure 4.8: Typical 2D sketch of a heating component (side view)

4.3.1.3 Membrane component

The HTA exercise for the maintenance of membrane component comprising membrane modules of the S3 case study resulted in two major tasks. Firstly, *pulling out a membrane module* task which referred to the subtask 3.3.1 (S3) while the second task was *inserting a membrane module into membrane housing* which referred to the subtask 3.3.5 (S3). The physical tasks involved a repetitive operation as the membrane system might consist of a series of membrane housings that containing several membrane modules, severally. Other concerns that were assessed through the task analysis including the length and weight of each membrane module, mounting elevation from a working surface, and the membrane system arrangement such as the number of modules installed in a series of membrane housings. A 2D sketch overview of typical membrane component is illustrated in Figure 4.9.

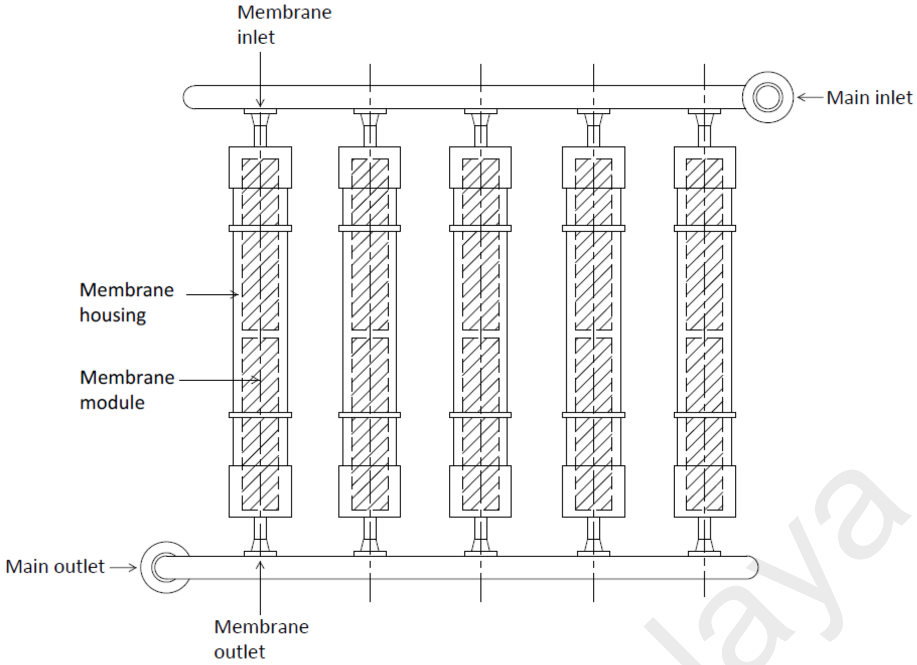

Figure 4.9: Typical 2D sketch of a membrane component (plan view)

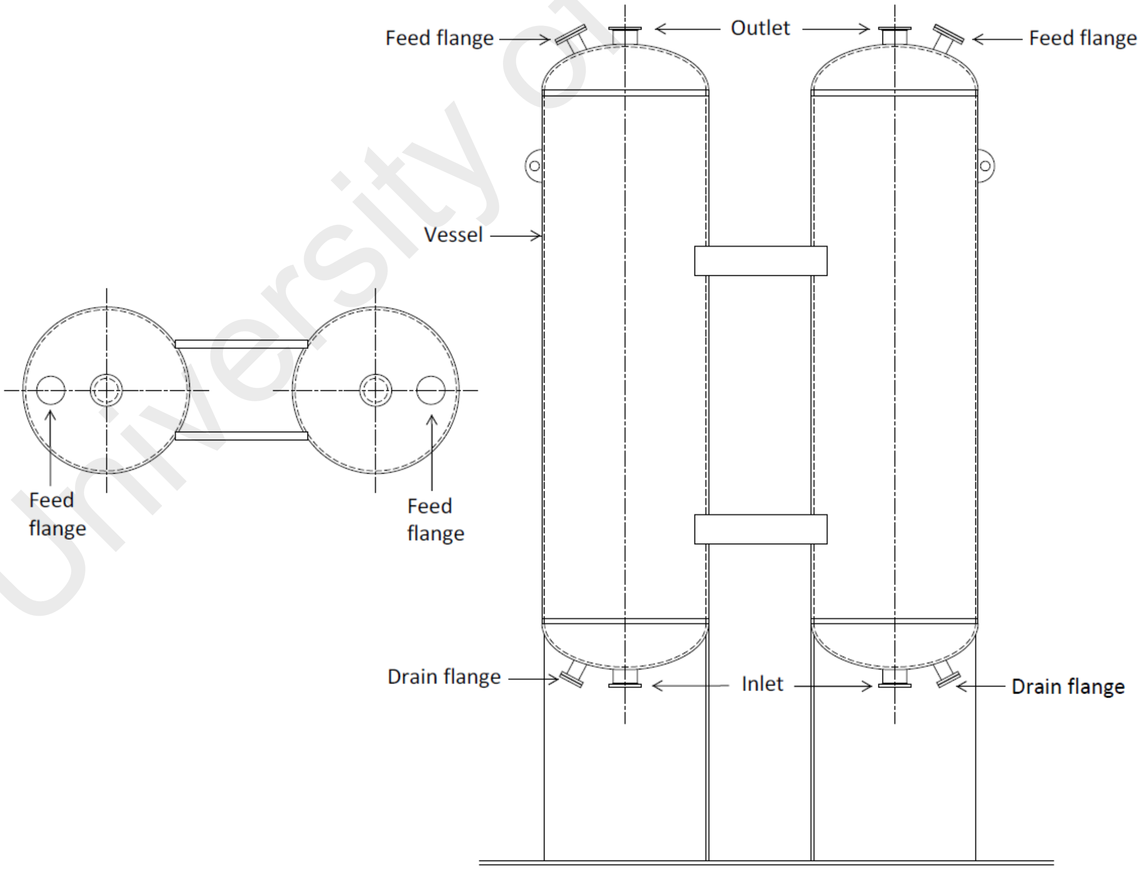

Figure 4.10: Typical 2D sketch of a filling medium type vessel: plan view (left) and side view (right)

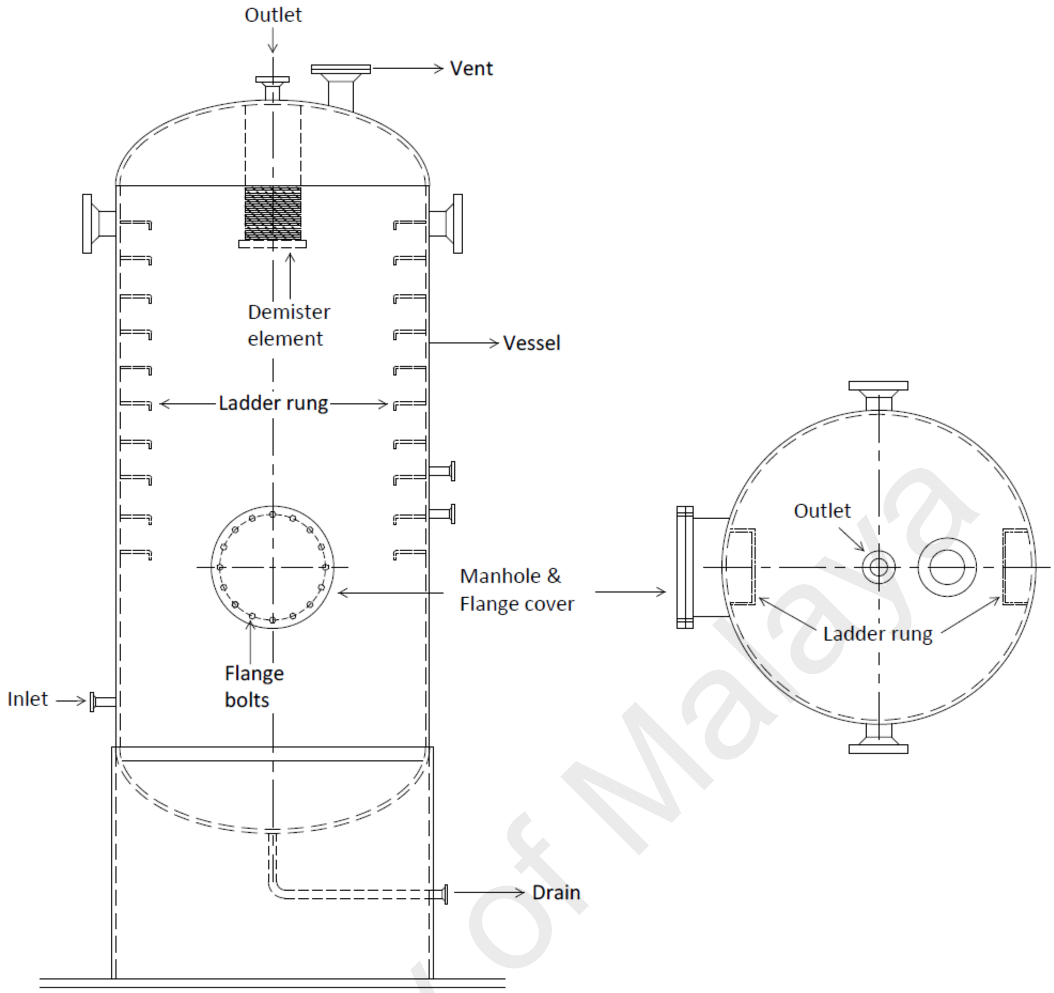

Figure 4.11: Typical 2D sketch of an empty container type vessel: side view (left) and plan view (right)

4.3.1.4 Vessel component

The HTA exercise for vessel components which were KO drum (S1) and desiccant vessel (S2) resulted in three major tasks. Nevertheless, both vessel components from the S1 and S2 case studies served different processing purposes. The KO drum was a pressurized empty container and equipped with demister element for removing liquid droplets from the fuel gas stream, while the desiccant vessel was a pressurized vessel that containing filling medium which allowed compressed air to pass the desiccant medium for drying purpose. A minimum overlapping physical task was identified from the two components with most of the tasks being non- identical. Hence, three major physical tasks were established: *removing internal parts* (subtask 3.4.2 of S1), *installing internal parts* (subtask 3.4.3 of S1), and *loading a filling medium bags into feed flange* (subtask 2.3.5 of S2). A few concerns that might differentiate one vessel to another would be the vessel height and diameter that could affect a manhole necessity and feed flange elevation, dimensions and weight of internal parts, and weight of filling media bag. For clarity, 2D sketches of both typical types of vessel component are illustrated in Figure 4.10 and Figure 4.11, respectively.

4.4 Assessing physical ergonomics issues and its consequences

This section describes the results of methodology Part 3 where industry experts were engaged to assess the potential physical ergonomics issues on each physical task of maintenance components. The consolidated data from the five respondents' feedback towards the physical ergonomics issues (PEI) are shown in Table 4.8 (filtering component), Table 4.9 (heating component), Table 4.10 (membrane component), and Table 4.11 (vessel component). Besides the 1–5 scores that reflected the number of respondents' acknowledgement on the PEI against each physical task, additional inputs from the respondents were also recorded. Duplicated additional inputs with the 15 predetermined PEI were filtered out and inputs with a similar context were merged to form a list of additional ergonomics issues that were related to relevant tasks. Subsequently, the data was incorporated into the same PEI Matrix of each maintenance component.

Generally, a score of 1 to 2 towards each PEI was interpreted as a *low likelihood* while a score of more than 2 to 5 was understood as a *high likelihood*, which the particular PEI was considered as repetitively exposed to or experienced by more than two respondents. Despite this, both likelihood classifications were evenly considered in assessing the design consequences and suggesting mitigation plans, to ensure the comprehensiveness of the intended design guidelines. The following sections summarize the results of the analysis for each maintenance component.

4.4.1 PEI Matrix of the filtering component

The consolidated tasks of the filtering components resulted in eight common tasks that might be involved in maintaining filter elements, as shown in Table 4.8. The distributions of high likelihood scores were related to the needs of access space for personnel (PEI-3), including an access platform for working at high elevation (PEI-1) and a withdrawal space for filter removal (PEI-4). The body posture issue that involved slightly flexed forward position (PEI-10), and twisting and forceful hand movements (PEI-11) when completing the tasks were also recorded. These ergonomics issues were mainly applicable for the two major physical tasks involved in maintaining a filtering component which had been discussed in Section 4.3.1.1.

4.4.2 PEI Matrix of the heating component

The consolidated tasks of the heating components resulted in five common tasks that might be involved in maintaining heater bundle elements. According to the trend comprising high likelihood scores, as shown in Table 4.9, seven PEI were acknowledged as pertinent to the three major physical tasks for maintaining a heating component that was previously elaborated in Section 4.3.1.2. These included an access space for personnel (PEI-3), withdrawal space for a tube bundle removal (PEI-4), the requirement of permanent or temporary materials handling equipment for handling loads, as well as reserved space to operate the equipment (PEI-6). In terms of body movement, an operator had a high probability to be involved in repetitive pulling or pushing operation within a short time and beyond the forearm length (PEI-9), slightly flexed forward body posture (PEI-10), forceful hand movement (PEI-11), and demand on a visual activity during the installation of heater bundle into its housing vessel (PEI-14).

4.4.3 PEI Matrix of the membrane component

As opposed to filtering and membrane components, there was no consolidated task for the membrane component as the PEI inputs were obtained from one case study only. Hence, the number of physical tasks remained four. The trend of high likelihood scores in Table 4.10 showed a scattered distribution. However, noteworthy ergonomics issues could be focused on the two major physical tasks as discussed in Section 4.3.1.3, namely *removing of membrane modules* and *installation of membrane modules* repetitively. The acknowledged PEI that would potentially occurred during membrane modules replacement were an access space for personnel (PEI-3) and withdrawal space for membrane modules removal (PEI-4). The requirement of an effective holding area design on a membrane element (PEI-7) was also raised by the respondents. In terms of body movement, an operator might be involved in repetitive lifting or handling operation within a short time, and lifting or handling beyond the forearm length (PEI-8), repetitive pulling or pushing operation within a short time, and pulling or pushing operation beyond the forearm length (PEI-9), slightly flexed forward body posture (PEI-10), as well as twisting and forceful hand movements (PEI-11).

4.4.4 PEI Matrix of the vessel component

The consolidated tasks of the vessel components did not present a common tasks list because of dissimilar function of the components as discussed in Section 4.3.1.4, except for the *vessel isolation* task at the earlier maintenance procedure. The scores of each maintenance task against the PEI were presented in Table 4.11. Three major tasks that should receive more attention for this maintenance component were *removing and installation of internal parts in a vessel*, as well as *loading filling medium bags into a vessel's feed flange*. These tasks recorded a high likelihood for the following PEI: an access space for operators within a confined vessel (PEI-3) and withdrawal clearance for internal parts (PEI-4). The tasks were also assessed with two potential awkward body postures which were manual handling above the shoulder height (PEI-8) and severely twisted body posture (PEI-10) when assessing a ladder rung simultaneously handling a demister pad from its overhead mounting location. The specific issue with regards to this task that also concerned the respondents was confined space entry into a vessel, where extra personal safety devices would be utilized during vessel entry and the requirement of secondary escape means if an emergency event occurs.

The task *of loading a filling medium into the vessel* recorded a high likelihood for the requirement of access platform with an adequate space for operator access and body movement (PEI-1 and PEI-3). Besides that, the task would also involve the risk of repetitive manual lifting within a short time and handling loads beyond the forearm length, subjected to a feed flange mounting location. To reach the feed flange, an operator had a high possibility to be exposed to severely flexed forward body posture (PEI-10).

Table 4.8: Consolidated physical ergonomics issue (PEI) matrix of filtering component

FILTERING COMPONENTS	Consolidated scores																											Additional inputs
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Depressurize the vessel																												
Close inlet valve		1	4										1	1			4				4	5				2	1	Some valves are located behind the vessel; visual, access with bending body, beyond the forearm length.
Close outlet valve		1	4										1	1			4				4	3				2	1	Space of valve's level handling not clashing with others
Open drain plug		1	4										1	1			4				3	3				2	1	Nowadays instrument uses a digital type to receive a signal - erect a scaffolding to check/replace level gauge
Nitrogen purging																												
Connect utility line to UC valve		2	4										1	1		1	3				2	1						
Open UC valve		2	4										1	1		1	3				4	3						
Check HC concentration		2	4														1				1	1						
Close UC valve		2	4										1	1		1	3				4	3						
Open top flange																												
Check pressure ~atm	2	2	4		2	1	2						4	1			2				4	3			1	2		Space for flange opening not obstructing access route
Unbolt top flange	2	1	4		2	1	2	2		2			2	1			3				4	2			1			Bottom entry - to support weight of cover by one hand
Lift top flange	2	1	4		1	1	2	2		3			1	1			4				1	1						Need to remove some pipes to provide space for a filter with sufficient withdrawal length
Place top flange temporarily	2		4			1	1						1	1			3					1						
Remove filter element																												
Unscrew filter element	2		5	3	2	2		2	2	3		3	2	2	1		3	1			4	3	2	1	2			Manual lifting/handling; vertical filter extraction involves high point; above shoulder weight.
Take out filter element	3		5	4	1	2		3	1	5		3	1	2	1		4	2			2	1	2	1	2			Dirty filter, dangerous to personnel
Remove O-ring	1		4		1					1				1			2				1			1				Step ladder/ stool is required to access the top flange
																												Clearance space should consider more length (spare)
																												Too frequent access (i.e. biweekly), repetitive bolting
																												Access platform to filter might be too low or too high - No optimal access, surrounding the filter - Standing on a railing to access (too low platform)
																												Dirt comes out from vessel downwards, drain.
																												A downward filter may require squatting/sitting space
Insert new filter element																												
Install new O-ring	2	1	3	1	1	1	1	1		2				1			3				1			1				Squatting position for a longer time for one personnel during filter change-out; not sufficient space
Insert filter element from opening flange	3	1	5	4	1	1	1	2		4		3	1	1			4	1			2	1		1	1			
Screw filter element into inlet manifold	2	1	5	1	2	1	1	2		4			3	1			3	1			5	4		1	1			
Tighten the filter element using fingers	2	1	3	1	2	1	1	1		1			4	1			2				3	4		1	1			
Close vessel																												
Swing blind flange to close vessel	2	1	4			1	2			3			1	1			4					1						
Install all flange bolts	2	1	4		2	1	1			2			3	1			3				3	4						
Tighten all bolts	2	1	4		2	1	1						4	1			2				5	4						

Table 4.8: Continued

FILTERING COMPONENTS	Consolidated scores																											Additional inputs
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Pressurize vessel																												
Open inlet valve		1	4										1	1			4				4	4				2	1	
Open outlet valve		1	4										1	1			4				4	3				2	1	
Close by-pass valve		1	4										1	1			4				4	4				2	1	
Nitrogen purging																												
Open UC valve		2	4										1	1		1	3				5	2					1	
Check O_2 concentration		2	4														2				1	1				5	1	Should be at eye level for a clear visibility
Close UC valve		2	4										1	1		1	3				5	2					1	The valves might be located at above shoulder level
Remove utility connection		2	4										1	1		1	3				3	3					1	

*Note: A = Activity, D = Design element, HC = Hydrocarbon, UC = Utility connection, O_2 = Oxygen

Table 4.9: Consolidated physical ergonomics issue (PEI) matrix of heating component

HEATING COMPONENT													**Consolidated scores**															**Additional inputs**
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Isolate pre-heater																												
Isolate electrical supply			3		2					2							1					1		1		3		The height of heater should be within the normal personnel height.
Remove terminal enclosure cover		1	5		4					1			2	2			1				1	2		1		1		
Check power supply		1	3		1					1														1		4		
Disconnect cables and busbars		1	3		2					2			1	1			2	1			1	2		1		4		
Remove all bolts		1	5		4.5					2			3	3			3.5	1.5			4	4		1		1		
Remove pre-heater bundle																												
Dismantle terminals		2	5		4	1				1			2	3	2		2	1			2	1		2		3		Manual pulling? If weight is heavy, lifting devices should be provided
Pull out the heater bundle		1	5	5	1.5	4	3	2.5		2.5		1	4.5	2.5			3	2			1	4	1.5	2.5			1	Withdrawal space should be within the skid or outside? Outside is better to save the space. If outside; affect the access/handling or emergency route?
Support the heater weight		1	3			5	3.5	1.5		1		1	2.5	1	1		1.5	1				3	1.5	1				Pull out activity requires extra force
Balance the load horizontally		1	4	3		5	4	2		2			2	2	1		3	2				3	1	1			1	Heater bundle support stand or lifting device is required to assist and support the heater element
Lower down the heater on floor/saddle		1	4	2		3	2	1		1			2	2	1		1					2	2					Aligning the tube bundle on a saddle point
Release weight support		1	2.5	2		2	1.5	1.5		2			2	1	1		1					1	1.5				1	Uneven/different elevation of working space due to the skid frame, cause ergonomic hazards
																												Subsequent pulling operation is manual, depends on weight, condition, elevation of heater bundle
																												Consider space for personnel access
																												If weight is not heavy, A-frame would be sufficient, provide adequate space
																												Sufficient lifting points are required to lift the load
Transfer pre-heater bundle																												
Place heater bundle on trolley			5	1		5	4		1				2	2			4	2.5				3					1	Lifting point on heater element for lifting load during tube bundle removal
Push trolley to dedicated location			5	1		4	4						4	5			2	4				4	1.5				2	Type of trolley should consider the correct practice
Unload the heater bundle from trolley			5	1		4	3		1				2	1			3	1.5				4	1.5				1	Temporary lifting device is required to assist and lift the heater bundle onto a trolley
																												Suitable temporary support/lashing to be provided
																												Depending on trolley and component size, the pathway should be clear
																												Suitable transport equipment; oversize, not enough length to support the tube bundle, handling way turning area, not to damage instrument/electrical devices

Table 4.9: Continued

HEATING COMPONENT	Consolidated scores																											Additional inputs
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Reinstall pre-heater bundle																												
Transfer new heater bundle to its location			4.5	1		3	4			1.5			4	3		1	2	3				4.5	1	1		1	1	Manual trolley is required to transport the heater bundle to dedicated location
Inspect new element (in good condition)						1	1										2	1								2		Temporary lifting device is required to lift and hold the heater bundle
Lift heater up to insertion level		1	4	5		5	4	1		2.5		1	3	4		1	3.5	1			1	3.5	1	1.5		1.5		Alignment of load, pushing load manually
Insert the heater bundle		1	4	5		2	2	1		2.5		1	4	5		1.5	3	3.5			1	2.5	2	1.5		2		Lifting aids are required for handling a heavy equipment
Remove the lifting appliances			4	2		2	1					1	1	1		1	3	2			2	3				1		Pulling with extra force to operate lifting aids
																												Monitor heater element while handling activity
Install flange bolts																												
Make sure both flanges match		1	5		1	1		2	2	1			1	1			2				1	1				1		
Install all bolts			5		2	1		1.5	1.5	1			3	2			2	2			4	4			2	2.5		
Tighten bolts		1	5		4	1		1					3	2			3	2			5	4			2	3		
Connect terminal enclosure cover			4		3			1		2			2				2				1	3				2		
Connect electrical supply			3		2					2							2				1	2				3		

*Note: A = Activity, D = Design element

Table 4.10: Consolidated physical ergonomics issue (PEI) matrix of membrane component

MEMBRANE COMPONENT	**Consolidated scores**																											**Additional inputs**
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Isolate train of membrane																												
Close inlet valve			4							2			3	2			4				5	4				3	1	Valves possibly located beyond the personnel height or obstructed by other pipes - Not easy to access and dismantle for replacement
Close outlet valve			4							2			3	2			4				5	3				3	1	Position of valve level, easy to handle and apply force?
Open depressurize valve			4							2			3	2			4				4	3				3	1	Operator need to go through a long parameter to access the inlet and outlet valves >5 meter
																												The membrane will be closed one by one. Long and repetitive walking distance (different level of decks)
Remove housing connection																												
Remove flange bolts	2	1	5		4			1	1	2	1		4	2	1	1	3	1	1		5	5			1	3		The needs of access platform is depending on vessel height
Take out flange spool	2	1	5		3			1	2	3	1		3	1	1	2	2	1	1		3	3			1	1		
Replace membrane element																												
Pull membrane element		1	5	5		2	2	3	1	3	1		4	4	1	2	4	2				4	1	1				Considered manual handling height at shoulder level, beyond forearm length.
Place membrane element at temporary storage		1	3	2		1	1	2	4	1	1		2		1		4	3				1	2	1				Working space for forceful pulling movement; tripping issue, slipping hazard.
Inspect new element (in good condition)			2					1	2								2	2					1			2		Trolley is required to transfer the elements to a storage area.
Lift new membrane element		1	5	2		1	1	3	4	2	2		2	2	1	1	4	2				1	1	1				Weight of wet membrane elements should be within the allowable manual handling limit
Insert into membrane housing		1	5	5		2	2	3	3	3	2		4	5	1	3	4	2				4	1	1		2		Repetitive task for higher elevation of membranes
																												Using a portable step ladder for repetitive tasks (holding loads, tools, large component)
Reconnect membrane housing																												
Install flange spool	1	1	4		3				2	3			2	2		2	3				1	3				2		Membrane elements weight shall be within the operator handling limit
Install all flange bolts	1	1	4		3				1	3			3	2		1	2				5	5				2	1	
Close depressurize valve			5							2			4	2			4				5	4				2	1	
Open outlet valve			5							2			4	2			4				4	2				2	2	
Open inlet valve	1		5							1			3	2			4				4	2				2	2	

*Note: A = Activity, D = Design element

Table 4.11: Consolidated physical ergonomics issue (PEI) matrix of vessel component

VESSEL COMPONENT	Consolidated scores																											Additional inputs
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Isolate vessel																												
Close inlet valve	2	2	5										1	2	2	1	4				3	4					4	May be located at below vessel
Close outlet valve	2	2	5										1	2	1	1	4				3	3					4	Depending on height of valves (critical valves)
Open blowdown valve	2	1	5										1	1	1		3				3	2						
Open depressurize valves	1	2	5										1	2			5				2	4					4	May be located at the top of vessel
Open drain valve		2	5										1	2	2		5				2	4					4	Drain of liquid/condensate cause wet floor, hydrocarbon substance
Open feed flange																												
Remove all bolts	4		5		4		1						3	2				2			4	4						Design of feed flange (including oil feed) should avoid potential liquid/filling spills (slipping hazards on floor)
Dismantle the blind flange	4		5		2		1						1					1			1	2						
Filling desiccant into vessel																												
Transfer bag from storage area			2			1	1	1	3	1		1	1					1					2				1	Pathway to be provided
Lift desiccant bag onto platform	3	1	3			1	1	2	5	2		3	1				1	1					3				1	- Not suitable for frequent access to transfer filling bags - Space location to store the bags temporarily?
Place desiccant bag on platform	3		3			1	1	1	5	1		2	1				2	1					2				1	Space enough for bags? Space enough only for one personnel to stand
Lift desiccant bag towards feed flange	4	1	5			1	1	2	5	2		3	2	2		2	1	3	1			1	3				1	- Trolley is required to transfer bags to a storage area - Temporary mobile crane is required to lift desiccant bag from ground to platform (suggestion)
Fill desiccant into feed flange	4	1	4			1	1	2	5	4		3	2	2		2	1	4	1			1	3			3		Bending the body while carrying loads to feed the desiccant towards the feed flange
Check the desiccant level	3		4														1						1			5		Checking level according to the height of vessels
																												Desiccant bag designed for manual handling (25 kg)
																												- bending body with load to reach feed flange
Close feed flange																												
Lift blind flange and place to feed flange	2		5		1		1			2			2	2				1			2	2						
Install all bolts	2		3		4		1			1			4	2				1			5	4						
Nitrogen purging																												
Close drain valve		2	5										1	2	1		5				2	4					3	- How to access the vent valve - intermittently - Labelling of valve cause faulty in operation
Connect utility line to UC valve		3	5										1	2	1		5				2	4				1	3	Quick connection for N_2 line
Open UC valve	1	3	5										1	1			4				2	4					3	
Check HC concentration	1	3	5														4					1				5	4	
Close UC valve	1	3	5							1			1	1			4				2	4					4	

Table 4.11: Continued

VESSEL COMPONENT	Consolidated scores																											Additional inputs
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Open manhole cover																												
Open vent valve	5	2	5										1			3	4	2			2	5				2	2	- Valve location is too high from the main floor - Top of the vessel, lack accessibility due to other valves, pipes - High point to access the valve
Check pressure ~atm	3	2	5														2									5	3	Access level to gauge elevation
Unbolt manhole flange	4	2	5		3								3	2		1	2	2			3	4			4	1	1	- Step ladder/stool is required to access the manhole cover - Temporary mobile crane is required to lift the manhole flange - Bolting work in squatting position - Suggest using a hydraulic tool for tightening bolts - These activities involve tools, require access platform if the elevation is high
Lift manhole flange (if required)	4	1	5	2		3	4	2					1	1			2	1				3			1			- Temporary mobile crane is required to lift the manhole flange - Suggest using a davit to support manhole cover - High elevation of the manhole, use a permanent device to support the manhole cover (heavy load) - Extra space is required to open the cover
																												Man entry - Space in front of the manhole (squatting/standing) - Space during escaping from the manhole is not sufficient - Confined space condition
Store manhole flange temporarily (if required)	1		5			3	4	2									1	2				1						- Opening of manhole might clash with pipe/ handrail/worker
Replace demister element																												
Unscrew support flat bar	4	2	5		5					2		2		1		2	1		2		4	5	1		2	2		- Man entry; the size of manhole should consider for coverall, hat, breathing apparatus (BA) - if required - Hold body load at ladder/rung during working in the vessel - Confined space in the vessel - escape during an emergency event - Access from a ladder inside the vessel - holding points?
Remove demister pad	3	1	4	4		1	3	3		3		4		1		1	1		3	2	1	1	1		3	2		- Suggest using a manual chain block to assist and remove a demister pad inside the vessel - Design for manual handling by one person in the vessel - Demister mounting elevation is too high, away from a ladder - Working at height inside the vessel - The weight of demister is beyond the manual handling limit
Insert demister into holder	3	1	4	4		1	3	3		3		4		1		1	1		3	2	1	1	1		3	2		- Suggest using manual chain block required to assist and insert the demister pad inside the vessel - Body posture when handling a demister (carrying load) from a ladder - Space constraint for MH equipment/ hand tool
Screw support flat bar	3	1	4		3					2		2	2	1		2	1		2		4	5	1		2	2		- Normally use bolting tool (powered) for a high-pressure manhole cover, failure in bolting connection
Close manhole flange																												
Lift the manhole flange (if required)	4	1	5			3	4						1	1			2	1				3			1			*Same issues as open manhole flange activity
Bolt the manhole flange	3	2	5		3								2	2			2	2			3	4			4			

Table 4.11: Continued

VESSEL COMPONENT	Consolidated scores																											Additional inputs
Potential Ergonomic Issues / Consolidated tasks	D	A	D	D	D	D	D	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	D	A	D	
	1	2	3	4	5	6.1	6.2	7	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	10.3	10.4	11.1	11.2	11.3	12	13	14	15	
Nitrogen purging																												
Open UC valve	1	3	5							1			1			1	3				1	5					3	
Check residual O_2 level	3	3	5														4									5	3	- Display level of O_2 gauge is not clear - Level gauge uses a digital meter - Display panel/view is not accessible
Close vent valve	3	3	5							1			1			3	4				1	5				1	3	Access platform within skid to access high points
Close UC valve	1	3	5							1			1			1	3				1	5					4	

*Note: A = Activity, D = Design element, HC = Hydrocarbon, UC = Utility connection, O_2 = Oxygen

4.5 Discussion

This section has discussed all findings from Part 1, Part 2, and Part 3 that completely answering the first research question of this study. The research question inquired about what were the concerns of Malaysian oil and gas operators and operational tasks that influenced the physical ergonomics requirements towards an offshore processing equipment design.

In the Part 1 study, a descriptive statistics exploration of the data from the questionnaire survey found that generally, the physical ergonomics awareness among the sample population shows a relatively good level. This indication reflected the ability of the respondents to identify the design criteria in an offshore workplace that related to physical ergonomics, understand the effects of physical ergonomics implementation in a workplace design, as well as being able to express their criticality ratings towards the tested issues. Nevertheless, based on the literature review discussion in Chapter 2, current challenges in the HFE implementation program and occurrence of occupational injuries at offshore workplaces would need a specific design formulation to ensure a processing equipment design meets the ergonomics design scheme.

The results also explain that the respondents' feedback is not influenced by the factor of having different types of experience. Besides that, statistical analysis of the data suggests no significant effect of the range of experience factor towards the level of physical ergonomics awareness, explaining less experienced engineers may have a good awareness of the subject matter compared to experienced engineers. On the other hand, the findings also deny a statement that less experienced engineers may have a lesser understanding of the physical ergonomics subject than experienced engineers. The ergonomics awareness might be exposed to any levels of oil and gas practitioner through hands-on work experiences, hence influencing their worldview on how the physical ergonomics issues affect the operators' safety and health within an offshore workplace. Such understanding on the industry working nature lays the crucial principle for developing a comprehensive (considering all relevant aspects), replicable (applicable in multiple design cases), and understandable (could be utilized by all levels of end user) physical ergonomics design guidelines (PEDG). The proposed PEDG should comprehensively standardize the ergonomics requirements in a design process so that it can be implemented by engineers or designers with different types and ranges of experience.

One of the findings from the questionnaire survey presents the noteworthy indication of ergonomics issue, which demonstrates a less awareness among the respondents towards an indirect design criterion that could trigger a tripping or slipping hazard. This is supported by a lower percentage of the respondents (65.4% for C3 and 69.2% for C7 design criteria), who inclined to consider these design criteria were related to physical ergonomics domain, as indicated in Table 4.2. In detail, C3 was related to the *requirement of coaming area to avoid hydrocarbon or water spillage* while C7 was related to the workplace condition where a *cable or pipe is installed across an access way*. These implicit concerns are significant to be fixed in the proposed design guidelines, thus ensuring any indirect ergonomics issues are eliminated and no critical ergonomics aspect is overlooked during the design process.

Apart from that, the factors of having different ranges of experience and types of experience also do not influence the criticality rating towards the tested physical ergonomics issues. Regardless of the factors, the findings are undoubtedly important in providing a strong consensus towards the ergonomics issues that are needed to be mitigated within a processing equipment design. Hence, the consensus must be reflected in the proposed design guidelines.

In Part 2 of this study, a classification of maintenance components from the HTA exercise resulted in four common maintenance components, namely filtering, heating, membrane, and vessel components. Since these components are commonly installed in a processing equipment design, the proposed PEDG could be widely replicated to a significant number of identical components that installed in other processing equipment packages, rather than the case studies equipment themselves.

The assessed PEI on the physical tasks of each maintenance component that was carried out under the Part 3 of this study, has provided a significant understanding of the common potential ergonomics hazards that exist within a processing equipment. There are similarities of types of maintenance component among the case studies, additionally with a few similar tasks and subtasks such as withdrawal of internal element, removal of manhole or flange cover, and valves operation. Hence, several common PEI is identified during the assessment and can be mitigated through the application of the same ergonomics principles.

Based on the literature review, past studies rarely focused on the sequential task requirements of a specific case study for assessing physical ergonomics issues in offshore oil and gas facilities. Skepper et al. (2000) for instance, assessed the operational design in unspecific area or equipment and resulted in random valves and instruments accessibility issue. A 3D model design review of six production units, one wastewater treatment unit and three utility units by Passero et al. (2012) raised several ergonomics concerns mainly on the accessibility of valves, instruments, and sampling connections, without discussing the maintenance task requirement that might involve the operation of materials handling devices and MMH risk. Hence, the exploration of ergonomics issues through the common types of maintenance component has provided an understanding of how the physical tasks expose the associated PEI towards operators, consequently increasing potential human errors, occupational injuries, and affect the maintainability of processing equipment. In addition, the findings have enhanced the potential design improvement areas compared to the current industry practices and past studies.

4.6 Summary

The findings of Part 1, Part 2, and Part 3 of the study have provided an understanding of the crucial ergonomics issues within a processing equipment design from the perspective of Malaysian practitioners and environment, as well as the operational tasks involved during maintenance activities. The level of awareness and its influencing factors, criticality ratings of ergonomics issues, and the critical PEI inputs for each maintenance task would be crucial for further mitigation plans assessment and PEDG development process. The previous discussion has emphasized several critical findings from these study parts which could enhance the ergonomics design guidelines. Therefore, the analysis of the inputs and outcomes of PEDG development will be elaborated in the subsequent section.

CHAPTER 5: DEVELOPMENT OF PHYSICAL ERGONOMICS DESIGN GUIDELINES

5.1 Introduction

This chapter discusses the development of PEDG for an offshore processing equipment and contains two sections. The first section describes the details of three components that are integrated as a basis for the PEDG development. The second section presents the summary of PEDG results and detail checklists of PEDG for filtering, heating, membrane, and vessel components. The PEI Matrix outcomes for all maintenance components from Part 3 of this study were converted into a tabulation form prior to further assessment of mitigation plans and developing the PEDG for an offshore processing equipment.

5.1.1 Integration of design specifications for PEDG development

Basically, the PEDG development involved three input components which were generated from Part 1, Part 2, and Part 3 of this study. Firstly, nine key design themes that were extracted from Part 3 were manipulated to construct a skeleton of the PEDG for every maintenance component. Secondly, additional design specifications which associated with the specific maintenance components were integrated into the PEDG checklist. These design specifications were extracted from the findings from the PEI criticality ratings of the questionnaire survey in Part 1 of this study. Thirdly, a cross-comparison exercise was performed between PEI Matrix outcomes and PEI criticality ratings from the findings of the questionnaire survey. The overall integration process is illustrated in Figure 5.1.

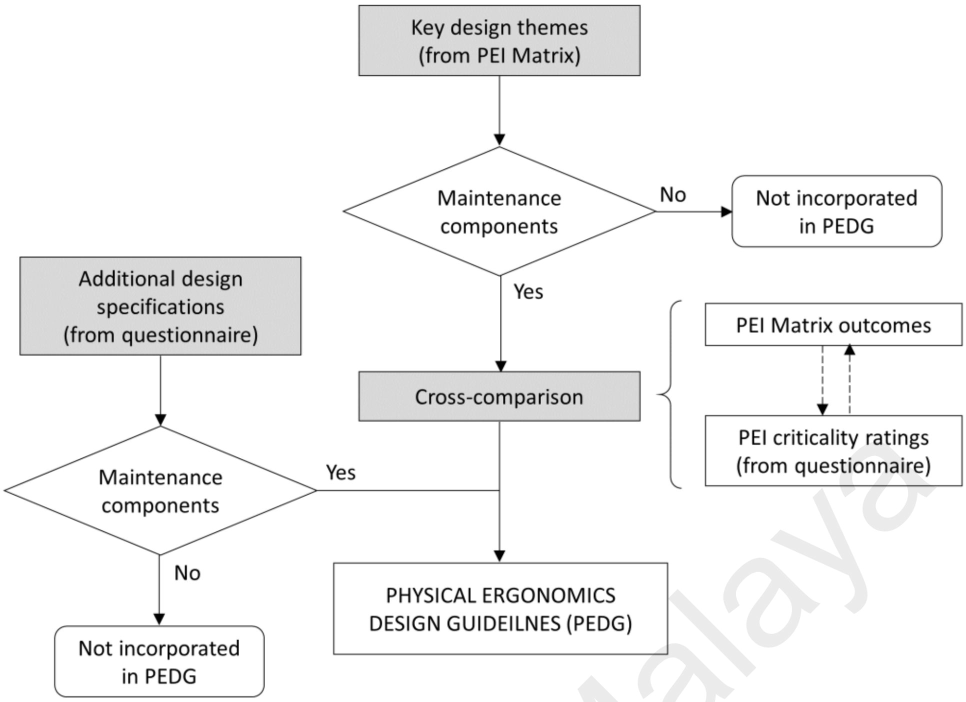

Figure 5.1: Flowchart of the physical ergonomics design guidelines (PEDG) development process

5.1.1.1 Key design themes

From the PEI Matrix of all maintenance components, mitigation plans were suggested to eliminate each ergonomics hazard, afterwards considered as design requirement inputs for developing the PEDG specifications. The mitigation plans were derived by adapting three ergonomics principles of workplace design as discussed in Section 3.5.2, whereby the body dimension and body posture, muscular strength, and body movement criteria must be accounted to all maintenance tasks. For example, the first PEI that applicable for the task of depressurizing a vessel of filtering component would be an *access platform requirement to complete the task, depending on the height of the valves.* Based on the assessment, a consequence of hazard that might be arisen for this PEI would trigger a bad working movement such as stepping on a pipe, steel frame, or sensitive equipment. This physical task was solely related to the height of operator's shoulder and whole body, as well as the optimum height of vertical hand reach point, whereby these factors were related to the body dimension and body posture criterion. Hence, a mitigation plan was suggested to ensure the *valves were mounted within the acceptable operator reaching height range* as well as to *provide a clear access space for the operator to access and operate the valve*. The overall assessment outcomes that outlined the mitigation plans for resolving the identified PEI of filtering, heating, membrane, and vessel components can be referred to Appendix D.

A qualitative content analysis of all the suggested mitigation plans found 61 design codes, which then were classified into nine relevant design themes namely *access space and reaching area, bolting, tripping and slipping hazards, material handling, personal protection, valves and controls configuration, working at height, confined space,* and *others*. The analysis outcomes are summarized in Figure 5.3.

. The design themes that mostly received an attention through the suggested mitigation plans for all maintenance components were the *material handling* with 15 design codes, followed by the *access space and reaching area* (14 design codes), *valves and controls configuration* (11 design codes), *tripping and slipping hazards* (5 design codes), and *others* (6 design codes), while the other three design themes accumulated two to three design codes, severally.

Figure 5.3 summarizes the distribution of the design codes for each maintenance component. The following sections explain the design requirements of each design theme.

(a) ***Material handling***

This design theme mainly involved the allocations of horizontal or vertical space for lifting, removing, and transferring maintenance components, including space for the operation of MH equipment such as a chain hoist and deck trolley. The design theme also covered the provision of MH equipment, special tool, or hand tool that were required during tasks execution. In addition, MMH operation that involved human physical efforts such as lifting, carrying, pulling, pushing, and structural design of handling way to withstand loads transfer were also considered under this design theme.

Muscular strength factor (Department of Standards Malaysia, 2005) involved during the completion of material handling tasks must be compatible with the physical strength capacity of the local operators, especially in a workplace with both genders are working in a team. The tasks often expose an operator to excessive force in lifting, pushing, and pulling, sometimes to a sudden torque and prolonged pressure contact onto sensitive body regions. Other than force, the muscular strength factor that was influenced by awkward working postures and the combination of both criteria—force and posture—would also increase the excessive stress on the musculoskeletal issues, thus developing the musculoskeletal disorder (MSD) risk towards an operator (Blaho & Button, 2013; Gallagher & Heberger, 2013).

Along with that, the vessel component had brought in the requirements for handling of a heavy flange or manhole cover, where an opening clearance and permanent lifting mechanism namely davit arm, must be ensured and designed according to the weight of the component.

(b) ***Access space and reaching area***

The criticality of workspace and access requirements are governed by the principle of accomplishment of necessary maintenance tasks quickly, safely, accurately, and effectively with minimum requirements for personnel, skills, and special tools (ABS, 2013). An adequate space for completing a physical task plays a significant role in the operability and maintainability of offshore processing equipment. Shortage of clearance and accessibility would trigger dangerous reactions from a worker, especially when design specifications ignore the anthropometric data of local workforces (IOGP, 2011).

When workers need to reach a high point by stepping on or holding steel structures or pipes due to unavailability of access ladder or elevated platform, they might be exposed to excessive forces and energy. This practice could affect the focus and effectiveness of human sensors when completing tasks (McLeod, 2015), and could cause a body movement with imbalance legs position (Blaho & Button, 2013). Consequently, the risk of physical injury at a workplace will be increased accordingly.

The analysis under this category found that several criteria for the access space requirement must be considered in an equipment design, which were clearance for operators' body positions such as standing, kneeling and squatting, as well as an ergonomic body position during applying force (pulling or pushing) and access way between two access points. The space allocation for different types of working position was dependent on a specific task of each maintenance component. The reaching parameter requirement explained the largest distance between a handling point and operator access location, taking into account the limitation of end users' body measurement specifically the arm length. As understood from this study, the ergonomics principle of body dimensions and postures could not be actualized without knowing a sequence of tasks, including which body parts and postures involved in completing the tasks. Duarte et al. (2012) discussed this configuration by using a 'setting of usage' concept, where several case studies were evaluated by anticipating the operational tasks in order to recommend the allocation of access region, height accessibility, unobstructed working space, and others. These design systems have a potential to trigger ergonomics problems and grow incident risks.

Besides that, sufficient space provisions for placing a step stool or portable ladder and also for erecting a scaffolding structure were required in a layout design. These items were purposely included under this design theme, as the raised physical concerns were related to the space allocation rather than the reaching or working at high point activity. An equipment that involved filling media such as desiccant, lubricant oil, or catalyst substance would require a dedicated storage area for the temporary storage of filling medium supply. In addition—the vessel—the one and only component that involved a confined space entry among the case studies, highlighted the important design code which was a manhole-size for personnel access into the vessel. Since the *access space and reaching area* were the basic principle of the physical ergonomics constraint, all the maintenance components were found relevant to these design codes.

(c) ***Valves and controls configuration***

This design theme covered the valves and controls accessibility and operability. The analysis explained that this design theme mostly affected the filtering and vessel components, especially for the vessel isolation purpose. The HTA results explained that the valves and controls of the vessel were often accessed before and after the removal of internal parts. The accessibility concern might be depending on the mounting location and elevation, multiple valves arrangement, valve design, and operation effort, as well as clearance for a lever-operated valve operation. The configuration might also be applicable for pressure and temperature gauges display for filtering, heating, and vessel components. In normal operation activities, an operator always became the victim of inefficient equipment design as they thought human body parts were more flexible than the existing equipment design or valve mounting location (Lind & Nenonen, 2008). To perform an urgent task and avoid a schedule delay, the operator usually willing to face difficulty in body movements and posture such as reaching an operating point beyond the duly reach parameter.

(d) ***Tripping and slipping hazards***

This category referred to any obstructions across an access way, handling way, access area, working space, or across the dedicated withdrawal space of maintenance component, sometimes hidden from an operator's view. Based on the results, it was found that a crossing pipe on floor, protruding pipe from underneath floor, steel obstruction, and electrical cables could initiate a tripping hazard within offshore workplaces. Besides that, the components that processed liquid media such as filter and heater vessels could cause liquid spillage on deck floor due to the improper procedure during maintenance activities, consequently exposing an operator to slipping hazard. Proper coaming area and drainage system at the vessel flange opening area might mitigate such hazard. The example of coaming design at the tank manhole area is shown in Figure 5.2.

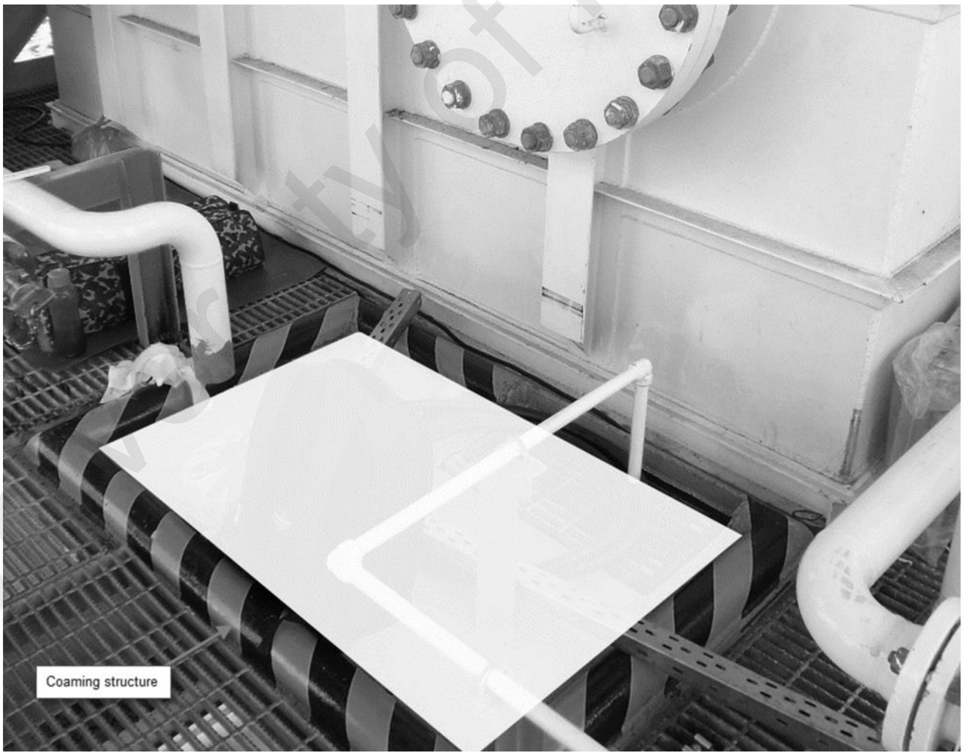

Figure 5.2: Example of coaming design at the tank manhole area

(e) ***Working at height***

Limited space within an offshore platform induced a stacked design arrangement, where an operator might be involved in handling, viewing, reading and reaching a higher elevation than the main deck surface. A few design requirements were identified from the analysis and reflected as design codes such as the appropriate height of step stool, ladders, stairs, or working platform for completing operation and maintenance tasks.

(f) ***Bolting***

Bolting design theme referred to the removing and installing bolts and nuts of vessel flange, and the needs of bolting tool for opening a tight and corroded bolt joint to reduce manually applied force by an operator. Besides that, enough clearance for hand access and bolting tool operation should be allocated, taking into account the length of bolts and the dimensions of bolting tool such as a manual wrench or hydraulic torqueing tool. This design theme was categorized separately from the others because it was identified as a distinctive ergonomics design issue. Generally, the bolting-related activities occurred in all the maintenance components that were constructed with a bolted joint, as summarized in Figure 5.3.

(g) ***Personal protection***

The needs for protection for operator safety and health encompassed the needs of insulation layer surrounding extremely hot or cold surfaces such as the high-temperature medium pipes and heating vessels, and personal protection equipment (PPE) for an operator such as the hand gloves during bolting task operation.

(h) ***Confined space***

The confined space design theme that was merely acquired from the vessel component discussed the requirements of confined space entry and secondary escape means from the huge confined vessel, concerning potential gas or chemical hazard inside the vessel. Such hazard required an operator to rapidly escape the vessel through the nearest manhole location.

(i) ***Others***

Any individual design codes found in the analysis were grouped into this design theme because the suggested design requirements were solely related to the specific maintenance component. For instance, a bottom flange type of filter vessel with downward filter withdrawal, membrane modules arrangement for a membrane equipment, and hand grip. The hand grip requirement referred to the design of hand-holding area at any maintenance component that involved MMH operation, to improve the operability issue while handling the load. Besides that, special design specifications were noticed under the vessel component, which were the lighting levels concern nearby the vessel's manhole area and the simplified joint mechanism of vessel's internal parts that could reduce dismantling time with moderate spending effort.

Design code / Component	Filtering	Heating	Membrane	Vessel
Materials handling	✓	✓	✓	✓
Handling clearance	✓	✓	✓	✓
Withdrawal clearance	✓	✓	✓	✓
MH Equipment	✓	✓	✓	✓
Manual handling	✓	✓	✓	✓
Hand tool	✓	✓	✓	
Special tool	✓	✓	✓	✓
Component weight	✓			
Headroom		✓		✓
Lifting points		✓		
Structural support		✓		
Handling way		✓	✓	✓
Maintenance procedure			✓	✓
Opening clearance	✓			✓
Davit arm				✓

Design theme		PEI criticality rating category (questionnaire)
Materials handling	↔	Materials handling system

Figure 5.3: Distribution of design codes and design themes for each type of maintenance component and the correlation with PEI criticality rating category

Design code / Component	Filtering	Heating	Membrane	Vessel
Access space (standing)	✓	✓	✓	✓
Access space (kneeling)			✓	
Access space (squatting)		✓	✓	✓
Access space (crawling)				✓
Access space (applying force)		✓	✓	
Reaching parameter	✓		✓	✓
Access way			✓	
Working space	✓	✓	✓	
Hand clearance	✓	✓	✓	✓
Space for scaffolding/portable ladder	✓			
Working surface			✓	
Manhole-size				✓
Working space				✓
Storage space				✓

Design Theme: Access space and reaching area ⟷ **PEI criticality rating category (questionnaire):** Workspace and access way

Design code / Component	Filtering	Heating	Membrane	Vessel
Valve mounting	✓		✓	✓
Valve access	✓			✓
Valve operation (force)	✓			
Valve clearance	✓		✓	
Valve design	✓			
Valve arrangement			✓	
Valve labelling				✓
Display mounting	✓	✓		✓
Display parameter		✓		
Quick connection				✓
Flange mounting				✓

Design Theme: Valves and controls configuration ⟷ **PEI criticality rating category (questionnaire):** Controls and valves

Figure 5.3: Continued

Design code / Component	Filtering	Heating	Membrane	Vessel	Design Theme	PEI criticality rating category (questionnaire)
Pipe obstruction	✓	✓	✓	✓	Tripping and slipping hazards	Worker safety
Drainage	✓	✓		✓		
Protruding pipe		✓				
Steel obstruction			✓			
Obstruction			✓	✓		
Working elevation	✓	✓	✓	✓	Working at height	Working at height
Step stool		✓	✓			
Working platform	✓			✓		
Bolting/screw clearance	✓	✓	✓	✓	Bolting	
Bolting tool	✓			✓		
Bolting operation	✓					
PPE	✓	✓	✓	✓	Personal protection	Worker safety
Insulation		✓	✓			
Secondary escape				✓	Confined space	
Confined space entry				✓		
Bottom flange	✓				Others	
Hand grip	✓		✓	✓		
Membrane design			✓			
Quick opening	✓					
Lighting				✓		
Joint mechanism				✓		

Figure 5.3: Continued

5.1.1.2 Additional design specifications

Additional design specifications were considered based on several highly-critical rated ergonomics issues from the questionnaire survey but subjected to the suitability of application in the particular types of maintenance component. Three out of 17 items from the criticality rating assessment were identified relevant for the maintenance components design. Table 5.1 summarizes the critical ergonomics issues and the associated maintenance components.

Table 5.1: Additional highly-critical rated ergonomics issues for developing the physical ergonomics design guidelines

Physical ergonomics issue	Description	Design theme	Maintenance component
CE04	Trapped within an equipment skid during emergency cases, and require extra time to escape due to an unclear access way	Access way and reaching area	Overall skid package, vessel, membrane
CE07	Secondary/alternative escape route within an equipment skid especially for an elevated deck, in case of an unexpected blockage along the primary escape routes	Access way and reaching area, working at height	Overall skid package, vessel, membrane
CE08	Filling point to any tank (lube oil, diesel, etc.) should be accessible and located at the edge of the tank	Access way and reaching area, working at height	Vessel

As explained previously, most of the respondents from the questionnaire survey believed that the physical ergonomics issues shown in Table 5.1 were high critical within an offshore processing equipment design; CE04 ergonomics issue recorded 88.9%, CE07 (83.3%), and CE08 (75.9%) of the respondents, respectively. In an equipment design process, the CE04 ergonomics issue would be applicable for an overall skid package design where a few processing components were integrated within a limited skid layout boundary, including a confined vessel component. As a mitigation plan, sufficient and unobstructed access routes should be properly planned within the skid package layout, especially for a huge skid layout and stacked decks arrangement. The previous assessment in the PEI Matrix suggested a vessel component would also require the appropriate manhole size for the operator entry, considering the operator was equipped with a complete PPE such as hard hat, breathing apparatus (for confined space entry), coverall, and hand tool. Internal access means and secondary escape manhole should also be considered for mitigating such PEI.

The CE07 ergonomics issue demanded a secondary access within an elevated deck, whereby the membrane and vessel components could possibly be involved if an elevated working platform was provided for accessing high elevated membrane modules or top mounting flanges on a vessel component. The purpose of the suggested mitigation plan was to provide an alternative escape route for the elevated working platform where appropriate, taking into account the factors of platform high and task execution period.

From the Air Dyer Package case study, it was found that the vessel component involved a filling media loading task through a top mounted feed flange. Hence, the CE08 ergonomics issue was significant for this component design by ensuring the feed flange was mounted adjacent to operator access areas, suitably to minimize body bending posture during handling and feeding the filling media bags towards the flange.

Apart from the three additional design specifications that had been presented earlier, all the other high critical PEI from the questionnaire survey were perceived aligned with the results of PEI Matrix assessment in Section 4.4, where nine key design themes were derived from the proposed mitigation plans of each maintenance component.

5.1.1.3 Cross-comparison of PEI Matrix outcomes with PEI criticality ratings

The analysis of the industry experts' feedback on the PEI Matrix reflected nine design themes while the analysis of the respondents' concern toward the critically of PEI that has been discussed in Section 4.2.3 resulted in six categories of criticality rating. All the categories were acknowledged as critical requirements in a processing equipment design. Cross-comparison between the design themes and the criticality rating categories were carried out based on matched criteria as demonstrated in

Figure 5.3. Four items that were identified matched with each other: *access space and workspace*, *materials handling*, *controls and valves*, and *working at height*. The *tripping and slipping hazards* and *personal protection* design themes were matched with the *worker safety* category while *bolting*, *confined space* and *others* design themes could not be significantly correlated with any criticality rating category.

The established correlations reflected that the suggested mitigation plans for the maintenance components complied with the criticality of the PEI and aligned with the respondents' consensus that was emphasized in the questionnaire survey. Furthermore, both comparable criteria were justified in both ways as illustrated in

Figure 5.3. In other words, the criticality of ergonomics issues that was raised by the industry experts during the interview sessions were justified, and the categories of criticality rating that were acknowledged by the oil and gas industry practitioners through the questionnaire survey were extensively explored in the context of multiple maintenance component types, namely filtering, heating, membrane, and vessel components.

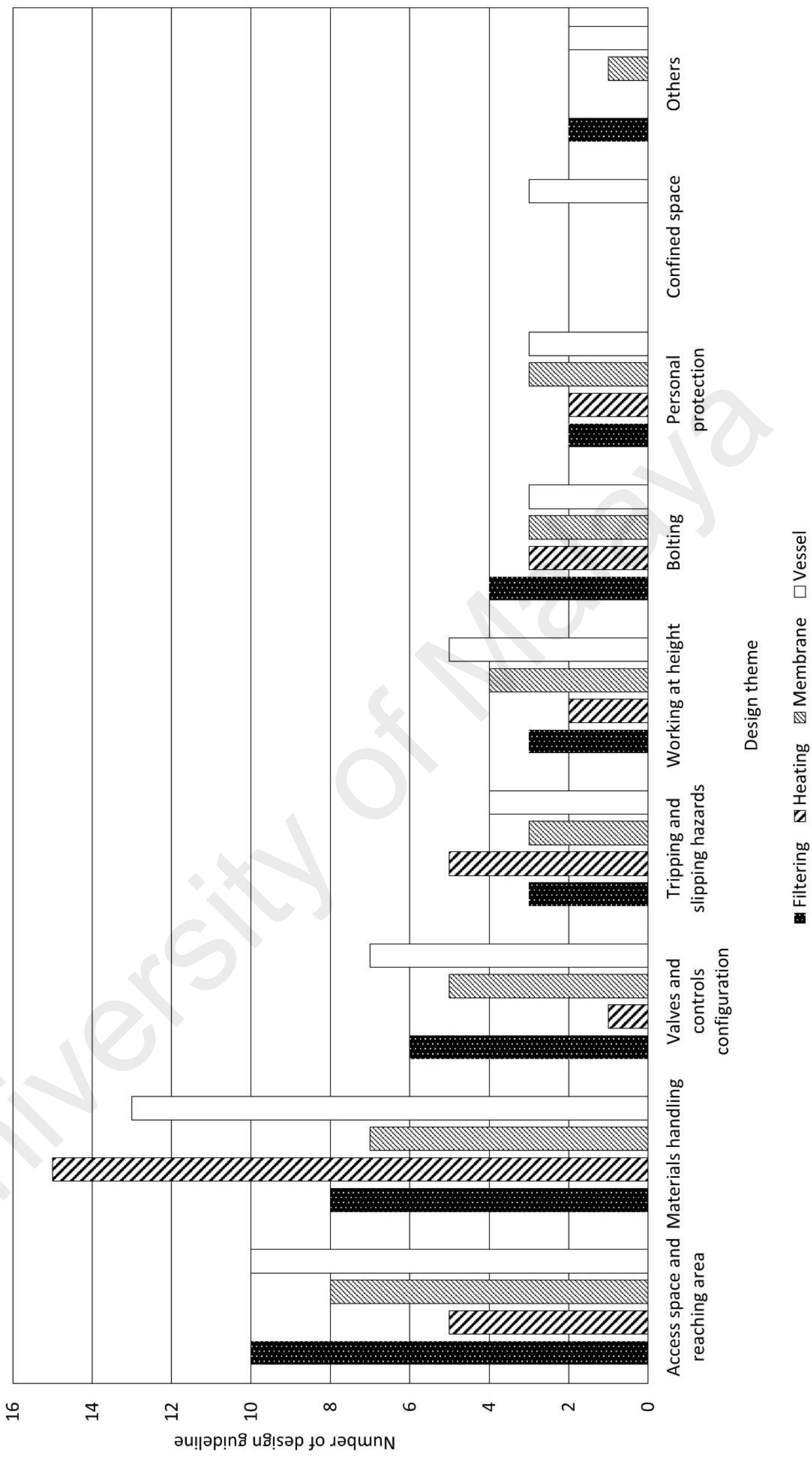

Figure 5.4: Summary of physical ergonomics design guidelines for filtering, heating, membrane, and vessel components

5.1.2 Physical ergonomics design guidelines (PEDG)

Guided by the nine key design themes, each of the mitigation plans for the maintenance component was excerpted while the overlapping requirements were combined simultaneously, to generate a series of physical ergonomics design guidelines (PEDG). This was to ensure the proposed design guidelines would mitigate all the ergonomics issues that might arise during maintenance activities. Figure 5.4 shows a comparison of generated design guidelines for each maintenance component which was grouped by the design themes. The graph indicates the *material handling* and *access space and reaching area* design themes accumulated the highest number of design guidelines. Overall, filtering component had 38 design guidelines, heating component (33), membrane component (34), and vessel component (50).

For the filtering component, 38 design guidelines were established for eliminating the potential PEI, as outlined in Table 5.2. The *access space and reaching area* design theme recorded the highest number of design guidelines, followed by the *material handling* theme. The design criteria that could indirectly cause slipping hazard to operators, specifically for the case of spillage from liquid filtering medium was also incorporated under the *tripping and slipping hazards* design theme. The heating component accumulated 33 design guidelines as listed in Table 5.3, with the *material handling* design theme recording the highest number of design guidelines, followed by the *access space and reaching area* design theme. There were two additional design guidelines that were extracted from the criticality rating of the questionnaire survey, firstly referring to the requirement of clear access and egress within a package skid boundary and surrounding area of the heating component footprint (included under the *access space and reaching area* design theme), and secondly regarding the indirect cause of slipping hazard to operators, attributed by spillage from liquid heating medium (included under the *tripping and slipping hazards* design theme).

A total of 34 design guidelines were generated for the membrane component as listed in Table 5.4, which were mostly related to the *material handling* and *access space and reaching area* design themes. A series of membrane modules were normally mounted within a skid package, hence an additional safety measure regarding clear access and egress routes was included in the design guidelines under the *access space and reaching area* design theme. Considering a larger number of membrane modules were needed for the high processing capacity, a constrained skid footprint would introduce stacked membrane lines arrangement together with an elevated access platform to ensure good accessibility within the equipment. Consequently, longer and multilevel connected access routes might be allocated, thus a secondary escape requirement as described in Table 5.1 (refer to CE07) must be considered in the PEDG for the membrane component. This design requirement was also incorporated under the *access space and reaching area* design theme.

Lastly, the vessel component established the highest number of design guidelines whereby 50 items were listed in Table 5.5. The qualitative content analysis had emphasized two design themes for the vessel component design, namely *material handling* and *access space and reaching area* with the highest number of design guidelines among the others. Additionally, the *confined space* design theme was introduced by this component through the three design specifications that would mitigate the related ergonomics issues when an operator gets into a confined vessel.

Table 5.2: Physical ergonomics design guidelines of the filtering component

Design theme	Design specification	Compliance		
		Yes	No	N/A
Access space and reaching area	1. Sufficient and accessible standing or squatting area for one operator to operate valves of the filter vessel			
	2. Sufficient accessible working space to accommodate an operator's body dimension and movement (i.e. body rotation, operate hand tools) surrounding of filter vessel's flange cover for bolting activity			
	3. Access space (on deck level or higher working platform) towards the vessel's flange cover for bolting activity is within the largest reaching parameter (arm length). L-shape access approach can be considered for large vessel diameter.			
	4. Sufficient and accessible standing space for an operator to lift and handle filter elements (top flange type)			
	5. Sufficient and accessible squatting space for an operator to remove and handle filter elements (bottom flange type)			
	6. Sufficient hand clearance between valve lever operating area and other valve or obstruction			
	7. Hand clearance at the surrounding area of the filter holding screws for manual operating/screwing by hand			
	8. Sufficient hand clearance inside the filter vessel to access and take out the filter elements			
	9. The distance between operator access space to valve mounting location is within the maximum reaching parameter (arm length)			
	10. Adequate and clear space for erecting scaffolding or placing a portable ladder or step stool to access high mounted valves or vessel's top flange cover for bolting and filter removal activity (if the permanent platform is not provided)			

Material handling	11. Dedicated lifting equipment or integrated davit arm is provided for handling a heavy filter vessel's flange cover (if the weight exceeds the manual handling limit)			
	12. The weight of the bottom flange cover is designed within manual handling limit for one hand operation (for downward filter vessel type)			
	13. Sufficient clearance for installation and operation of MH equipment for handling filter elements is allocated (if required)			
	14. An unobstructed full opening path is allocated for top/bottom vessel's flange cover with davit arm; no potential clashing with operator's standing/access area or other obstructions			
	15. Adequate withdrawal clearance of filter elements, based on the filter length including extra clearance to improve handling flexibility			
	16. Dedicated lifting equipment is provided to lift and transfer heavy filter elements (if the weight exceeds the manual handling limit)			
	17. Sufficient path clearance is provided for lifting and transferring filter elements from a filter vessel to temporary storage area			
	18. The weight of a single dry and wet filter element is designed within the manual handling limit			
Valves and controls configuration	19. Pressure and temperature gauges are mounted within the preferred display height range			
	20. Valves (inlet, outlet, pressurize, etc.) mounting location are within the acceptable height range of standing and squatting positions			
	21. Valves mounting location are facing towards an operator access direction; a parallel or perpendicular arrangement for lever-operated valve			
	22. Unobstructed space is allocated for opening and closing lever-operated valves			
	23. Valve lever is designed with extra length to reduce forceful effort during valves operation			
	24. A hand tool is required to loosen the stuck valve's lever or hand wheel during initial valve operation			

Tripping and slipping hazard	25.	Drainage system and coaming area are provided for liquid medium filter elements (water, chemical, hydrocarbon, etc.)			
	26.	No pipe, structure, electrical cable and instrument item within and across the access way towards valves access area			
	27.	No pipe, structure, electrical cables and instrumentation items within and across the access way towards the surrounding area of top/bottom vessel's flange cover			
Working at height	28.	Top vessel's flange elevation (with or without elevated working platform) is within the preferred working height range for bolting task			
	29.	Filter depth level inside the filter vessel (with or without elevated working platform) is within the preferred working height range for lifting and handling the filter elements			
	30.	The gap between the working platform and filter vessel is minimized to ensure handling activity is within the maximum reaching parameter (arm length)			
Bolting	31.	Clearance for wrench or hand tool operation at the surrounding area of bolts and nuts; consider standard wrench length			
	32.	Use pneumatic or electrical powered wrench for repetitive bolting activities			
	33.	Clearance for wrench or hand tool operation at the surrounding area of bolts and nuts; consider standard wrench length			
	34.	Use pneumatic or electrical powered wrench for repetitive bolting activities			
Personal protection	35.	Use a hand glove to operate manual wrench or hand tool			
	36.	Use a hand glove to lift and handle dirty filter elements to avoid contaminant hazard			
Others	37.	Holding area of the filter element is designed according to the minimum hand-holding dimension			
	38.	Quick-opening or hinged type of filter vessel's flange cover is considered for frequent filter elements replacement i.e. weekly change out			

Table 5.3: Physical ergonomics design guidelines of the heating component

Design theme	Design specification	Compliance		
		Yes	No	N/A
Access space and reaching area	1. Sufficient and accessible standing or squatting space for one operator to access electric terminal enclosure for equipment isolation (subject to an elevation of heater terminal)			
	2. Access to the terminal enclosure is within the maximum reaching parameter (arm length)			
	3. Sufficient and accessible working space for standing and pulling positions in front of heater flange and tube bundle removal area			
	4. Sufficient standing or squatting space at the surrounding area of a heater flange for bolting tasks; consider maximum reaching parameter (arm length)			
	5. Clear access and egress routes to/from the heating component within a skid package is ensured; minimize travel distance to the adjacent emergency route			
Material handling	6. Adequate lifting headroom above the tube bundle withdrawal level is provided to improve flexibility during handling and aligning the load; consider headroom for the full length of the tube bundle			
	7. Unobstructed handling route is allocated from heating equipment location to appropriate transfer destination (e.g. laydown area)			
	8. Sufficient height, width and turning area of handling routes are allocated for transferring the heater bundle; consider maximum trolley width and trolley/tube bundle length			
	9. Movable lifting equipment (monorail with trolley hoist) is installed along the bundle withdrawal path with sufficient monorail length and load capacity			
	10. Alternatively, portable and dismantlable A-frame is considered as a lifting equipment for lighter tube bundle weight; consider sufficient installation space, reinforced A-frame load points, and operators access area			

	11. Pulling arrangement (i.e. pulling device with pulling post) is provided for removing a tube bundle from its vessel with appropriate pulling load capacity (for a heating component weight that exceeds the manual handling limit)			
	12. Use of powered lifting equipment (electrical or pneumatic driven) is considered for frequent lifting and transferring of the heavy tube bundle			
	13. Sufficient working space for a minimum of two operators at the surrounding area of a tube bundle withdrawal area for handling and aligning the load before placing on a tube bundle trolley or bar cradle carts			
	14. Design specification of tube bundle trolley or bar cradle carts for transportation; consider the full length, diameter and weight of tube bundle			
	15. Minimum two lifting points (temporary or permanent) are provided at a tube bundle body			
	16. Special handling device for tube bundle lifting support is considered to avoid damage on the tube bundle (if required)			
	17. Use of load pusher/puller or motorized bundle trolley is considered to assist a heavy tube bundle movement through handling routes			
	18. Ensure the next lifting and handling equipment at a service area or laydown area is available to take out the tube bundle from bundle trolley or bar cradle carts			
	19. Sufficient and unobstructed withdrawal clearance for a full length of tube bundle including extra clearance to improve handling flexibility			
	20. Adequate access space for one operator to operate a monorail trolley hoist or chain hoist (if require materials handling equipment)			
Valves and controls configuration	21. Elevation of electric terminal connections and controls are mounted within squatting or standing display height range			

Tripping and slipping hazard	22. Drainage system and coaming area at heater flange opening area are provided for liquid heating medium			
	23. No pipe, structure, electrical cable or instrument item across an access way towards the electric terminal box			
	24. No pipe, structure, electrical cable or instrument item across working space and tube bundle withdrawal area			
	25. No different elevations within the working surface for a tube bundle removal and installation activities to avoid tripping hazard i.e. between package skid and platform deck floor			
	26. Heater flange is located at the edge of package skid with sufficient operator's standing and pulling positions space at outer skid boundary			
Working at height	27. Heater flange and tube bundle are installed within the acceptable pulling height range (if pulling the component manually)			
	28. Portable stool or elevated working platform is provided for the heating component that is mounted at higher level than the acceptable pulling height range			
Bolting	29. Sufficient clearance is allocated at the surrounding area of bolts and nuts of heater flange for wrench or powered bolting tool operation; consider standard wrench length			
	30. Sufficient clearance between bolts and nuts of heater flange for the manual bolting task by fingers			
	31. Use pneumatic or electrical powered wrench for bolting activity to reduce the excessive force to hand			
Personal protection	32. Heat insulation layer for potential cold or hot piping, valve, or heater vessel that adjacent to access and working areas			
	33. Use hand glove for manual bolting tasks			

Table 5.4: Physical ergonomics design guidelines of the membrane component

Design theme	Design specification	Compliance		
		Yes	No	N/A
Access space & reaching area	1. Sufficient and accessible standing or squatting space for one operator is available in front of inlet and outlet valves of membrane modules (subject to an elevation of membrane modules)			
	2. Sufficient working space is allocated for one operator's standing and pulling (applying force) positions in front of membrane modules			
	3. Clear access and egress routes within membrane skid package; minimum travel distance to the adjacent emergency route			
	4. Sufficient working space in front of membrane modules is provided for full body rotation and movement during handling of membrane modules			
	5. Clear and unobstructed access routes are allocated between both ends of membrane modules			
	6. Travelling distance between inlet and outlet valves location is minimized e.g. by limiting the overall length of membrane modules			
	7. Operator access space from membrane module flanges is allocated within the maximum reaching parameter (arm length)			
	8. Adequate secondary escape routes are allocated along the elevated access/working platform within the membrane skid package			
Material handling	9. The dry and wet weight of membrane elements is designed within the manual handling limits			
	10. Special tool for pulling membrane modules that are installed deep inside a membrane housing is provided (tool requirement and design should be advised by manufacturer)			
	11. Sufficient working space in front of membrane modules to operate a pulling device or special tool; consider the exact length of the tool			

	12. Clear and unobstructed withdrawal space for membrane elements; consider its actual length and extra clearance to ensure task flexibility			
	13. Lifting equipment is provided for transferring membrane modules between the higher working platform and lower deck floor e.g. lifting davit			
	14. Procedures of membrane modules replacement during maintenance period are designed for the partial line by line basis, to avoid repetitive tasks within a short time frame			
	15. Proper trolley design for transferring membrane modules; consider the length, diameter, and weight of membrane elements			
Valves and controls configuration	16. Unobstructed clearance is allocated for opening and closing lever-operated valves			
	17. A group of valves with similar functions are installed in the same configurations; mounting elevation and access area for valves operation			
	18. Opening (counter-clockwise) and closing (clockwise) directions are standardized for all valves			
	19. Valves mounting location are within the acceptable height range and reaching parameter of operator's standing or squatting position			
	20. Valves mounting orientation (parallel or perpendicular) are clearly accessible from the operator's access direction			
Tripping and slipping hazard	21. No pipe, structure, electrical cable or instrument item within and across an access way towards valves location			
	22. No pipe, structure, electrical cable or instrument item within and across an access way towards membrane modules removal area			
	23. No different elevations of working surface in front of the membrane modules removal area; between inner and outer membrane skid package boundary to eliminate a tripping hazard			

Working at height	24. Elevation of membrane modules is mounted within the acceptable display and working height range			
	25. Portable stool or working platform is provided for accessing membrane modules that are mounted beyond the acceptable working height range			
	26. The dimension of elevated working platform or portable stool is designed sufficiently to accommodate an operator's body size and movement i.e. body rotation, hand tool operation			
	27. No membrane module is mounted below the acceptable working height range from working surface level i.e. below knee height			
Bolting	28. Clearance at surrounding area of a membrane module flange (bolts and nuts) is allocated for wrench operation or powered hand tool; consider standard wrench length			
	29. Use pneumatic or electrical powered wrench for bolting tasks			
	30. Sufficient clearance between the flange and other obstructions for withdrawing stud bolts and nuts; consider the length of the stud with extra clearance to improve task flexibility			
Personal protection	31. Use hand gloves for repetitive handling of flange spool and membrane elements			
	32. Use hand glove for repetitive manual bolting tasks to avoid sharp edge exposure			
	33. Use hand glove to operate manual wrench or hand tool to reduce excessive stress on hand			
Others	34. Holding area of membrane modules is designed according to comfortable two hand-holding position			

Table 5.5: Physical ergonomics design guidelines of the vessel component

Design theme	Design specification	Compliance		
		Yes	No	N/A
Access space and reaching area	1. Sufficient and accessible standing or squatting space for one operator to operate valves (subject to valves mounting elevation)			
	2. The distance between an operator's access area and valves mounting point is within the maximum reaching parameter (arm length)			
	3. Hand clearance at the surrounding area of valves' lever and hand wheel operation area			
	4. Sufficient standing area for one operator' access and body movement in front of vessel's feed flange, including temporary space allocation for filling medium bags			
	5. A dedicated temporary storage area for filling medium bags prior to transferring to installation location is considered in the layout			
	6. Adequate access platform space for an operator's standing, squatting and crawling (for man escape from the vessel) positions in front of vessel's manhole flange area			
	7. Sufficient clearance at surrounding of vessel's manhole flange (bolts and nuts) for wrench or powered bolting tool operation; consider standard wrench length or powered bolting tool dimensions			
	8. Proper and adequate access platform for one standing operator inside a confined vessel; for operating hand tool and accessing a flat bar support of demister pad			
	9. Access platform inside the vessel is within the maximum reaching parameter (arm length) towards a demister pad mounting location			
	10. Adequate standing headroom clearance above the access platform inside the confined vessel			

Material handling	11. Permanent davit arm with a flexible joint is provided for lifting a vessel’s feed flange cover or manhole flange cover (if the weight exceeds the manual handling limit)			
	12. Opening clearance for vessel’s manhole flange cover; consider extra space in front of opening clearance for operator's access space			
	13. Provision of loading funnel or loading chute for filling medium loading through vessel’s feed flange			
	14. Lifting aid is provided for lifting and loading filling medium bags/drums into the vessel’s feed flange (if the weight exceeds the manual handling limit)			
	15. Adequate headroom for lifting aid operation above the vessel’s feed flange (if required)			
	16. Sufficient size and load capacity of deck trolley is provided for materials handling purpose			
	17. Sufficient width and turning area of handling way from the storage area to the installation location for transferring filling medium bags using deck trolley; considering maximum trolley width			
	18. The weight of the filling medium bags is within the manual handling limit			
	19. The weight of the vessel internal part (e.g. demister pad) is within the manual handling limit			
	20. Design of demister pad can accommodate one-hand holding operation to improve handling flexibility inside the confined vessel			
	21. Sufficient withdrawal clearance to remove demister pad inside the vessel; considering extra clearance to improve handling flexibility			
	22. Lifting aid arrangement is provided for lowering down the demister pad inside the vessel (if the weight exceeds the manual handling limit)			
	23. Space clearance for lifting aid installation is allocated with sufficient lifting headroom; consider the demister pad dimensions			

Valves and controls configuration	24. Valves mounting location are within the acceptable height range of operator's standing or squatting position			
	25. Valves mounting location face the operator access direction			
	26. Feed flange (for filling medium container, tank, vessel, etc.) is mounted towards the operator's access area; provide flange extension if the mounting location is beyond the operator's reaching parameter			
	27. Correct labelling of critical valves to avoid human error during valves operation			
	28. Quick connection valve type is considered for frequently accessed utility connection			
	29. Pressure and temperature gauge are mounted within the preferred standing or squatting display range; consider access platform for a higher mounting location gauge			
	30. Pressure and temperature gauge are mounted facing towards the operator access direction			
Tripping and slipping hazard	31. No pipe, electrical cable, steel structure or instrument item within and across the valves access area			
	32. No pipe, electrical cable, steel structure or instrument item in between operator's access area and vessel's feed flange			
	33. No pipe, electrical cable, steel structure or instrument item across in front of vessel manhole area			
	34. Adequate coaming area and drainage system at the drain valve area to prevent liquid spillage on the deck surface			
Working at height	35. Appropriate access/working platform height for accessing the feed flange of the vessel, to ensure the elevation is within the operator's preferred working height			
	36. Vessel's manhole flange elevation is mounted within the preferred access height range from access platform or main deck surface			
	37. Vessel's internal part (e.g. demister pad) mounting elevation is within the acceptable working height range from the access platform			

	38. A portable stool is provided for accessing non-critical valves mounted at a higher elevation			
	39. Sufficient access platform for a standing operator to access pressure/temperature gauge display point			
Bolting	40. Clearance for wrench or hand tool operation at the surrounding area of feed flange (bolts and nuts); consider standard wrench length			
	41. Use of pneumatic or electric powered bolting tool for tightening the flange cover's bolts and nuts; feed flange and manhole flange (for the high-pressure vessel)			
	42. Sufficient clearance for bolting tool access at the bolted joint of vessel's internal part (e.g. demister pad)			
Personal protection	43. Use hand gloves for bolting tasks to prevent hand injury			
	44. Use hand gloves to handle demister pad to prevent contaminant and hand injury			
	45. Adequate hand holding bars inside the vessel are provided for operator's body balancing purpose during dismantling demister pad			
Confined space	46. Manhole flange cover at vessel is mounted within an operator's maximum reaching parameter (arm length) from access platform			
	47. Manhole dimension is sufficient for operator entry that is equipped with coverall, hard hat, breathing apparatus (if required subject to hazard assessment), hand tool, and other safety accessories.			
	48. Provision of secondary escape manhole is considered for confined space entry (subject to vessel size; diameter and height/length)			
Others	49. Sufficient lighting provision in front of vessel manhole to improve the visibility of manhole location from inside the vessel; for rapid escape purpose during an emergency case			
	50. Simple and secured joint mechanism of demister pad is considered to ease removal procedures and eliminate the needs of excessive force and poor body posture			

5.2 Discussion on PEDG

The second research question of this study encompassed the topic on how to effectively integrate the physical ergonomics requirements in an offshore processing equipment during the early design stage while sustaining its technical configurations. The data analysis on the industry experts' evaluation towards the physical ergonomics issues concluded that the maintenance physical tasks had exposed the ergonomics issues towards operators through nine different factors as presented in Figure 5.3. The factors were *material handling*, *access space and reaching area*, *valves and controls configuration, tripping and slipping hazards, working at height, bolting, personal protection,* and *others.* As described previously, these factors were considered as the applicable design themes in a processing equipment design. These inputs were derived from the application of three ergonomics principles—body dimension and body posture, muscular strength, and body movement—which definitely played an important role in eliminating the ergonomics issues in a workplace design (Department of Standards Malaysia, 2005).

The adaption of the ergonomics principles on the assessed PEI had suggested a set of mitigations plan for eliminating the PEI that might arise during maintenance activities. The derived PEDG in this study had outlined the comprehensive specifications of the related maintenance components for engineers' consideration. However, this study has not explored and identify the specific measurements of each design specification to accommodate the Malaysian anthropometrics data. Even though Wulff et al., (1999b) clarified in their study that designers would prefer to have a specific formulation with appropriate design measurements in the HFE specifications rather than general recommendations, the findings from this study had provided a significant ergonomics design basis for an offshore processing equipment, which could be further developed in future study.

5.3 Application of PEDG in projects

To understand how the proposed PEDG could be integrated with an equipment design process, this section will discuss a case study application based on a relevant project phases sequence. In Section 2.4, a discussion on the HFE implementation program has emphasized on two project phases which are FEED and DED stages. The key engineering design activities for the Mechanical discipline during the FEED stage would be an equipment sizing exercise based on processing capacity requirement, bidding process that involved a technology selection and project cost estimation for the final investment decision, and also a layout arrangement and weight control studies to fit the processing equipment within the overall platform limitation. While during the DED stage, the equipment design will be detailed out according to the updated processing design parameters, producing detail engineering design such as general arrangement drawing and other design documents for fabrication and installation stages. The following descriptions explain how the PEDG specifications should be applied in both project phases.

5.3.1 Application of PEDG during FEED stage

Implementation of PEDG during this stage must be initiated through the identification of related packaged equipment that consisted of filtering, heating, membrane, and vessel components. Instead of the processing equipment case studies explained in Section 3.3.1, other packaged equipment within offshore installations that might contain the similar maintenance components are CO_2 membrane removal, oil and gas medium filter vessels, seawater and produced water filters, KO drum, suction scrubber, separator vessels, and many others.

During the FEED stage, these requirements would normally be incorporated into the equipment's specification and scope of supply document, together with the PEDG checklists attachment. This requirement must be recognized as part of the contractual equipment's specifications so that the equipment vendor would incorporate the design requirement in their bid proposal submission and include under the preliminary cost structure for a precise project cost estimation. Between the project management team and engineering disciplines coordination, they must come to a consensus where the PEDG specifications are treated as a mandatory requirement and any deviation should be raised for further evaluation and approval.

Below is a sample of the HFE requirement description that could be incorporated into the equipment's specification document:

> *All aspects of the packaged equipment design shall comply with the Physical Ergonomics Design Guidelines (PEDG) checklists as part of the HFE design process approach. The PEDG checklists are attached in the Appendix section. Vendor shall complete all the checklists and ensure its compliance in respective design documents i.e. General arrangement drawings, 3D model design, etc. If there is any conflict between the PEDG checklist and the process design requirements, the Vendor shall immediately notify the Contractor's HFE Specialist to resolve the conflict.*
>
> *The Vendor shall be responsible for the inclusion of the HFE design standards into their equipment design, by reviewing all relevant engineering documents, layouts, specifications, Vendor's bid package, drawings, operation and maintenance manuals, 3D model, etc. For the verification role, Vendor shall engage with the Contractor's HFE Specialist to audit its compliance. If the Vendor is unable to comply with the specified PEDG requirements, they shall notify the Contractor's HFE Specialist for the non-compliance and provide its justification. An HFE assessment by the*

HFE Specialist shall take place prior to Contractor and Client approval. Any HFE issues or action items shall be tracked through the PEDG checklists.

Both the Contractor and Client have every right to inspect and audit the PEDG compliance within the packaged equipment at the fabrication site during and after the fabrication period.

Subsequently, a request for quotation (RFQ) would be sent to equipment vendors or suppliers to acquire bid proposals of the specific processing equipment. When receiving a bid proposal, an engineer should confirm that the bid proposal has addressed the compliance towards the PEDG specifications as part of their design development and must be considered within the base equipment layout and preliminary cost structure during FEED stage. This is to ensure the physical ergonomics requirements within the processing equipment would not impact the overall platform's layout arrangement and not raise any cost deviation at a later stage.

5.3.2 Application of PEDG during DED stage

The same equipment's specification document from the FEED stage would be forwarded to the DED stage. The PEDG specification should be revisited to ensure it is aligned with the latest design requirement, such as changes in process configuration and components of the equipment. The same process during FEED stage would be performed, which are ensuring the integration of PEDG in the Material Requisition (MR) document as part of the equipment's scope of supply and reviewing its inclusion in bid proposals from vendors.

During the detailed design stage, preparation and evaluation of a technical bid tabulation (TBT) should consider the PEDG compliance as part of weighted factors to accept the offered bid. The HFE Specialist must actively participate in a bid clarification meeting (BCM) and kick-off meeting (KOM) after a purchase order (PO) of the equipment has been placed, to ensure the offered bid package has considered the ergonomic design requirements. When an equipment's vendor submits their design documents and drawings, the compliance section (*yes, no, not applicable*) in the PEDG checklists must be completed by the vendor and reflected in the design details.

The most important process is to carry out a design verification exercise either through 2D or 3D design approach, subject to the availability of 3D model design. The design review is deliberately carried out to verify the adherence to PEDG checklists and explore a potential improvement area with regards to ergonomic design. Any non-compliance issue should be documented as an action item that must be resolved by the vendor. By utilizing the PEDG checklists, the design review exercise could be carried out by the packaged engineer itself with minimum involvement of HFE Specialist. Nevertheless, a complex packaged equipment with unusual physical task approaches might require a specific design review session with full involvement of HFE Specialist (Pray et al., 2014), operation team, and vendor representative. Where the equipment design requires a significant adjustment to comply with the PEDG specifications, a proper approach for tracing the modification progress could also be achieved through the PEDG checklists.

There might be cases where the ergonomic design requirements are not considered during the FEED stage due to the lack of expertise from design contractor and lack of emphasis by facilities owners. In this case, the PEDG checklists could be imposed during the DED stage, as long as the ergonomics consideration which could impact equipment layout and components arrangement are resolved during the early design stage.

The whole PEDG application approach is illustrated in Figure 5.5.

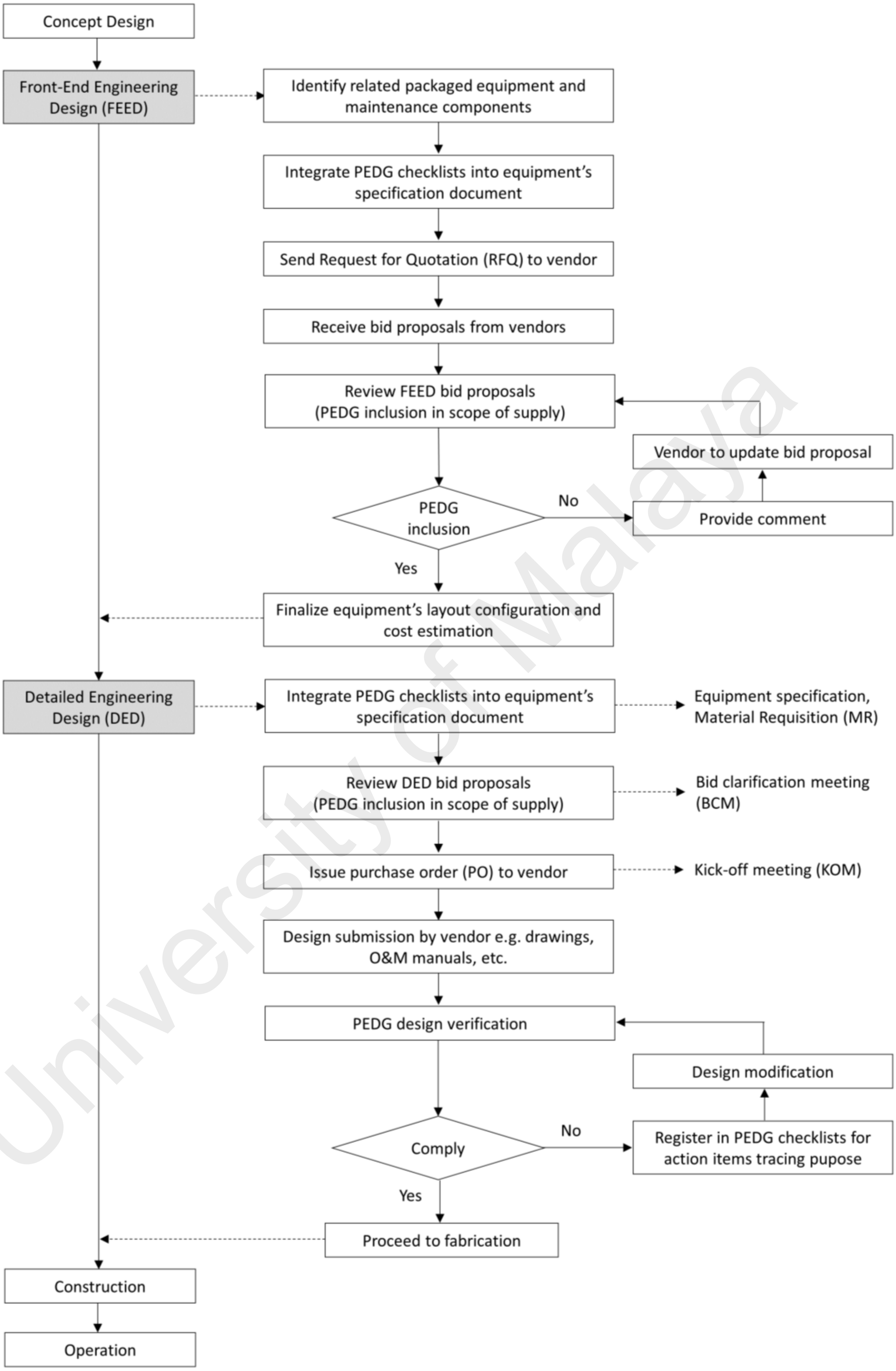

Figure 5.5: PEDG application within project execution phases

5.4 Summary

The previous discussions had elaborated the findings of Part 4 this study and sufficiently addressed the main research problem on how the Malaysian oil and gas practitioners' concerns and operational tasks could influence the physical ergonomics requirements in an offshore processing equipment design. Subsequently, the influenced factors were converted into structured PEDG checklists which could be used by engineers or designers during the early stage of design process.

In summary, the proposed PEDG would benefit end users through the following notations:

i) Addressing the specific and comprehensive physical ergonomics needs for typical maintenance components of offshore processing equipment. The implementation of these front-end design requirements could be properly ensured by package engineers or manufacturers during the early stage of the project.

ii) The nine design themes approach that is established through the PEDG development process might circumstantially improve the physical ergonomics awareness among engineers and designers during the design process. This could be achieved due to the design themes, as elaborated previously, provide a comprehensive outlook towards the crucial physical ergonomics factors in a processing equipment design.

To ensure the proposed PEDG is beneficial to the targeted end users, a validation exercise was carried out on the PEDG checklists and results are presented in Chapter 6.

CHAPTER 6: VALIDATION OF PHYSICAL ERGONOMICS DESIGN GUIDELINES

6.1 Introduction

This chapter discusses the results of PEDG validation towards the end users' expectation criteria, which were evaluated from the technical recommendation and project management perspectives. The results were concluded based on the inputs from five engineers who were involving in designing offshore facility projects. Basically, the validation results explained that the proposed PEDG for the four common maintenance components met the end users' needs of physical ergonomics guidelines during an equipment design process. The following sections describe the validation results in a greater detail.

6.2 Validation result

6.2.1 Technical recommendation

This section presents the results of the end users' feedback towards the technical recommendation criterion against the proposed PEDG, which covers three different factors namely comprehensiveness, design improvement, and technical understanding. The end users' feedback on the comprehensiveness factor would explain how the proposed PEDG added value to the current practice of HFE implementation in a processing equipment design process, where general ergonomics guidelines were required for further interpretation by an engineer to suit the specific requirement in maintenance components design (Wulff, 1999b). In terms of the design improvement factor, it would depend on how the proposed PEDG empowered an engineer to consider the operation and maintenance needs within an equipment design process during the early stage of projects. Lastly, the technical understanding factor would ensure that the proposed design specifications in the PEDG could be easily applied by end users without requiring a further interpretation that might complicate its implementation process.

Table 6.1 presents the percentage of scores from the respondents towards the three validation factors. In view that a positive response referred to the combination of scale rating 4 (*agree*) and 5 (*strongly agree*), the findings indicated that 100% of the respondents agreed the PEDG had fulfilled their expectation during a design process, to such a degree that the PEDG comprehensively covered the ergonomics requirements in a processing equipment design and helped to improve physical ergonomics issues during a design process. Only 60% of the respondents agreed the proposed theme-based PEDG approach was understandable and easy to be implemented in a design process, while the rest were undecided (answer: *neither agree nor disagree*) on their understanding towards the design specifications in the PEDG.

Therefore, based on the validation exercise, it could be concluded that the proposed PEDG was worthy to be implemented in an equipment design process by engineers or designers, simultaneously would enhance the current design approach in ensuring the ergonomics compliance in design.

Table 6.1: Percentage of scores for the technical recommendation criteria

Validation variables	Percentage (%)				
	1	2	3	4	5
Reflecting the comprehensiveness of ergonomics requirements in the components design?	-	-	-	100.0	-
Helping to improve the design issues in an offshore processing equipment design?	-	-	-	60.0	40.0
Technically understandable and easy to implement through the design process?	-	-	40.0	60.0	-

Note: Scores 1 = *Totally disagree*, 2 = *Disagree*, 3 = *Neither agree nor disagree*, 4 = *Agree*, 5 = *Totally agree*.

6.2.2 Project management

The analysis of the project management criterion was divided into two parts. Firstly, the respondents' feedback described their opinion on how important the proposed PEDG should be integrated into different project phases. This finding would prove that the established PEDG from this study was beneficial to enhance their design process in relevant project stages, especially regarding a proper timeline for managing the ergonomics design requirements during projects execution. As shown in Table 6.2, it was found that the respondents believed that the proposed PEDG would be very important (median score: 5) to be applied during the DED phase, similar to the results of percentage calculation where 100% of the respondents scored 4 (*important*) and 5 (*very important*). This was followed by the FEED phase, where a median score was 3 (*moderately important*). Other design phases for the PEDG application were evaluated as a score 1 (*not important)* and 2 (*slightly important*), indicated that those design phases were less significant for the PEDG application.

Table 6.2: Descriptive statistics for the project management factor

Project phase	Median	Description
Concept design	1	Not important
Front-end engineering design (FEED)	3	Moderately important
Detailed engineering design (DED)	5	Very important
Construction	2	Slightly important
Operation	1	Not important

From these findings, it could be concluded that the trend of the most significant project phases for the PEDG application should be briefly applied during FEED and strongly emphasized during DED phases. This approach is aligned with what has been discussed about the application of PEDG during project design phases in Section 5.3.

Lastly, the respondents were asked about the requirement of HFE Specialist supervision for applying the PEDG during a project execution. From the respondents' feedback, a median score recorded *less supervision* answer, showing most of the respondents believed that the application of the PEDG in design process would require less intervention from the HFE Specialist to ensure the physical ergonomic design compliance.

As indicated earlier, 60% of the respondents thought that the technical recommendations in the PEDG were understandable and easy to be implemented in a design process, while the rest were undecided. Hence, the minimum supervision from the HFE Specialist could close this gap and assist the PEDG application. Integrating the role of HFE Specialist into a project organization is crucial to provide a technical support the project team and ensure ergonomics issues are successfully eliminated, due to the ergonomics requirement is not a layman's common sense (Wulff et al., 1999a). To a certain extent, the ergonomics implementation requires an extensive assessment by a professional ergonomist to investigate causes of human errors within an equipment design (Wulff et al., 1999b). In the oil and gas industry that having advanced processing technology systems, a collaboration between the HFE Specialist and industry know-how experts would be very advantageous for exchanging engineering design process and technical information (Halimahtun & Helander, 2012), as well as operational knowledge in offshore installations (McCafferty et al., 2002). The proposed PEDG application arrangement could improve the physical ergonomics requirement in a processing equipment design while maintaining its technical and processing performance.

6.3 Summary

This chapter has described the findings of PEDG validation exercise, which resulted in the proposed PEDG would benefit end-users from the technical and project management perspectives. However, with the availability of PEDG for the filtering, heating, membrane, and vessel components, the HFE Specialist support was still required in a design process with lesser intervention. The role of HFE Specialist here could be to monitor the PEDG implementation and ensure all the physical ergonomics specifications were well incorporated in a processing equipment design throughout project execution phases.

The following notes summarize the results of the PEDG validation exercise:

(a) The PEDG application is most appropriate during the FEED stage through the integration of the PEDG requirements into an equipment design specification as part of contractual requirements during a bidding stage. Thereafter, the PEDG application is continued during the DED stage for verifying ergonomics compliance and design review exercises. This PEDG application approach throughout the engineering design process is aligned with the recommendations from past studies.

(b) It is acknowledged that the PEDG could help to improve the design process of processing equipment in order to mitigate physical ergonomics issues. This approach would reduce the HFE Specialist workload in managing the ergonomics design requirements within the overall facility systems, simultaneously improving the efficiency of working procedures. While ensuring the ergonomics compliance in design by using the PEDG checklists, engineers or designers could pay more attention to other critical design configurations.

The findings of the PEDG validation exercise had answered the third research question of this study.

CHAPTER 7: CONCLUSION

In the previous chapters, the results from the five parts of this study had been discussed to answer the research questions. This chapter recaps the objectives of the study and presents some conclusions, limitation of the study, and recommendations for a future work.

7.1 Conclusion

The central objective addressed in this study was to develop the PEDG for an offshore processing equipment design, by taking into account the Malaysian region perspective and environment. Before summarizing the contribution of this study towards the body of knowledge and industrial design practice, the following notations addressing the three sub-objectives are concluded pertaining to this research work.

The first sub-objective focused on the evaluation of Malaysian oil and gas practitioners' concern and operational tasks during maintenance activities. From the study, the assessment of the Malaysian practitioners' concern towards the physical ergonomics issues within an offshore workplace had provided three important indications. Firstly, their overview of the physical ergonomics subject was not determined by the range of offshore experience and the type of experience factors. Secondly, from some operators' perspective, it was noticed that indirect causes of tripping and slipping accidents at a workplace had been overlooked, which should be considered as part of the PEDG specifications. Thirdly, the criticality ratings of the relevant physical ergonomics issues were identified and had cross-justified the design themes that were established through the PEI assessment (Part 3 of this study). Overall, the three indications that acknowledged through the questionnaire survey suggested the basic philosophies for developing the final PEDG. Additionally, through the PEI analysis of all the maintenance components, nine design themes were identified as the influencing ergonomics factors in a processing equipment design. However, the overall design themes were not applicable to all types of maintenance component due to dissimilar design configurations and maintenance procedures. These findings had ensured the study achieved the first sub-objective.

Second sub-objective aimed to develop the PEDG for maintenance components of offshore processing equipment. As elaborated in Chapter 4, the final PEDG specifications had been developed in a theme-based design approach based on the inputs from Malaysian practitioners' concern and the outcome from operational tasks assessment. In addition, the classified maintenance components based on its similarities in design configuration and maintenance procedures had concluded the outputs in four different sets of PEDG checklist, specifically for the filtering, heating, membrane, and vessel components.

Meanwhile, the third sub-objective set the validation requirement for the proposed PEDG. From the validation process, the proposed PEDG was found to meet the end-users' expectation in the industry practice, whereby most of the respondents intended to integrate the proposed PEDG during preliminary design stages prior to the construction phase and upwards. Thus, the validation outcome fulfilled the third sub-objective of this study.

In contributing to the body of knowledge, the overview of physical ergonomics awareness among the Malaysian oil and gas practitioners which was explored in this study had complemented the additional perspective into the state of ergonomics development and awareness among other industry sectors in the Malaysian region. Furthermore, this study had also contributed to the identification of the crucial physical ergonomics factors that must be considered in a processing equipment design, rather than a general HFE design specification which might not adequately address the specific concerns when carrying operation and maintenance tasks. From a point of view of the industry practice, the outcome of this study had offered added value to the industrial design process, especially when designing a processing equipment during FEED and DED phases. Even though the previous studies stressed the requirement of HFE Specialist's involvement for assessing potential human errors in an equipment design, suggesting recommendations, and completing thorough HFE design review (Wulff, 1999a; Wulff, 1999b; Halimahtun & Helander, 2012; Pray et al., 2014; Chandrasegaran et al., 2016), the proposed PEDG would reduce the workload of the HFE Specialist during a project execution. Besides that, the PEDG could also help to improve the HFE design compliance review by utilizing the theme-based design specifications checklist, simultaneously overcoming the challenging part when a single HFE Specialist with a small HFE working group need to cover more than 200 units of processing equipment in a particular offshore processing platform project.

In summary, the development of PEDG could enhance the engineering design process especially during the preparation stage of the equipment design specification and datasheet, as well as during the vendor data review (VDR), where the general arrangement drawing, and operation and maintenance manuals are developed prior to fabrication and installation stages.

7.2 Limitation of study

The limitation of the scope of this study had facilitated the methodology plan throughout the research campaign and achieved the research objectives within the relevant time boundary. Furthermore, the predetermined scope had driven the exploration of knowledge and industry design exercise within the focused research area, namely the physical ergonomics in offshore facilities design. In the previous discussion, the findings of the physical ergonomics awareness level among the Malaysian oil and gas practitioners were constructed based on their perception towards the common physical ergonomics issues in an offshore workplace. The finding did not comprehensively elucidate from the respondents, a deeper understanding of the theoretical physical ergonomics subject and the competency level of HFE implementation in a design process, as these parameters would require a more comprehensive investigation.

The limitation on the four selected case studies of offshore processing equipment had also been established in this study, hence the findings of the common maintenance components might not cover all types of components that could be possibly installed in an overall processing platform. It was concluded that the proposed PEDG checklists were only specified for the filtering, heating, membrane, and vessel components. Besides that, the assessment of physical ergonomics issues in completing the operation and maintenance tasks was carried out through a face-to-face interview session, guided by the predetermined potential PEI. Although to some extent, this methodology perceived a significant understanding on the study matter, it must be acknowledged that the research findings were limited in the context of the selected case studies and the respondents' feedback leveraged upon the personal hands-on experience within offshore workplaces.

Lastly, the outcome of the study was limited to the PEDG in design specifications checklist form, taking into account the Malaysian perspective and the environment of the local industry. The design specifications did not extend to adapting the Malaysian anthropometric data into each design specification such as integrating the 95th percentile of Malaysian body dimensions into a standing space measurement. The reason was that this exercise might involve an extensive effort by taking into account multiple factors prior to establishing the appropriate calculation of dimensions for the overall workplace design specifications.

Instead of devaluing the outcome of this study, the stated limitations certainly suggested a potential future work to improve the proposed PEDG and pursue the same methodology framework towards a broader scope of maintenance components within an offshore processing platform or other oil and gas facilities design.

7.3 Recommendation for future work

The investigation of potential physical ergonomics issues could be expanded to other relevant case studies which could possibly reflect other categories of maintenance component such as shell and tube heat exchanger, gas turbine, submersible pump, and others. The complexity of physical tasks might increase in a larger and heavier maintenance component, especially for proposing a mitigation plan under the *material handling* design theme.

The effectiveness of the PEDG application could be further improved by manipulating the Malaysian anthropometrics data into the ergonomics design specifications. For instance, further evaluation needs to be carried out to study how the height of the Malaysian population could influence the range of optimum reading height while in a standing or squatting position. To get a proper height range, the evaluation exercise should keep in mind a wide range of body dimensions from 95^{th} percentile male and 5^{th} percentile female data (Hassan et al., 2015). The anthropometric data should suitably be adapted into the proposed PEDG to ensure end-users could apply the ergonomics requirements objectively during the design process, hence curbing an improper interpretation by different engineers or designers on the optimum dimensions of workplace design specifications.

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