A Strategic Decision Support Tool for Shipyard Production Performance Evaluation and Support in Budgeting for Performance Improvement

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Declaration

'This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

Signed:

Date: 21 April 2022

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Abstract

This research has been motivated by a demand from industry for an efficient decision support tool for shipyards to select and implement the right performance improvement strategies that fit the nature of their own business. This research project has developed a strategic approach, named shipyard production performance management (SPPM), to support shipyards to optimise their performance management strategy. The key functionalities of the algorithm include performance evaluation and budget optimisation for planning the improvement activities.

SPPM is designed to evaluate the production performance using an advanced approach based on Key Performance Indicator (KPI) principles. The production performance of the shipyard is reviewed comprehensively from seven aspects, including Health and Safety, economic, environmental, technical, human resource, security and supply chain management. In total, there are 30 KPIs with their calculation details defined to measure the performance from these perspectives. Accordingly, the hotspots can be identified to prioritise the focus for the future improvement. This is not only to select the suitable emerging technology, but also to determine the capital investment required for such activities. How to optimise the budget for performance improvement then becomes the next question for which the shipyards need to find a solution. The budget optimisation function in SPPM has two functions named Performance Based Budgeting (PBB) and Budget Allocation Optimisation (BAO). PBB defines the total budget required with its allocation via adopting the framework of Cooperate Performance Management (CPM), while BAO applies when the total available fund is restricted. Depending on the decision

context and data availability, the BAO can be performed by different calculation methods, including multi-criteria decision analysis (MCDA), utility theory and mathematical programming, for which procedures have been developed in this research.

The development of SPPM is supported by a comprehensive knowledge-based that contains various well-established theories and models, practical experience shared by shipyards as well as numerous relevant researches in the field. More than just direct usage of this knowledge base, SPPM is the extension and combination of various existing theories or the application of these theories in new fields. Benefited from involvement of the shipyards, the developed algorithm has strong practicality, which has been developed as the extracted essence from intensive researches, taking into account of usefulness in measuring performance of each PPI, the data availability of the input parameters, and the level of acceptability and comprehensibility of the algorithm for users, etc. SPPM evaluate the production performance from multiple angles, such as technical, socioeconomics, sustainability, collaboration with third parties, and all the supportive and administrative activities at the shipyard, etc., and provide step-by-step instruction for the assessment. Besides, this tool has also provided the function that allows centralised performance data management.

To sum up from the points above, the SPPM is an innovative and advanced strategic approach that can provide valuable support for the shipyard production performance management.

Content

List of Figures

List of Tables

Abbreviation and Nomenclature

ABC	Activity-Based Costing
AHP	Analytic Hierarchy Process
ATS	Applicant Tracking System
BAO	Budget Allocation Optimisation
BC	Budget Control
BSC	Balanced Scorecard
CE	Concurrent Engineering
CER	Cost Evaluation Relationships
CGT	Compensated Gross Tonnage
CI	Consistency Indexes
CODP	Customer Order Decoupling
CPM	Cooperate Performance Management
CPNI	Centre For The Protection Of National Infrastructure
CSR	Cooperate Social Responsibility
CWBS	Cost Work Breakdown Structure
DALYs	Disability Adjusted Life Years
DEA	Data Envelopment Analysis
DMU	Decision Making Units
DP	Dynamic Programming
EFQM	European Foundation Of Quality Management

EP	Eutrophication Potential
ERP	Enterprise Resource Planning
ETO	Engineer-To-Order
FBC	Feature-Based Costing
FMEA	Failure Modes And Effects Analysis
FRP	Fibre-Reinforced Plastic
GWP	Global Warming Potential
H&S	Health And Safety
HR	Human Resources
HRM	Human Resource Management
HSE	Health And Safety Executive
HVAC	Heating, Ventilation & Air Conditioning
ICT	Information Communication Technology Tools
IOT	Industrial Internet Of Things
IP	Integer Programming
ISO	International Organization For Standardization
IT	Information Technology
KCI	Key Control Indicators
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDT	Light Displacement Ton
LIME	Life Cycle Impact Assessment Method Based On Endpoint Modelling

LP	Linear Programming
MAUT	Multi-Attribute Utility Theory
MC	Marginal Cost
MCDA	Multi-Criteria Decision Analysis
MIP	Mixed Integer Programming
MP	Mathematical Programming
MRS	Marginal Rate Of Substitution
MU	Marginal Utility
NLP	Nonlinear Programming
O&M	Operation And Maintenance
OECD	Organization For Economic Cooperation And Development
OSH	Occupational Safety And Health
P	Rank Of The Probability Of Failure
PBB	Performance Based Budgeting
PI	Performance Indications
PM	Particulate Matters
POCP	Photochemical Oxidant Creation Potential
PPE	Personal Protective Equipment
PPIs	Production Performance Indicators
PWBS	Product Work Breakdown Structure
q	Change In PPI Rating
QC	Quality Control
RI	Random Inconsistency Indices

ROI	Return On Investment
RPN	Risk Priority Number
RTO	Regenerative Thermal Oxidisers
S	Rank Of The Severity Of Failure
SCM	Supply Chain Management
SE	Sequential Engineering
SMART	Specific, Measurable, Attainable, Relevant, And Time-Bound
SMEs	Subject Matter Experts
SOP	Standard Operating Procedures
SP	Stochastic Programming
SPPM	Shipyard Production Performance Management
SWBS	Ship Work Breakdown Structure
T	Rank Of The Adjustment Factor
TB	Total Budget
TC	Total Cost
TQCS	Time, Quality, Cost, Service
VOC	Volatile Organic Compounds
$\mathrm{KPI}_{\mathrm{value}}$	The Measurement Of Actual Performance Directly Calculated From PIs
$\mathrm{KPI}_{\mathrm{min,max}}$	User Defined Acceptance Limit For Each $\mathrm{KPI}_{\mathrm{Value}}$
$\mathrm{KPI}_{\mathrm{target}}$	The Ideal Value Of $\mathrm{KPI}_{\mathrm{Value}}$
$\mathrm{KPI}_{\mathrm{rating}}$	Rate Of Each KPI By A Score Between 0 And 100
$\mathrm{rate}_{\mathrm{j}}$	The Rate Calculated For j^{th} PPI Using The AHP Model
$\Delta\mathrm{PPI}_{\mathrm{i}}$	The percentage of the PPI rating increment for the ith PPI category

PPI_i'	The expected PPI rating after improvement
PPI_i	The original PPI rating
$\overline{\Delta \mathrm{PPI}}$	The average value among $\Delta\mathrm{PPI}_i$ of all categories
w_i	Weighting factors
Cost_n	Cost associated with PPI improvement activities
w_{PPI}	Weighting factors
w_{Cost}	Weighting factors
$S_{\overline{\Delta \mathrm{PPI}},i}$	MAUT score from comparing alternative PBB routes
$WS_{\overline{\Delta \mathrm{PPI}},i}$	Weighted MAUT score from comparing alternative PBB routes
$U()$	Utility function
$f_j(a_i)$	The evaluation of the alternative a_i against criterion j ($j = 1, \cdots, q$) on the corresponded attribute
w_j	Weighting factors
v_k^j	Priority vector for k[th] alternative on criterion j
$P(a_k)$	Total priority level evaluation for each alternative
$S_{j:q}$	The score when comparing Criterion j to Criterion q
λ	Parameter used for AHP inconsistency check
CI	Consistency Indexes
RI	Random Inconsistency Indices
$E(\mathrm{PPI}_i)$	The evaluation of the effort required for different PPI category
BA_i	The budget to be allocated to each category
$\mathrm{PPI}_{i,\mathrm{target}}$	The ideal PPI rating
$\mathrm{PPI}_{i,\mathrm{present}}$	The estimated current PPI rating

p_i	Price
$\theta()$	An arbitrary function
PBB()	The function of calculating the cost associated with improving the PPI from its current status to the ideal solution at the end of the period using the PBB approach

Chapter 1: Introduction

"The secret of getting ahead is getting started."

- Mark Twain

1.1. Background

The shipbuilding industry is dynamic and antagonistic, which confronts increasingly fierce competition from all over the world (OECD, 2018). It is at a critical position in the industrial chain, surrounded by its upstream suppliers such as steel, metals, and machinery products manufacturers, and the downstream customers, such as maritime transport, offshore oil & gas, and vessel recycling etc. (Gavalas, D, et. al, 2021). The development of shipbuilding industry is driven by the demand for shipping various products around the world. According to the market report published by Research and Market, The shipbuilding market was valued at USD 132.52 billion in 2021, and it is anticipated to reach USD 175.98 billion by 2027, at a compound annual growth rate of 4.84% during the forecast period (2022- 2027) (Research and Market, 2022). Such estimation presents an indication of the direction and growing trend of the ship demand.

Building vessels is a gargantuan and complex undertaking that can involve millions of parts and operations, interdisciplinary expertise, hundreds of employees, numerous partners, suppliers and multiple construction sites. At the same time, the competitive market forces shipbuilders to deliver ships faster with minimal production cost to survive. Therefore, shipyards are under considerable pressure to continually monitor and improve their production performance. Manufacturing is widely recognised around the world as a key area for innovation and productivity gains, and shipyard production can be benefited from innovative strategies and technologies such as greater automation or digital manufacturing. However, there is a challenge that shipyards need to select and implement the right performance improvement strategies that fit the nature of their own business to ensure the effectiveness of such strategies.

Performance management is an important part of operations management, widely applied by corporations of all sizes, regardless of their industry sectors and segments (Harbour, J., 2017). It can support the decision making and ensure the company's development and operation strategy is effectively executed. For shipbuilding, the general practice for this can be described as follows. Firstly, the shipyard will carry out a production performance evaluation to benchmark their current performance against their expectations or industry standards to identify aspects for improvement. Traditionally, this was primarily done from the financial point of view, but nowadays, corporations have started to measure their performance from multiple dimensions, including both financial and non-financial perspectives. Accordingly, they can then plan for the improvement activities. This is not only to select the suitable emerging technology but also to determine the capital investment required for such activities. How to optimise the budget for performance improvement then becomes another question for which the shipyards need to find a solution. Considering the sophisticated nature of the shipbuilding industry, a holistic and highly flexible production performance management tool is needed.

Motivated by such industrial demand, this research project developed a strategic approach, named Shipyard Production Performance Management (SPPM) tool, to support shipyards to optimise their performance management strategy.

1.2. Research motivation and gap analysis

Production performance analysis, or performance management, is a common practice widely applied by businesses in manufacturing dominated industries. The research in this field has a long history and there have been numerous well-established theories and models implemented to support business development (Altiok, T., 1997). There has been a long recognition about the importance of performance measurement and management for any business (Melnyk, S. et. al, 2014). It effectively facilitate the control and correction of a firm's strategy by identifying its objectives, the drivers to achieve the objectives, the framework of planned goals, standards and skills required, and all activities to ensure the objectives are met (Osmani, F. and Maliqi. G, 2012). To some researchers (Magretta, J. and Stone, N., 2014), performance management enables the organisations to convey their strategies to everyone else within the organisation via measurable metrics so that they can understand what exactly actions should be taken by each individual on their own role. It was also described by some researchers (Beer, S., 1985; Bititci, U, et. al. 1997) that performance management in a business is equivalent to the body's nervous system that connects the objectives and actions, while sensing the environment and allowing the organisation to adapt along the way. This indicates how important a mature performance management system is for the business to achieve the best results of their development strategy, which motivated the development of SPPM.

The scope of SPPM covers two tasks within the performance management framework: measurement and improvement. To develop the best performance improvement strategy, the cost should also be considered so that the cost-effective activity plan can be developed as profitability is important for all business. Another requirement for an effective strategy is the fit among the environment, strategic intent and what is being measured (Franco-Santos, M, et. al, 2012). Without such a fit, there will be misalignment between what has been measured and what is important to the business, which will result in significant consequences (Johnson, H. and Kaplan, R., 1987), such as waste of resources (such as money, human resources, time, etc.), effort spent in different direction, misuse of the resources or misinterpretation of policies and regulations, etc. Performance management delivers success only if it is integrated or strategically aligned (Smith, M. and Smith, D., 2007) to track the implementation of the firm's strategies and comparing the actual results with the strategic goals and objectives. Therefore, in practice, customisation of the performance management models is necessary when apply to different business fields, such as shipbuilding, to fit the nature of such business. Particularly for shipbuilding, there have been several research works and publications reviewed to understand the state-of-the-art for this topic. The detailed literature review on this topic will be introduced in Chapter 2 Section 2.3.3 in this thesis. In the following paragraphs, the key findings that lead to the research gaps and expectations will be abstracted and highlighted from the literature review section.

The primary observation from the literature review of other researches in shipbuilding performance analysis is that most of them have focused on a particular angle of the production performance rather than developing global metrics. When analysing all the literature together, it can be concluded that the performance should be measured from multiple dimensions, including both technical and non-technical perspectives. Shipbuilding is a sophisticated process, which can be influenced by numerous factors such as human, market, regulation, environment, internal process, supply chain, technology development, and so on. It will require considerable effort to develop a holistic model that could provide decision-makers with the overall picture of their production performance. The ultimate goal for performance management is to develop a strategy for maintenance and improvement. An effective, accurate, and exhaustive performance measurement model builds the foundation for decision-makers to make fair judgements when planning for the improvement activities. Another observation from the literature review is about the level of computation detail of the models. Most reviewed publications have proposed indicators without providing detailed calculation procedures, which may affect the practicality of the models for users to implement. Therefore, developing a comprehensive performance measurement model with a detailed computation procedure becomes the primary requirement for this PhD research. It is not a task just to collect research outcomes from others regarding different aspects of shipbuilding and then simply aggregate for a final result. It is envisaged that the development of SPPM would be based on in-depth research of shipbuilding activities and shipyard management structure. The finalised indicators and their computation procedure will be a combination of collection from existing researches and the innovative ones that are believed important but have not been recognised by some others. Besides, another challenge in this task is to develop a mechanism that could integrate and standardise all the indicators into a comparable scale. This is an indispensable step because otherwise the results cannot be interpreted appropriately, which will affect the subsequent improvement planning, especially when many of the indicators are interrelated.

After a detailed performance measurement, the improvement activities can be proposed focusing on the aspects that are considered as ‘hotspots’. However, the most reviewed relevant researches are normally carried out separately without linking to the performance evaluation. The decision-maker would need to evaluate the effectiveness of such technologies from various angles. To make the right decision all these pros and cons should be considered and compared, which requires a holistic model to be developed that covers all essential figures and have integrated all factors to make the measurements comparable. In addition, the performance management strategy is not only about selecting the useful technology, but also optimising the budget for the improvement. This is not often seen in publications in the context of shipbuilding performance management, although there is a good number of studies of budget optimisation in other applications. Therefore, this PhD research will also include a task to look for the solution to integrate the budget optimisation models into SPPM to form a holistic and highly flexible production performance management tool that can fit the nature of the shipbuilding industry.

There has been also noticed during the initial study that in the shipyard, the data generated every day is innumerable with a great deal of variety, especially for the shipyards that are equipped with advanced digital techniques. For this reason, it will be beneficial that SPPM can also serve as a centralised performance data management system, which allows quick access to the consistent information related to performance management reported from various departments. These data can be either input parameters required for performance measurement or the outputs from SPPM recorded for continuous monitoring.

In summary, it is expected that this research can provide contribution to support shipyards to enhance their competitiveness through implementing effective production performance measurement and improvement strategy. This will be achieved by researching the solutions for the following two questions:

- How to accurately benchmark the production performance at the shipyard and identify the critical areas for improvement.

- How to develop the cost-effective strategy for performance improvement, including plans for activities and optimisation of the associated budgets.

1.3. Research objectives

The ultimate aim of this PhD research is to provide contributions to improve the competitiveness of the shipyards through enhanced production performance measurement and improvement strategy. This research will develop a strategic decision support tool, namely SPPM, for shipyard performance management with focus on shipbuilding related activities. SPPM is consisted of two functionalities: the production performance evaluation and support in developing the cost effective performance improvement plan. It is envisaged that this aim can be achieved through the following objectives:

Objective 1. Repository development of data, information, and knowledge related to shipyard production performance and budget optimisation

This repository provides the information that supports the development of SPPM, which is the cornerstone of the model. It includes secondary database, key factors influencing performance, activities that can potentially improve the performance, mathematical formulas, theoretical models, and information related to shipbuilding activities or shipyard organisation structures, etc.

Objective 2. Model development for shipyard production performance evaluation

This model is part of SPPM, developed using the KPI (key performance indicator) based approach. The model evaluates the shipyard through reviewing its production performance in the aspects, named Production Performance Indicators (PPIs), of technical, economic, environmental, H&S, security, Human Resources (HR), and supply chain. The employment of KPI model was determined after comparison of several popular performance management tools. While the selection of PPIs is based on the literature review and consultation with shipyard SMEs regarding the shipbuilding procedures and shipyard operation practices.

Objective 3. Model development to support the budget optimisation for performance improvement planning

This model provides decision makers the function to optimise the budget that is planned to invest on performance improvement activities aiming at achieving the maximum effectiveness from such investment. Depending on the purpose of the optimisation, it can be carried out to as Performance Based Budgeting (PBB) where the most cost-effective performance improvement activities can be planned. The algorithm can also be performed to help with budget allocation in the scenario when the total available fund is restricted.

Objective 4. Presentation of model applicability and capability through a demonstrative case study

A demonstrative case study is designed to simulate the actual situation of the shipyard to the greatest extent possible. It is envisaged that most data used in the case study will be collected from the collaborative shipyards. Where there is concern in confidentiality, the assumed data or literature data will be applied and reviewed by the shipyards to ensure its validity.

1.4. Research innovation and advancement

As the main outcome achieved by this research, a strategic approach has been developed to support the production performance management of shipyards with focus on the shipbuilding related activities. To summarise, the knowledge-base that supports the development of SPPM contains various well-established theories and models, practical experience shared by shipyards as well as numerous relevant researches in the field, which ensures the validity of the developed algorithm. Meanwhile, the final deliverable of SPPM is not just a direct usage of this knowledge base. It is, in fact, the extension and combination of various existing theories or the application of these theories in new fields. This is where the innovation and advancement of SPPM can be primarily reflected. Descriptions about SPPM algorithm and its development process have been explained in the Chapter 2 and 3 in detail.

Moreover, strong practicality is also one of the advantages of SPPM. The choice of every KPI, and budget optimisation models is the extracted essence from intensive researches, which takes into account of its usefulness in measuring performance of each PPI, the data availability of the input parameters, and the level of acceptability and comprehensibility of the algorithm for users, etc. There were active involvement from shipyards during this research process. In fact, many of the KPIs were selected based on their comments about the real issues they have actually experienced during the production.

The development target of SPPM is to create a very comprehensive tool to support the shipyard’s production performance management. As observed from literature review, there have been various researches carried out regarding the shipbuilding performance and some of them have also applied the KPI based approach. However, comparing with existing researches elsewhere, there can be seen the strong advancement of SPPM in terms of its completeness and level of detail and coverage. Most existing studies, as per the literature review, are focusing on the performance evaluation from technical perspective, such as productivity, quality control, or cost estimation, etc. There are also separate researches performed considering the socio-economic performance of the shipbuilding industry. However, most of these publications are rather introductory and relatively one-sided. This is partially because of the diverse backgrounds and research interests of the researchers. There are two conclusions that can be drawn from such observation. Firstly, the production performance should be a result of impacts from multiple factors, including technical, socioeconomics, sustainability, collaboration with third parties, and all the supportive and administrative activities at the shipyard, etc. Therefore, an innovative and advanced performance management tool, such as SPPM, that can evaluate the performance from multiple different but interrelated dimensions is desired. In addition, SPPM has paid specific attention to detail providing step-by-step instruction for measuring each KPI including what inputs are required, who is responsible, how to calculate, how to interpret the results, etc.

Another advancement of SPPM is the service provided after the performance evaluation. The performance measured from multiple aspects will be interpreted using MCDA approach to support the decision making for the future improvement. Comparative studies can be also performed against historical record or other shipyards. Moreover, in addition to performance benchmarking where most studies have concluded at, SPPM will take advantage of such assessment results and continue to provide budget optimisation function with detailed calculation procedures for improvement activities, aiming at achieving the most efficient and cost-effective activity plan. The application of such functions is innovative in this context, and it is believed that it can provide valuable support for users to formulate future improvement plans.

Besides, this tool has also provided the function that allows centralised performance data management. The unified data model allows user to establish a single repository where they can quickly access consistent information related to performance management reported from various departments, easily move between reporting the past and projecting the future, and drill to detailed information. This has been discussed further in Chapter 3.

To sum up from the points above, the SPPM is an innovative and advanced strategic approach that can provide valuable support for the shipyard production performance management.

1.5. Research approach

The main research activities carried out in this project include desktop study, site visits and interviews. Figure 1 shows the overall flowchart of the project and the task dependency.

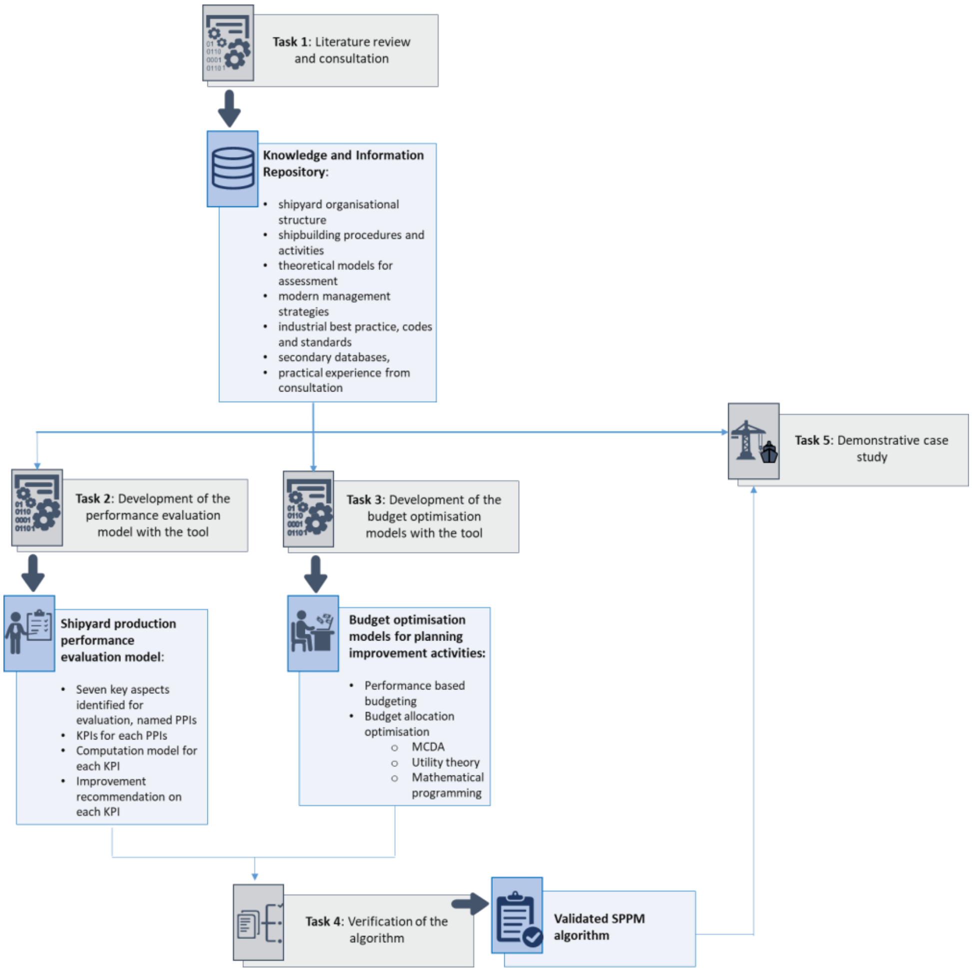

Figure 1: The project flowchart and task dependency graph

The research objectives are expected to be achieved through the following tasks:

Task 1. Literature review and consultation

In this task, a comprehensive literature review has been carried out including review of secondary databases, relevant publications, industrial best practice, codes and standards, etc. The scope of the review consists topics such as shipyard organisational structure, shipbuilding procedures and activities, the information and data related to each PPI (such as indicators, measurement models, activities that can potentially improve the performance), the theoretical models for assessment such as KPI approach, budget optimisation, Multi-Criteria Decision Analysis (MCDA), utility theory, and mathematical programming. The review also includes the emerging technologies or modern management strategies that shipyard can potentially implement to improve their production performance in various aspects. These potential activities is part of SPPM database that provides recommendations when plan for the future improvement. This task also includes consultation with Subject Matter Experts (SMEs) from shipbuilding industry, including shipyard, ship owners, classification society, relevant technology providers, etc. Such consultation can provide practical information beyond the textbook knowledge, which is an efficient way to guide the direction of the research, to identify the key area where this research should pay more attention to, and to help in verification of the innovative models developed in this project. The outcome from this task is the development of the repository, which provides the information supporting the development of SPPM. To summarise, this knowledge-base can support the development of SPPM that contains various well-established theories and models, practical experience shared by shipyards as well as numerous relevant researches in the field, which ensures the validity of the developed algorithm. Meanwhile, the final deliverable of SPPM is not just a direct usage of this knowledge base. It will be, in fact, the extension and combination of various existing theories or the application of these theories in new fields.

Task 2. Development of the performance evaluation model with the tool

This task aims at developing the algorithm of performance evaluation model, and implement it into a prototype using Microsoft Excel. The relevant data, know-how, information and expert judgement collected from Task 1 will be used to support this task. Firstly, the principle of KPI approach is reviewed to identify the suitability of this approach for SPPM, and to develop the specific performance evaluation framework for

SPPM. Secondly, the shipyard organisational structure and shipbuilding activities are reviewed to identify the PPIs. Accordingly, each PPI is studied in detail to develop its performance evaluation procedure. For each PPI, the shipbuilding activities within such aspect are reviewed followed by identification of the corresponding KPIs and their associated computation procedures. Finally, the recommendations on potential improvement activities against each KPI are derived from the repository developed in Task 1.

Task 3. Development of the budget optimisation models with the tool

This task aims at developing the algorithm of budget optimisation model, and implement it into a prototype using Microsoft Excel. The relevant data, know-how, information and expert judgement collected from Task 1 is used to support this task. The task starts from reviewing a range of well-established budget optimisation models to shortlist the suitable ones for use in SPPM. Then, the principles of these shortlisted models are studied in detail. Accordingly, specific optimisation procedures are derived from these theoretical models to fit for the purpose of SPPM. As defined in objectives, the budget optimisation in SPPM has two directions named PBB (Performance based Budgeting) and BAO (Budget Allocation Optimisation). The calculation methods selected for BAO are MCDA, utility theory and mathematical programming.

Task 4. Verification of the algorithm

The developed algorithm of SPPM is verified in this task. The verification is performed by calibrating the algorithm through its supportive theoretical models, the industrial best practice, codes and standards, as well as the relevant research work carried out elsewhere. It is also be supported by model review from SMEs through presentation at knowledge exchange event and interviews.

Task 5. Demonstrative case study

In this task, a case study is designed to demonstrate the assessment procedure and model capability of SPPM. The repository developed in Task 1, especially the information collected through consultation to the SMEs, provides the input data to design the case study, aiming at simulating the actual situation of the shipyard to the greatest extent possible. All theoretical models that have been reviewed and developed in this research are applied to this case. Performance improvement plan is proposed based on the recommended activities reviewed in Task 2. The effectiveness of such improvement activities will be analysed in the context of the case study.

1.6. Structure of the thesis

The overall structure of this thesis is in line with the development process of SPPM. It is expected that this thesis will provide the detailed introduction of the functionalities built in SPPM as well as the corresponded theoretical models implemented. It will also include the description of the work carried out towards the achievement of the abovementioned research objectives. All technical chapters are consisted with literature review, model description and the process towards model development. In total, this thesis contains five chapters:

Chapter 1. Introduction

This chapter is the overall introduction of this project and the research work carried out. It includes the introduction of project background and motivations, research objectives, research innovation and advancement, research approaches and the structure of this thesis.

Chapter 2. Literature Review

In this chapter, the findings from literature review and consultations with shipyard SMEs are documented. The scope of the review and the consultation has been summarised in the Task 1 description.

Chapter 3. Shipyard Production Performance Management (SPPM) Tool

This chapter provides the detailed introduction of the functionalities built in SPPM. It explains the stepwise procedure on how to use SPPM to evaluate the shipyard production performance and to optimise the budget plan for improvement activities. Besides, this chapter also includes the clarification of the basic assumptions applied as well as discussion about the applicability, capability and limitations of the algorithm as a whole.

Chapter 4. Model verification and case study

This chapter consists of the description of the effort spent on verifying the developed assessment models and a hypothetical case study to demonstrate the procedure, applicability and capability of SPPM.

Chapter 5. Conclusions and future works

This chapter is the conclusive summary of this PhD, which is the list of all findings, developments, achievements and future expectations from this research project. It is also followed by a discussion about the future work that can be carried out beyond the current PhD.

Chapter 2: Literature Review

"There is no friend as loyal as a book."

- Ernest Hemingway

2.1. The shipyard and shipbuilding overview

This section is the overview of the shipyard organisation and shipbuilding process based on literature review as well as consultation with experts from shipyards. During the review, several shipyard organisational charts were reviewed to understand how the shipyard is organised and managed in general. Figure 2 to Figure 6 are some examples of typical organisation charts reviewed from shipyards in India, Turkey, China and Japan (Goa Shipyard, 2021; Citizen Charter 2021; Selah Shipyard, 2021; COSCO, 2022; Tsuneishi Shipbuilding, 2021).

As can be seen, although each shipyard has different departments or offices, there is a similar hierarchy in it, which is the two levels of general management. The management Board is on the top level to be responsible for the destiny of the entire enterprise. On the other level, the management is focusing on more routine operational activities. This arrangement would provide the executives at the Board level more time, information and even psychological commitment for long-term planning and appraisal of the shipyard business. At the same time, the responsibility and necessary authority for the operational administration is assigned to the general managers of the multifunction divisions (Wood, J. and Wood, M., 2003). This hierarchy is a result of the change of the operation mode happened to the shipyard during early 1960s, when more shipyards started to adopt the product oriented organisation mode rather than function oriented organisations. Modern shipyards are organised mainly in three ways – function, product and hybrid (matrix). With the development and application of concurrent engineering and group technology, the product or product oriented hybrid (matrix) organisation structure becomes more popular for the shipyards worldwide (Roque, P. and Gordo, J., 2020). It helps shipyards to overcome the fundamental weakness of functional organisation structure which is the lack of communication between departments.

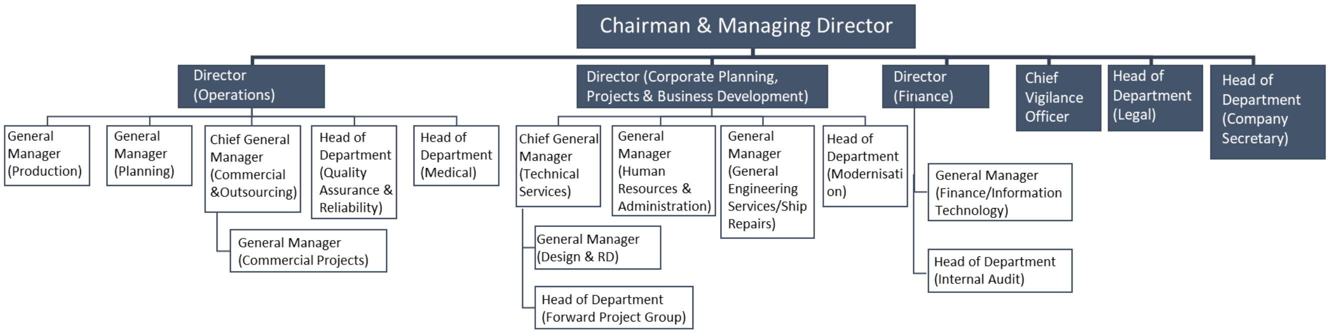

Figure 2: Typical organisation chart of a shipyard in India (Goa Shipyard, 2921)

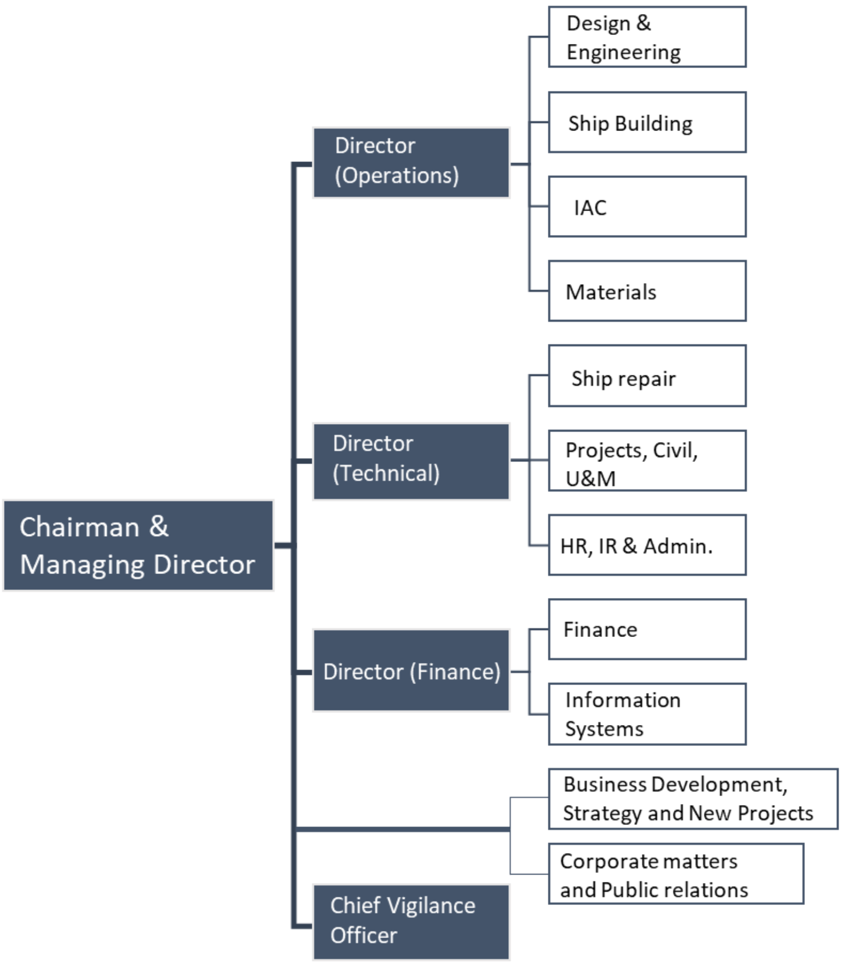

Figure 3: Typical organisation chart of a shipyard in India (Citizen Charter 2021)

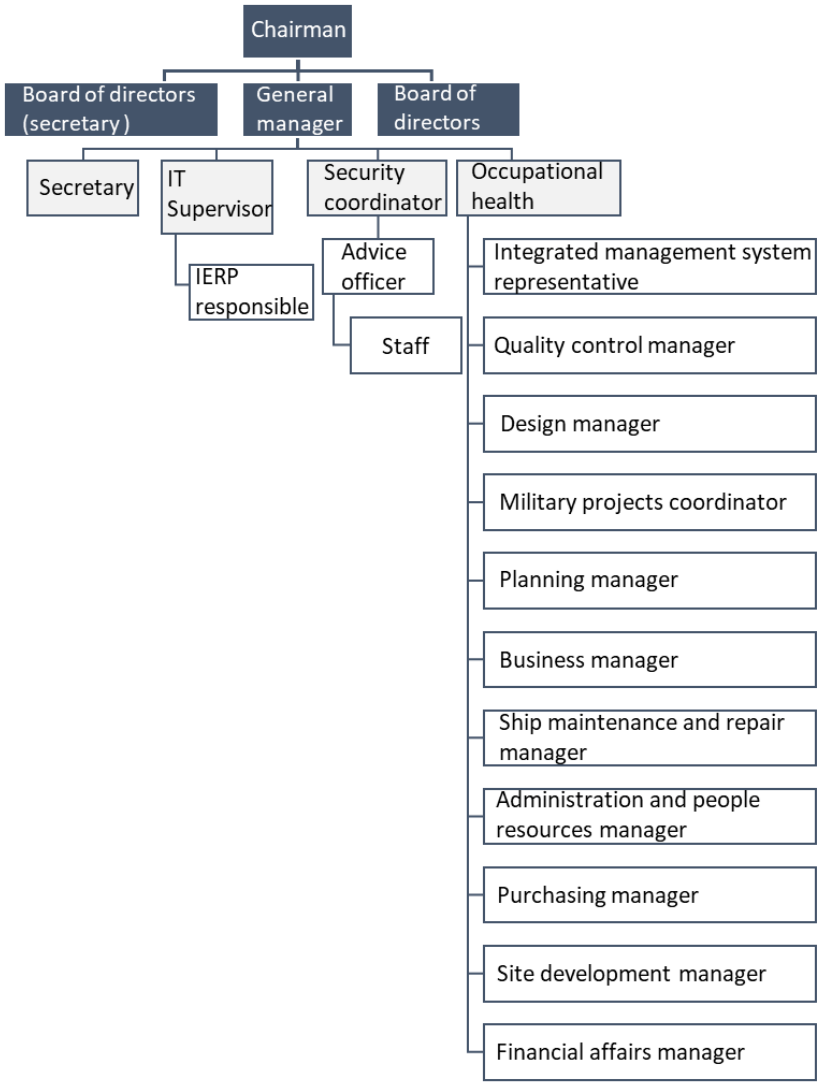

Figure 4: Typical organisation chart of a shipyard in Turkey (Selah Shipyard, 2021)

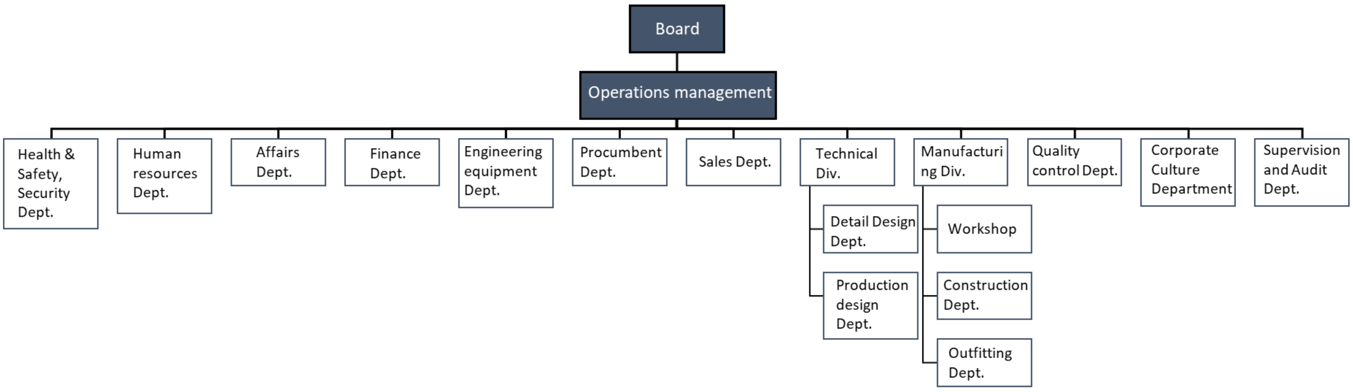

Figure 5: Typical organisation chart of a shipyard in China (COSCO, 2022)

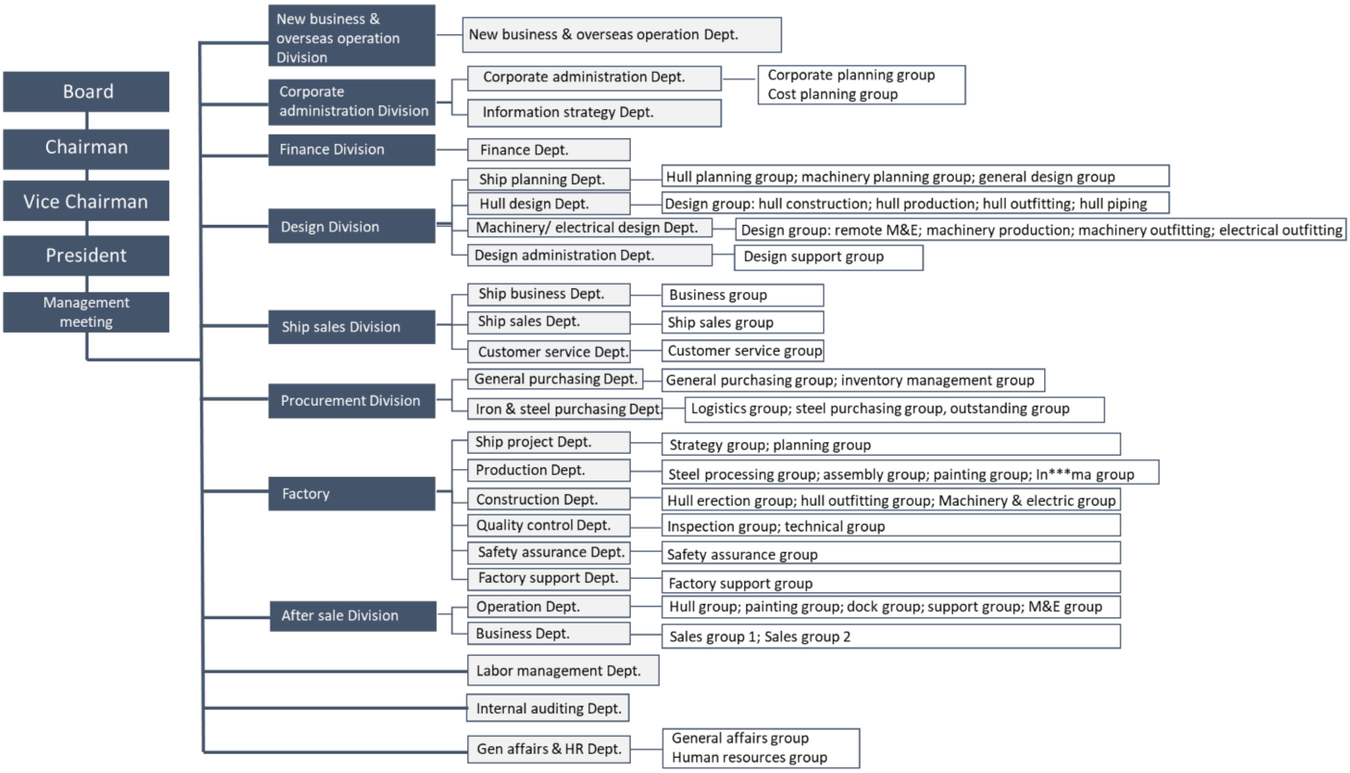

Figure 6: Typical organisation chart of a shipyard in Japan (Tsuneishi Shipbuilding, 2021)

In general, any shipbuilding processes will go through the phases such as Contract signing, Basic project, Detailed production project, Ship hull production, Outfitting, Sea trails and certification, and Ship owner delivery (Van Dokkum, K., 2008). Particularly with regard to the construction related phases, each shipyard will adopt their own production strategy. One of the widely implemented production strategies in today's shipyards is based on Product Work Breakdown Structure (PWBS) developed to support the group technology. It generally suits for a product oriented organisational arrangement (Pal, M., 2015). In practice, most of the shipyards will build several ships at the same time with significant variations (Roque, P. and Gordo, J., 2020). Applying group technology means the shipyard can make the use of standardisation to gain the benefit of mass production. The identical products will be grouped and the work can be hence broken down accordingly. When applying PWBS, the parts and sub-assemblies will be grouped by their common permanent characteristics, such as form, dimensions, tolerances, material, and types and complexity of production machinery operations. Such classifications relates the parts or sub-assemblies to a zone of a ship as well as to work processes (Pal, M., 2015). When the work has been subdivided, a natural breakdown for schedule reporting and collection of financial data can be provided. PWBS will also define the methods of planning, scheduling, and construction actually to be used by the shipbuilder.

Based on the principle of ship PWBS and group technology, the shipbuilding activities can be summarised as shown in Figure 7 below (Roque, P. and Gordo, J., 2020; Pal, M., 2015). These activities can be grouped as production activities, engineering activities and support activities. The production activities includes hull work (includes steelwork and outfitting steelwork), outfitting (includes piping, electrical and HVAC (Heating, Ventilation & Air Conditioning) work), painting, accommodations installation and other support activities. Typically, the work flow can be described as shown in Figure 8 (Pal, M., 2015; OECD, 2010). The fabricated and surface treated basic steel parts will be assembled into blocks, then the blocks will be fitted and welded for erection of ship structure. After this, there will be outfitting of the ships with equipment as well as preparation and installation of parts that are not for structural purpose.

Support activities, such as management, tendering, QC (quality control), logistics, cost control, and safety, are not directly involved in production, but are essential to support and provide information to the production. For each activity, there will be associated cost centre where the hours and resources allocated for such activity are registered. Table 1 lists some examples of such resources (Pal, M., 2015).

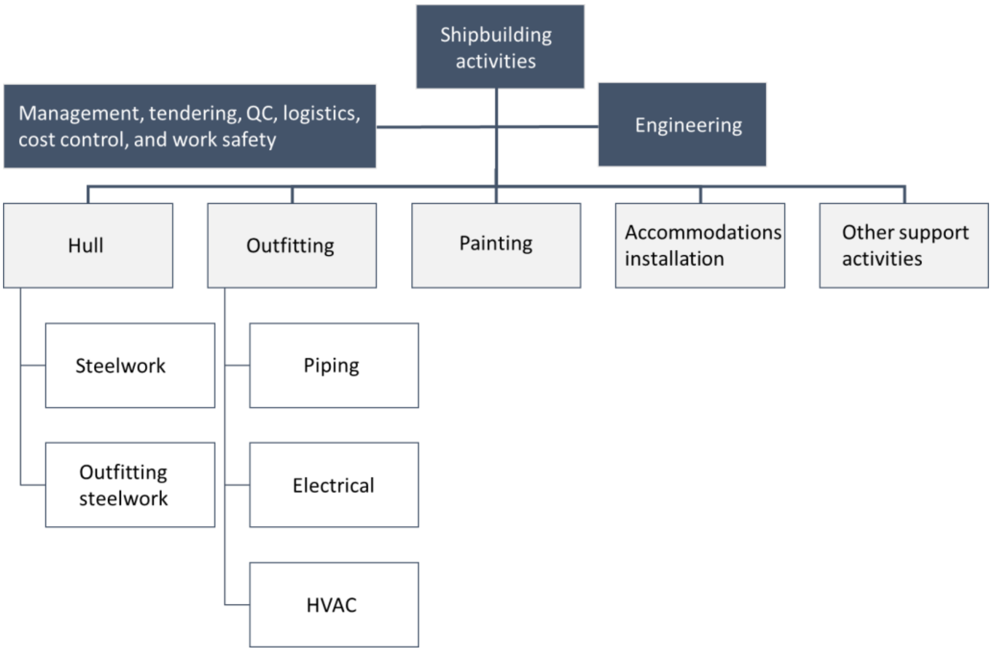

Figure 7: Overview of shipbuilding activities

Furthermore, according to PWBS, the interim products can be classified by four product aspects which controls the production processes (U.S. Department of Commerce, 1980; Doerry, N., 2006). These four terms are system, zone, area and stage. System and zone are related to ship design function. System refers to a structural or an operational characteristic of a production, such as fuel-oil service system, deck lighting system, etc. Zone means a geographical division of a product and their subdivisions or combinations, such as engine room, cargo hold, operations room, etc. Area and stage are with remit of production function. Area is a division that enables production processes into similar types of work problems by features, quantity, quality, or work type, etc. Finally, the stage means the different stages during production cycle, e.g. preparation, fabrication, assembly, etc.

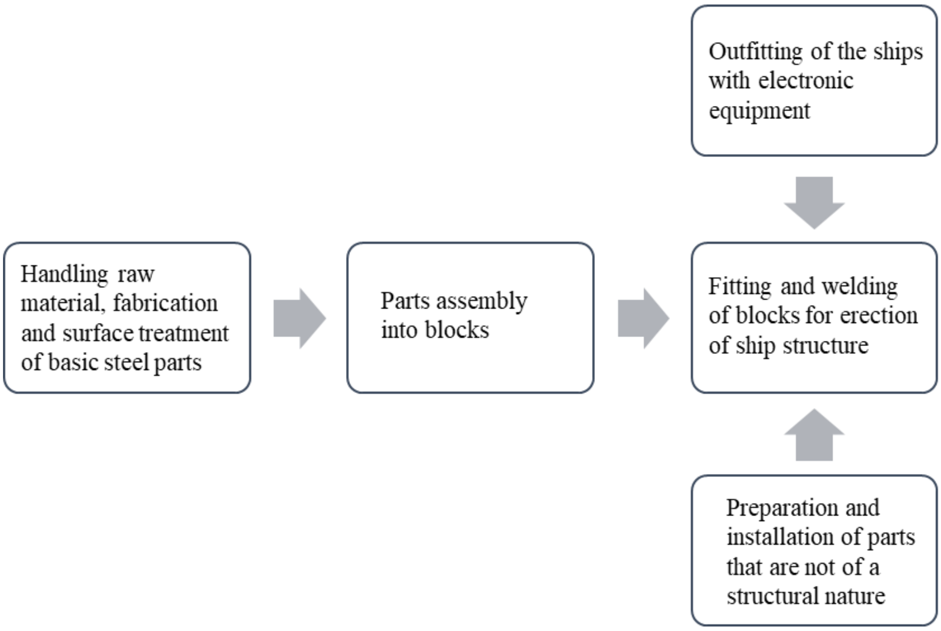

Figure 8: Brief flowchart of production activities for shipbuilding

Table 1: Examples of resources needed for shipbuilding classified by PWBS

Resource categories	**Examples**
Material	Steel plate, consumables, cable, etc.
Labour	Welder, fitter, rigger, transporter, etc.
Facilities	Building, docks, machinery, tools, etc.
Expenses	Designing, transportation, sea trials, procurement, etc.

Moreover, there is another widely applied work breakdown model for shipbuilding named Ship Work Breakdown Structure (SWBS). SWBS is a modular concept technology which breaks down the ship in to definable sub-products, such as ship – blocks – sections – assemblies – subassemblies – parts. Along with each sub-product, the associated work stages and work types will also be defined following the path illustrated in Figure 9 (Caprace, J. and Rigo, P., 2012). According to this production model, the shipyard will be organised based on hierarchical work stages and work types. The shipyard will be arranged with various sectors, which will rely on different workshops to carry out the production tasks at different production stages. For example, at the assembly stage, the ship erection sector will perform the work relying on the dry dock workshop. One of the tasks involved in this stage is welding and activities for welding include machining, preparation, welding and tracing, etc.

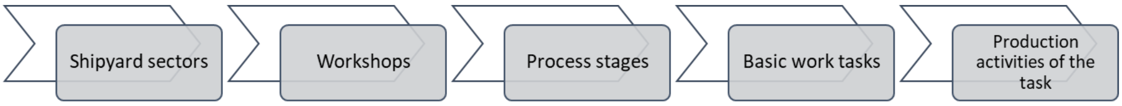

Figure 9: Illustration of the complete work path of the SWBS model (Caprace, J. and Rigo, P., 2012)

In addition, the application of PWBS may also provide the foundation for modular ship system production, which divided the ship production process into number of modules used in parallel construction. In this production system, the same blocks will be produced in one batch and assigned to different shipyards. Then these blocks will be assembled at one shipyard into a ship (Intan, B.,et. al. 2020).

Similar to PWBS and SWBS, there are many other models to break down the production work, such as the Zone Work Breakdown Structure (ZWBS), SFI group system, Ship Work Breakdown Structure (SWBS), Program Work Breakdown Structure, and so on.

Another technology contributed to the shipyard organisation and operation revolution is the employment of concurrent engineering (CE), which encouraged the development of hybrid (matrix) type of organisation chart. CE is a work methodology aiming at improving product quality while reducing the cost and time required to bring the product to market by emphasising the parallelisation of tasks using integrated product team (NPD Solutions, 2016). This concept was first well-defined by the Institute of Defence Analyses in America in 1988 (Ma, Y., et. al. 2008). To apply CE, firstly, a multifunctioning project team consisted of personnel of design engineering, manufacturing engineering, and other functions are built at the beginning of the project. This will ensure the requirements and information of the entire product life cycle can be provided to the designers so that many foreseen risks can be taken into account at the design stage (including design of product and production process) to improve the design quality and reduce the wastage. Comparing with the traditional sequential engineering (SE), CE is more process and object-oriented. This means though everyone in the project team is given different tasks, when performing their function, they should all be guided by the product objective and consider collaboration with other team members to ensure the integration of the entire process. The target of CE is to achieve the optimisation of the entire system, rather than improving the performance of a single department or quality of an element of the product. For example, the competitiveness of a product is normally evaluated by their TQCS figure: time (to deliver), quality, cost and service (Fish, L., 2011). Every business has its own reasonable position of competing objectives, sometimes it maybe cost, sometime it maybe quality, and sometimes it maybe the aggregation of all TQCS. In such situation, the production system guided by CE work methodology can be every time customised to meet the different objectives. This is in line with the core idea of SPPM that the production performance of a shipyard is based on a comprehensive evaluation of the entire shipbuilding process involving activities performed by various functional departments, and can be customised based on the individual business objective.

Figure 10 is an example of how to relate different tools and people to design process and how they communicate with each other in shipbuilding using CE work methodology, adapted from a proposed generic CE environment framework for boatbuilding (Pahl, G., et. al. 2007; Sobey, A., et. al. 2012). According to this framework, personnel associated with design, production, sales and the customers themselves together with the computer system and databases are all available to the design team through access to the CE environment. All input information is stored in the database and can be used for conceptual design to optimise the structure and production process, by applying techniques such as quality function deployment and neural networks. These optimisations will also take into account of comments from teams to be involved in detailed design and production stage and will be an iterative process.

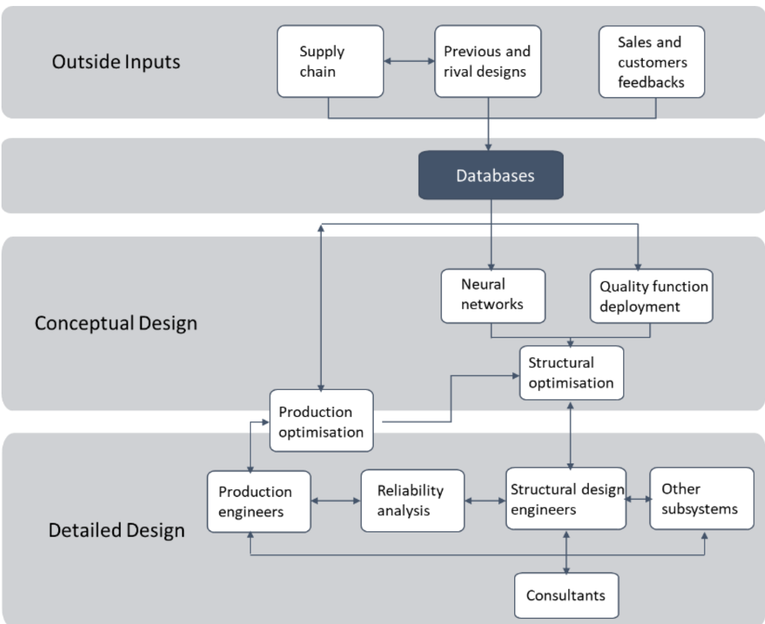

Figure 10: Example of relationship between different tools and people and design process in CE environment (Pahl, G., et. al. 2007; Sobey, A., et. al. 2012)

Statistics shows that the use of CE can make significant change in shipbuilding performance. Table 2 is the gains achieved in shipbuilding by implementation of CE methodology (Eaglesham, M., 1998; Bennett, J. and Lamb, T., 1996; Sobey, A., et. al. 2012).

Table 2: Gains achieved in shipbuilding by implementation of CE methodology

Characteristic	**Change**
Development time	30–70 % reduction
Engineering changes	65–90 % reduction
Time to market	20–90 % reduction
Overall quality	200–600 % improvement
Productivity	20–110 % improvement
Dollar sales	5–50 % improvement
Return on assets	20–120 % improvement

Overall, though each shipyard is organised differently based on their own production and operation strategy, some of the departments (or divisions) that involved in production process are common. This means regardless of the diversity of the business nature, these aspects of the strategy are important to all shipyards and must be operated and managed appropriately. Therefore, to achieve their targeted overall production performance, the shipyard should focus on maintaining a high level of performance in these aspects. Therefore, in SPPM, these aspects are assigned to be the criteria to measure the shipyard production performance, i.e. the Production Performance Indicators (PPIs). PPIs is the terminology employed by SPPM in this research which will be explained in detail in Chapter 3. These departments includes Technical departments (including ship repair, engineering, construction, QC, etc.), General operation departments (including H&S and security, etc.), HR and administration department, Finance department, and Procurement department. In addition, most reviewed shipyards also have departments, such as business development, cooperate matters and governance, sales and after sales, etc., are in common. However, considering these are not directly involved in the production process, such aspects of the shipyard business are excluded from the scope of the current research.

According to the above literature review, technical departments, also named as manufacturing, construction or shipbuilding departments, are responsible for core production activities. This includes planning and execution of all shipbuilding projects, allocation of resources among the different shipbuilding and ship repair projects for optimum returns, and maintenance of shipbuilding assets including plant and machinery for smooth operations, etc. In SPPM, the performance related to these technical departments is measured by its corresponded PPI, denoted as$\mathrm{PPI_{tech}}$, or $\mathrm{PPI_4}$, which will be discussed in Chapter 3. The involvement of general operation departments to production process as supportive activities mainly includes departments that are responsible for H&S and security. In SPPM, these aspects are assessed by corresponded PPIs $-\mathrm{PPI_{H\&S}}$ (or $\mathrm{PPI_1}$) , and $\mathrm{PPI_{sec}}$ (or $\mathrm{PPI_6}$) respectively. Management of security includes both site security and information security. In some shipyards, the information system is managed by finance department, but it will not affect the applicability of SPPM in this context. Moreover, as the awareness of environmental impact during production raises, all shipyards are taking actions to ensure their business to satisfy the environmental regulations. During the review, it was noticed that different shipyard has assigned this task to different department to manage and it is normally a collaborative activity among various groups. In SPPM, this matter is considered as an important criteria to measure the performance so that a specific PPI (denoted as $\mathrm{PPI_{env}}$, or $\mathrm{PPI_3}$) is included in the algorithm, and is considered as supportive activities managed by general operation departments. The HR and administration department is common in all businesses, which covers all aspects related to the employees in the shipyard. A PPI, denoted as $\mathrm{PPI_{HR}}$, or $\mathrm{PPI_5}$, has been included in SPPM for this matter, which will be discussed in Chapter 3 in detail. Finance department manages all aspects related to the cooperate accounts and project financing, such as fund management, budget, revenue accounts (includes financial vetting of contracts), and risk management via insurance agreement, etc. In the context of the production process, a PPI ($\mathrm{PPI}_{\mathrm{ec}}$, or PPI_2) related to the economic performance has been designed to cover the content that managed by finance department. The last but not the least one is procurement department. The procurement process for ships under construction consists of purchasing and transporting material, various equipment, pipes, cables, fittings and so on. In the other word, it is the management of supply chain for shipbuilding project. Denoted as $\mathrm{PPI}_{\mathrm{sup}}$ (or PPI_7), a PPI is included in SPPM to cover this matter.

2.2. Shipyard Production Performance Indications

In this section, the literature review of each above mentioned PPI will be conducted, including its definition, the scope covered, the evaluation criteria, the measurement models, and the potential improvement activities.

2.2.1. Health and safety performance evaluation

The term H&S, as defined by Oxford Language (LEXICO, 2022a), means ‘regulations and procedures intended to prevent accident or injury in workplaces or public environments’, which is a multidisciplinary subject consisted with concerns regarding the safety, health, and welfare of people. Specifically for H&S in the workplace, the term Occupational safety and health (OSH) is another frequently used term in this topic. As observed from literature review and interviews at the shipyards, a safe and healthy workplace was rated by majority of the shipyards as the first priority to assure their production performance and sustainability. As one of the heaviest production industries all over the world, the shipbuilding process contains numerous production activities that result in OSH hazards.

The impact and cost associated with consequences due to OHS accidents is enormous, which may include delay of the project delivery, loss of reputation, employee turnover, and even regulatory fines and legal action, etc. For instance, as mentioned by one of the shipyards interviewed, the OSH incidents must be statistically recorded and reported with investigation of the cause of the incidents as well as remediation actions applied afterwards. When serious OSH accidents happens, the rules in their country requires that the investigation from external authorities will be conducted and until a conclusion is made, the shipyard must pause all of their production and operation activities. Unlike other PPIs studied in this research, in most countries and industries, OHS is legally enforced by government with detailed requirements clearly mentioned in rules and regulations, which must be strictly followed, otherwise, shipyard (or any organisations) will face severe punishment. Therefore, shipyards will develop their own OHS policies and procedures in light of the regulations and guidelines from relevant government agencies and authorities, such as the Health and Safety Executive (HSE) in the UK, Occupational Safety and Health Administration (OSHA) in the USA, and International Organization for Standardization (ISO). Some of the OHS codes and standards that widely followed in shipbuilding industries, for example, are ISO 45001:2018 (Shipyard Famagusta, 2021), ISO 9000, ISO 14000 and OHSAS 18000 (Çelebi, U., et. al. 2010).

Based on review of the above mentioned industrial standards and OHS policies shared or published by various shipyards (Shipyard Famagusta, 2021; Ajans, P., 2022; Sanmar Shipyards, 2021; OSHA, 2015; European Commission, 2012; HSE, 2022b.)，the activities that involved in shipyard OHS management practices can be generally summarised in Figure 11.

Figure 11: Summary of general activities involved in shipyard OHS practices

The first task is to identify the OHS hazards, which is normally carried out respectively for health and safety topics. With regard to the concern of safety, statistics shows that shipbuilders are more susceptible to injuries than workers from other industries (BLS, 2017a; BLS, 2017b). According to UK HSE, more than half of the accidents reported every year to HSE are because of lifting and moving goods or slips, trips and falls. Between 10 - 15% of accidents involve the use of machinery (HSE, 2022b). Specifically for shipbuilding process, Figure 12 shows a survey result regarding classification of fatal occupational accidents in Turkish shipyards (Yilmaz, A.,et. al. 2015), and Figure 13 listed some of the common risks concerned for occupational safety at the shipyard (Celebi, U., et. al. 2007).

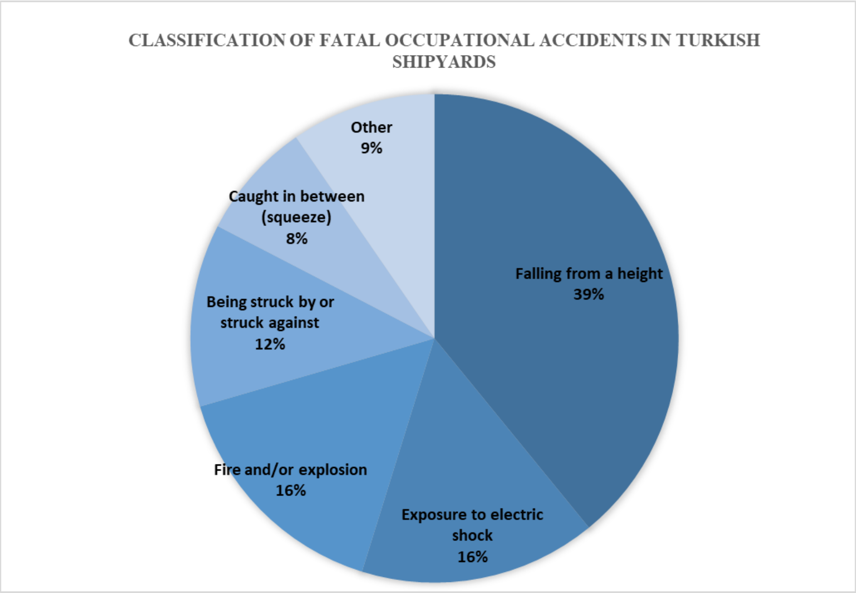

Figure 12: Classification of fatal occupational accidents in Turkish shipyards (Yilmaz, A., 2015)

In terms of threats to health, as suggested by HSE (HSE, 2022a), the common concerns for all engineering industries include:

- Exposure to metalworking fluids, which can cause irritation of the skin/dermatitis and lung diseases
- Exposure to welding fume, which can result in illness
- Nosie, which can cause hearing damage and tinnitus, fatigue and tiredness, reduce efficiency, affect morale and distract and disrupt job performance
- Exposure to the vapour or liquids from the organic solvents used in degreasing, which may be harmful to health, affecting the nervous system in particular

Specifically during the shipbuilding processes, most of these health related hazards are introduced by carrying out production activities for surface preparation, painting and welding (Çelebi, U., et. al. 2010).

Figure 13: Risk of Occupational Safety in Shipbuilding Industry (Celebi, U., et. al. 2007)

After identifying the hazards, next step is for shipyard to plan and implement the prevention and protective measures focusing on such predefined hazards. For each engineering activities or production process, HSE has provided detailed OHS guidance which should be followed by shipyards in the UK. Similarly, OHS authorities or agencies in different countries have also provided the equivalent guidance for the local shipyards in planning their own OHS procedures and policies. Summarising from these guideline documents, the widely employed measures by shipyards can be listed in Table 3 below:

Table 3: List of widely applied safety measures by shipyards

Safety measures	**Examples**
Personal Protective Equipment (PPE)	Use of protective clothing, helmet, safety shoes, safety hand gloves, goggles, ear muff/plug, safety harness, face mask, chemical suit and welding shield
Protecting structure	Sufficient lighting, railings, platforms and mid rails, etc.

Specialised personnel	The skilled technical workers and safety specialists
Staff training	First Aid Training, legal awareness, and shipyard OHS procedures and policies, etc.
Communication	Activities ensuring smooth communication between workers and authorities

In addition to the safety measures, shipyard should also have their incident response procedures in place, and staff should be trained at appropriate level. The responsibility of responders should be clearly explained and made aware to all staff as well as visitors and contractors on site. Finally, all incidents should be investigated, reported, and recorded. Then, the corrective actions will be taken to avoid the recurrence of such accident.

The OHS performance is normally the responsibility of the safety manager at the shipyard. The goal of H&S performance improvement is to minimise the number of incidents. An accident analysis conducted for a Turkish shipyard between 2011 and 2013 found that the most important cause of accidents was “inadequate or non-use of PPE (23%)” followed by “unsafe design (18%)”, “unsafe arrangement (17%)” and “defective or deficient equipment (13%)” (Yilmaz, A., 2015). Therefore, in order to plan for the improvement activities and associated budget plan, shipyard could first carry out the self-assessment regarding implementation efficiency of their OHS policies and procedures with particular focus on if adequate PPE and protective structure has been provided, or if the design and arrangement is safe, or if the maintenance of the equipment is sufficient, etc. However, it was also mentioned by the interviewed shipyards that, though all safety measures and procedures are in place and adequate training has been provided, not all staff will follow the procedure or use the PPEs correctly. Ignorance is the big trouble for shipyard to maintain their H&S

performance based on SMEs' opinions. This means actions should be taken to not only raise the staff awareness OHS measures, but also enforce the procedure to be followed appropriately. For instance, professional safety officer can be employed to inspect and monitor people's OHS behaviour. Incentive and punishment measures regarding cooperation and compliance of the OHS procedures may also be considered to include in the company police.

Moreover, as discussed in the previous section, one of the OHS hazard is the exposure to the metalworking fluids or other chemicals and asbestos. In addition to the corresponded protective measures, shipyard may also considered to replace such production material to alternatives which is less harmful. Various research has been carried out to look for the replacement that is friendly to human and environment. However, this may increase the cost of production so that the decision needs to be made taking into account of its impact on the economic performance of the production as well. Similarly, shipyard may also consider to introduce automated technology and robotic systems to assist the production, such as using robotic arms for welding, blasting and painting etc. (Lee, D., 2014). Use of such robots for manufacturing can help to avoid exposure of the workers to the extreme production environment and hazards that could potentially cause physical injuries. However, this change will have great impact on the entire shipyard production and operation arrangement. Firstly, there will be extra cost associated with this including cost of facilities purchasing and installation, training, rearrangement of the work space, etc. Moreover, there will also be concerns about employee redundancy and upskill because of automated production process that requires less labour and different skills to operate.

Considering the above information collected from literature review, the effectiveness of performance in OHS could be measured from the viewpoints such as OHS risk assessment, effectiveness of safety measures implementation and afterwards corrective actions in case of incidents.

2.2.2. Economic performance evaluation

Economic performance is another important aspect of the overall production performance of a shipyard as a business. It is expected that a good production performance should enhance the profitability of the business. However, it is worth mentioning that the metrics to measure a company's profitability, such as return on investment, return on equity, income, payback period, etc., are a very complex topic, involving too many factors that are beyond the scope of SPPM applicability and less relevant to the actual shipbuilding activities. Considering the objectives of SPPM, the literature review was conducted to the aspects that are directly related to the context of production activities, which are the shipbuilding cost focusing on budget control and shipyard productivity. Such assessment is normally carried out collaboratively by project manager, financial manager and contract manager.

The scope of the budget control (BC) estimation is dependent on the scope of the project that is under evaluation. It indicates how accurate the cost estimation is and how efficient the finance management of the project is. The cost of shipbuilding generally includes the cost of labour, material and manufacturing (energy consumption and equipment depreciation) (Shi, J. and Yuan, K., 2018). More specifically, Figure 14 shows a cost structure of a typical container ship (Lin, C. and Shaw, H., 2017), which is normally managed using cost centres and in line with the work breakdown structure adopted by the shipyard. Research has also shown that half of the construction cost of most vessels' hull is the labour cost but also depends on the complexity of the equipment and type of vessel (Leal, M. and Gordo, J., 2017). The price of material, energy and purchased services is dependent on the locations (e.g. yard in China and Europe will purchase steel at different prices), as well as the labour cost which is also different from country to country. The cost associated with the shipyard's general operation or overhead is not included in the costing model, as it is not directly relevant to the production activities, which may mislead the direction of assessment. The popular cost estimation methods are top-down, bottom-up, life cycle and feature-based costing methods (Leal, M. and Gordo, J., 2017). Each of them has different requirements on cost data availability and can be used in different design stages (Lin, C. and Shaw, H., 2017). The procedures and characteristics of each method are briefly described as follows.

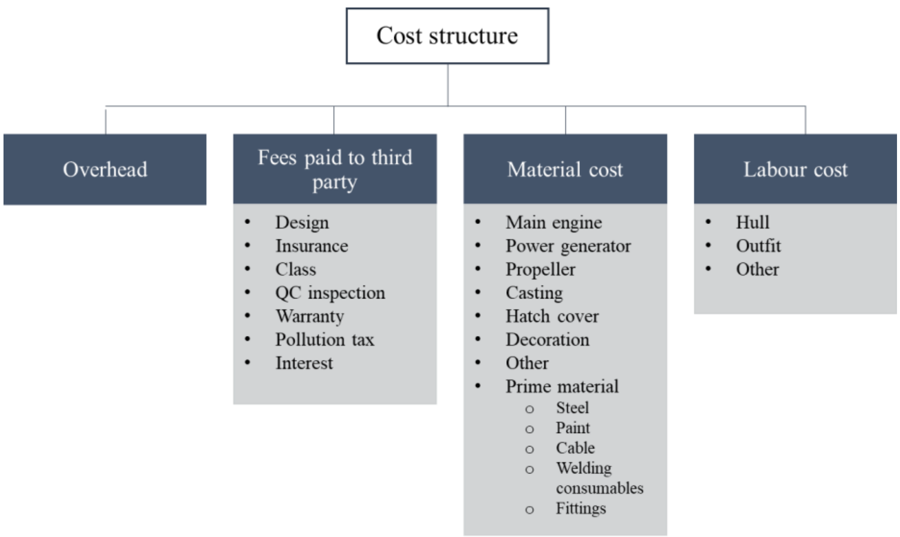

Figure 14: Cost structure of a typical container ship (Shi, J. and Yuan, K., 2018)

- Top-down

  The top-down cost estimation method is a parametric approach estimating the cost of new ships based on the empirical relationships between product parameters and the costs developed using statistical regression from historical cost databases. The parametric relationship can be continuously refined and recalibrated to enhance the accuracy of the estimation. It is a macro approach predicting the cost from the higher level of specification, suitable to use at the early design stage when the detailed design information is not available. The parameters usually required are ship type, ship size, the weight of the hull, the block coefficient, ship area and complexity, etc. hence it is also known as a weight-based approach (Barentine, J., 1996). Top-down is an easy and quick approach, usually used as a reference to support the bid at the very early stage. However, the approach has limitations. Firstly, it is highly dependent on the quality and availability of the database, meaning it only works when there is data of similar previous ships. Moreover, as this is, in fact, the extrapolation from the historical cost database, the method cannot reflect the cost reduction resulting from the implementation of the new technology or new production methods.

To apply top-down, a number of closed-form equations is developed from the historical database. The inputs of these equations are the global parameters that can be derived from the tender document and the output is the approximate cost of the construction.

- Bottom-up

Contrary to the top-down method, bottom-up is a micro approach that breaks the project down to the most fundamental products (e.g. plate) and evaluates the associated costs in detail. It features the change of the production processes the advancement in new technologies. Therefore, it is very suitable for estimating the cost of a new product or performing the optimisation exercises. The basic procedure of bottom-up is firstly breaking the ship into basic products and intermediate products, then estimate the associated costs (e.g. cost of machining, tracking, coating, assembling, etc.), then proceed into its associated intermediate product and the next, more mature intermediate product, and so on (Caprace, J. and Rigo, P., 2012). The bottom-up method considers the actual work content for the shipbuilding to provide a realistic estimation for the construction effort. When working with the design team, it can help to optimise the scantling and shape for achieving the most cost-effective design. The disadvantages of this method are mainly because of its requirement of a large amount of effort and time. The amount of data required to perform this approach made it difficult for the most shipyards to use it as their routine operation.

- Life cycle cost analysis (LCCA)

  LCCA estimates the cost from the ship life cycle perspective. The cost occurred at each life cycle stage of a ship from cradle to grave is calculated using the either top-down or bottom-up method. The life cycle stages are generally including design, production, operation and maintenance (O&M) and disposal. There is a well-accepted fact that over 70% of the product cost are decided in the first 20% of the product development cycle (Fischer, J. and Holbach, G., 2008). This means the use of LCCA can help with a cost-saving from the life cycle perspective. For example, the selection of the coating material in the design and production stage would decide the corrosion resistance of the ship hence affecting the maintenance requirement and service life span. This assessment is normally combined with other assessments for achieving the target of sustainability such as circular economy or

Life Cycle Assessment. However, this is not a popular method among shipyards. It is because the method itself is difficult requiring information to be collected from a variety of levels at different life cycle stages. Besides, the life cycle cost may not be interesting to the shipyard as different stakeholders are involved in the different stages of the life cycle, though it can be used by the shipyard to bid the project by presenting their design can help ship-owners save money from O&M (Bharadwaj, U.,et. al. 2017).

- Feature-based costing (FBC)

  As observed from the review of literature and cost estimation sheets from the collaborative shipyards, the FBC method is widely accepted by many shipyards. FBC is a type of method using analytical approach which is believed to be more accurate comparing with the top-down while more practical when compares with bottom-up and LCCA. This method estimates the cost based on the product's elementary characteristics, i.e. features. To perform FBC, a cost work breakdown structure (CWBS) needs to be developed based on the SWBS as introduced in Section 2.1, hence a sufficient level of detailed design and configuration information will be required.

  Costs of activities can usually be indexed to weight (£/t), distances (£/m), time (£/h) and required person-hours (Ph). Such relationship is called cost evaluation relationships (CERs) (Leal, M. and Gordo, J., 2017). The shipyard usually uses the same attributes for the same activities for each ship it builds and develops a database of CERs for each of its production activities. The database development and FBC execution are normally assisted by delegated software either purchased or developed by the shipyards for their own use. Table 4 presents some of the most common CERs attributed to person-hours (Leal, M. and Gordo, J., 2017). The full list of material and equipment costs are normally assumed to be available information and no estimation is required when using FBC. Based on the CERs, the cost function of each production activity as defined in CWBS can be established. CERs and the corresponding cost functions are shipyard dependent because they are related to the shipyard production facilities, tools and equipment, skill levels of the work, etc. (Caprace, J. and Rigo, P., 2012). For example, Equation (1) is the generic expression of the labour cost ($\mathrm{Cost_L}$) for a simple manufacturing activity (e.g. welding of two steel plates) (Caprace, J. and Rigo, P., 2012) or Equation (2) is for the cost of plasma cutting ($\mathrm{Cost_{PC}}$) (Leal, M. and Gordo, J., 2017).

Table 4: Typical CERs attributed to person-hours (Leal, M. and Gordo, J., 2017)

Production activity	**CER**
Steel preparation	Ph/t
Steel fabrication	Ph/t
Block assembly	Ph/m (of welding)
Block painting	Ph/m^2
Pipe outfitting	Ph/m
Outfit fittings	Ph/EA
Block erection	Ph/t
Cargo hold	Ph/ m^2

$$\mathrm{Cost_L} = \mathrm{Q} \times \mathrm{U} \times \mathrm{CO} \times \mathrm{CA} \times \mathrm{CW} \quad (1).$$

Where, Q is the quantity, such as welding length; U is unitary cost (cost per unit), such as Ph/m (of welding); CO is the corrective coefficient used to calibrate U taking into account of adjustments such as production facilities improvements and productivity, learning effect, economic inflation, high volume business material savings, etc.; CA is the accessibility/ complexity coefficient linking the manufacturing cost with the relative accessibilities/complexities of the ship or their sub-assemblies, Table 5 lists some typical CA values for passenger ship working areas (Lamb, T., 2003); CW is workshop coefficient reflecting the productivity changes from one workshop to another.

$$\mathrm{Cost_{PC}} = \mathrm{Cost_L} + \mathrm{Cost_E} + \mathrm{Cost_{PG}} + \mathrm{Cost_{DE}} = [\mathrm{N} \times \mathrm{S} \times \mathrm{time}] + [\mathrm{E} \times \mathrm{PriceE} \times \mathrm{time}] + [\mathrm{Gas} \times \mathrm{PriceG} \times \mathrm{time}] + [\mathrm{CD} \times \mathrm{time}] \quad (2).$$

Where, N is number of workers performing the activity, S is the worker's wage; time is the hours used for the activity (can be calculated as a function of cutting speed and cutting length); E is the electricity consumption; PriceE is the electricity unit price; Gas is the plasma gas consumption; PriceG is plasma gas unit price; CD is the depreciation cost.

Table 5: Typical CA values for passenger ship working areas (Lamb, T., 2003)

Working area	**CA**
Inside a workshop	1
On passenger deck	1.05
Double Bottom	1.25
Superstructure	1.25
Engine or pump room	1.5

The other proposed evaluation criteria for economic performance benchmarking is the shipyard's productivity. By definition, productivity is the ratio between production inputs and outputs. There are various metrics to measure productivity depending on the intended purpose of the assessment. Table 6 below is a review of productivity metrics and values for major shipbuilding countries: China, Korea, Japan, and Europe (from a survey published in 2007) (Lamb, T., 2007.).

Table 6: Review of productivity metrics and values for major shipbuilding countries (year 2007)

Productivity metrics	**Europe**	**Japan**	**Korea**	**China**
Man hours/CGT, incl. subcontract	12-15	9-15	16-21	52-103
Steel tonnes/Shop area m^2	0.48-0.52	1.7-2.8	1.9-3	1
CGT/Shipyard total area m^2	0.28-0.78	0.3-0.8	0.4-1.25	0.18-0.5
Production workers incl. subcontract/Total employees	0.7-0.79	0.72-0.83	0.7-0.9	0.83-0.93
Total employees/Total area m^2	0.003-0.011	0.001-0.003	0.0043-0.01	0.01-0.016
Annual CGT/Shop area m^2	1.12-2.04	3-6	3-8.5	0.5-1.41
CGT/Employee-year, incl. subcontract	25-140	125-205	95-121	22-39
Steel tonnes/Worker-year, incl. subcontract	8-36	100-270	33-56	15.6-30

As can be seen from the table, inputs for assessing productivity can be the labour, the capital (productive assets), the energy, material and purchased services, or shipyard total area, etc. while the output is usually represented by CGT (compensated gross tonnage) or quantity of the steel processed (Coelli, T., et. al. 2005). Equation (3) below can be used to calculate the CGT for various types of ships:

$$\mathrm{CGT} = \mathrm{A} \cdot \mathrm{gt}^{\mathrm{B}} \qquad (3).$$

Where, gt is the tonnage of a ship (i.e. a calculation of the volume or cargo volume, or cargo-carrying capacity of a ship) A, B are the CGT coefficients depending mainly on the ship types, which can be found in Table 7 as studied by OECD's Council Working Party on Shipbuilding (WP6) (Hopman, J., et. al. 2010).

Depending on the purpose of the assessment, the productivity can be calculated partially or systematically. The partial measurement of productivity, i.e. ratio between individual input parameter and CGT, can be used to study the effectiveness of the resource utilisation when specific type of inputs is targeted. This is easy and straightforward, but cannot provide decision-maker the accurate overview of the productivity which is actually the result of multiple factors. The scientific approach that can be applied to assess productivity from multiple inputs is the Data Envelopment Analysis (DEA) method.

Table 7: CGT coefficient by OECD

Ship type	**A**	**B**
Oil tankers (double hull)	48	0.57
Chemical tankers	84	0.55
Bulk carriers	29	0.61
Combined carriers	33	0.62
General cargo ships	27	0.64
Reefers	27	0.68
Full container	19	0.68
Ro ro vessels	32	0.63
Car carriers	15	0.7
LPG carriers	62	0.57
LNG carriers	32	0.68
Ferries	20	0.71
Passenger ships	49	0.67

Fishing vessels	24	0.71
NCCV	46	0.62
Mega Yacht	278	0.58

The DEA method was initially developed by Charnes A., W. W. Cooper and E. Rhodes in 1978 to measure the productive efficiency from multiple dimensional inputs and outputs (Charnes, A., et. al. 1978). It is a popular method adopted by various manufacturing industries to measure productivity, including the shipbuilding industry. Numerous researches have been published to demonstrate the application of DEA in different manufacturing scenarios (Krishnan, S., 2012; Pourjavad, E. and Shirouyehzad, H., 2014; Amirteimoori, A. and Kordrostami, S., 2012; Ruales. G., et. al. 2021). DEA is a non-parametric approach to assess the relative efficiencies of a set of peer units, called Decision Making Units (DMUs) (Khezrimotlagh, D., et. al. 2014). It uses statistical methods to develop the production frontier from historical data (historical relationships between inputs and outputs) and then compare the frontier with the new production parameters to evaluate and obtain the optimised solution for production planning and comparison among different plans to develop the future production strategy. The principle of DEA is to estimate the optimised solution, which is also known as a projected value in DEA, based on the distance between DMU and the production frontiers. In addition to the examination of production efficiency, it can also provide information such as radial movement or slack movement that can be referred for production scheduling or resources allocation. To put it simply, DEA can be used to judge whether a production plan with a given quantity of input and output is productive and effective and if not, it will recommend how to modify it. One of the advantages of DEA is that it does not require a standardisation of the input parameters. It directly assesses the technical and scale efficiency only based on the technical parameters, which means no weighting factors are required hence the result is less subjective.

To perform DEA, there are several software or prototype tools that can be used, such as SPSSAU, DEAP2.1, or various packages of Python, R or Stata, and so on. Most of these tools will require the identification of inputs, outputs and the DMUs. To assess the productivity of shipbuilding, the input parameters can be chosen from the labour, the capital (productive assets), the energy, material and purchased services, or shipyard total area, etc. or using all of them. The output is the CGT as result of such inputs. Regarding DMUs, depending on the user's preference and data availability, it can be identified as annual total CGT, or CGT of different types of ships delivered within the assessment period, or CGT of each ship (regardless of the ship types) delivered within the assessment period, and so on.

Focusing on the proposed criteria, i.e. BC and productivity, the improvement activities discussed in this section are aiming at improving the accuracy of the cost assessment, the effectiveness of cost control and the productivity.

The primary challenge for cost estimation is the data and database management issues, such as the quality, the timeliness and the capability of the database. As a common practice, the shipyard has to conduct the cost estimation for the bidding purpose in the very early stage based on extrapolation from the historical cost database, i.e. the top-down method discussed in the previous section. However, the historical cost may lag behind the point in time for decision making and changes due to new technology or new production process cannot be reflected. The types of cost is dependent on the ship type which is hard to compare their relative cost data. For this reason, shipyard should spend effort in keeping the database up to date including the approach to take into account of the potential influence from cost variation factors. Late changes introduced into the design can have considerable cost impacts. Such variation factors typically include technology change, material cost, labour cost, social and political situations, inflation, regulations, and so on. Furthermore, the measurement of the real spending should be as accurate as possible and as the same work breakdown structure as the model used. Moreover, using good cost estimation software will also be helpful, which can be also used to manage the CERs efficiently. Besides, uncoupling between design and cost engineering would also increase the difficulties for the cost estimation. Indeed, costing can be only performed after technical details identified, and the more detailed the design, the more accurate the estimation. This is a two-stage process and usually cost is the secondary consideration for the technical design engineers (Bole, M., 2007). Such degree of separation could result in difficulties for cost optimisation as numerous iterations may be required, especially in the situation that various departments involved with different degree of knowledge of the project. To solve this problem, the adoption of the concurrent engineering (CE) with multifunctioning project team built in the beginning of the project emphasising the parallelisation of tasks may be a good solution. More details about CE has been reviewed in Section 2.1.

When the cost has been accurately estimated, then the control of the spending becomes the responsibility of the project managers (PM). Management of work is synonymous with management of costs (Bruce, G. and Reay, K., 1991). Professional project management software, such as MS Project, is a good option to enhance the project management efficiency. In addition, the project must be appropriately planned before execution which is the actual driving force of the project. There should also be sufficient preparation for unexpected corrective action when necessary. Many shipyards has adopted a hierarchical planning with different time horizons and levels of detail (Caprace, J. and Rigo, P., 2012): strategic (e.g. plan over years), tactical (e.g. plan over months), and operational (e.g. plan over weeks). The plan should also be prepared considering the uncertainties in the project which may highly dependent on the PM's experience, but keeping a detailed risk register or other equivalent log book to record what has happened during the construction can provide good reference for the future work.

Answer as to how to improve productivity is not straightforward, there has to be the specific analysis of specific issues. In general, it can be considered from perspectives such as supply chain reliability, subcontractors, employee skills, quality of the machineries, and capability of the workshop areas, etc. Most of these improvement solutions that through enhancing the hardware at the shipyard are very costly and has to be discussed at the shipyard strategic level or work with the company ERP (Enterprise resource planning) system (or equivalent). Therefore, it may be a good idea to start with a more reasonable allocation of existing resources to make improvements. To do so, the DEA model for evaluating production efficiency will be very useful, because it also provides information such as radial motion or relaxation motion to guide resource allocation. Introduction of new technologies such as application of smart shipping, advanced materials, big data, robotics, AI and condition monitoring system or self-adaptive QA/QC system, etc. can also help to improve the productivity. However, such new technology will bring additional concerns about its adaptability to the existing production system. It will also require the corresponded H&S and cyber security procedure to be in place and additional training for the workforce.

In summary, if BC reflects the economic performance of shipbuilding processes at the project level, then productivity can be seen as a comprehensive indicator of the shipyard's effectiveness of the resource utilisation, capacity and capital (Krishnan, S., 2012).

2.2.3. Environmental performance evaluation

Climate change is a topic of global concern, and all walks of life are constantly striving to improve it. Whether it is part of corporate social responsibility or enforcement by the government or authorities, shipyards must pay attention to maintain their performance in terms of environmental impact. The international environmental regulations listed in MARPOL (Marine Pollution) has provided shipyard with guidance for protection from oil, bulk NOx liquids, dangerous goods in packaging, dirty water / wastewater, waste and air pollution (Basuki, A. 2016). There have been numerous researches regarding the environmental impact from shipbuilding activities. In summary, the activities in shipbuilding that of highest environmental concern are including metal working activities, surface treatment operations, ship maintenance and repair activities, and noise (OECD, 2010). Maintenance and repair processes vary from job to job, but many of the operations are equivalent to those used in new ship building, though the scale is smaller. Table 8 provides review of such activities with its associated potential environmental impacts, reported by OECD Council Working Party on Shipbuilding (WP6).

Table 8: Review of shipbuilding activities and associated environmental impact OECD, 2010)

Activity Category	**Activity**	**Potential Environmental impact**
Metal working operation	Thermal metal cutting	Emissions of Particulate Matter (PM) and hazardous air pollutants associated with the fumes; composition of the pollutants varies with the metal being cut and its coating

	Welding operations	Emissions from welding include GHG, toxic chemicals, and criteria air pollutant (CAPs) which include ozone (O3), particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO2) and lead (Pb)
	Metal grinding	Polluting PM; fugitive air emissions of metal dust and fumes, as solid waste and as metal dust and chips from waste grinding tools; GHG from electricity used;
Surface treatment	Cleaning and coating	Use of chemicals that include heavy metals (up to 30%), solvents, copper, and hazardous or flammable materials, and are associated with emissions of lead, PM, volatile organic compounds (VOCs), zinc and other air pollutants;
	Abrasive blasting	Noise; large quantities of wastes such as paint chips, oil and toxic metals to waterways; toxic air contaminants;
	Anti-fouling paints	highly toxic to marine life, leading to significant damages in marine ecosystems as they enter into the wider food chain through bioaccumulation, which eventually can reach humans;
Various	Many construction, maintenance, and repair activities	Noise; Workers may be exposed to continuous sound levels of between 85 and 105 dBA, with highest levels of dBA exposure experienced during welding, fitting and blasting activities. exposure to such sound levels may lead to loss of hearing.

In addition, as observed from literatures regarding more detailed assessment, the main concerns of environmental impact from shipbuilding were found to be the use of material and energy consumption. Figure 15 shows results from one study performed by NMRI (2018) regarding environmental impact caused by shipbuilding processes (Kameyama, M.,et. al. 2018), which represents the identical trend among most similar studies reviewed.

The first is the use of steel. In terms of quantity, steel is the most important material for ships, although the proportions between various ship types are slightly different. Some studies regarding the use of steel in shipbuilding have shown that almost 75% of material streams of tankers and bulker ships in LDT (Light Displacement Ton) are composed of steel (Andersen, A., et. al. 2001), and amounts of steel vary from 56% of LDT for general cargo to 85% for oil tanker (Sujauddin, M., et. al. 2014). There are various ongoing researches and trails (e.g. H2020 project FIBRESHIP, RAMSSES, etc.) on replacing steel with alternative materials, such as fibre-reinforced plastic (FRP), however, there is still a long way to go before its actual industrial implementation especially for large ships. The steel production is known to be among the world's most energy intensive industrial processes, and generally associated with environmental concerns such as large volume of wastewater, solid and hazardous waste, air pollutants and waste from mining activities, as well as GHG emissions and concerns associated with coal and iron ore (OECD, 2007). Although there are arguments that the burden caused by steel production is unfairly borne by the shipyard, considering the importance of steel in the shipbuilding industry, the shipyard still needs to bear indirect responsibility to minimise the impact of the steel used in ship construction. For this reason, most assessments regarding environmental performance of shipbuilding processes will take steel production into account. As can be seen from most studies, the steel production process is responsible for large quantities of CO2, CO, PM and NOx emissions (Chatzinikolaou, S. and Ventikos, N., 2014).

Another notable result from the review is that the surface treatment was found to be the most environmentally hazardous processes performed as part of ship construction directly. The contaminants are mainly from the chemicals used in coating, painting and cleaning activities, which usually contains heavy metals, solvents, copper, and hazardous or flammable materials, and are associated with emissions of lead, PM, volatile organic compounds (VOCs), zinc and other air pollutants (OSHA, 2006). Moreover, there is also waste and PM emissions during the process of blasting.

Electricity is the main type of energy consumed during ship construction. On average the electricity required for building the ship model at the yard was estimated as 1.7m kWh (Kameyama, M.,et. al. 2018), or 96 kWh per 1 ton net steel (Harish, C. and Sunil, S., 2015). Environmental impact associated with this is highly dependent on what is the specific supply of such electricity mix, hence this figure will vary from shipyard of one region to another.

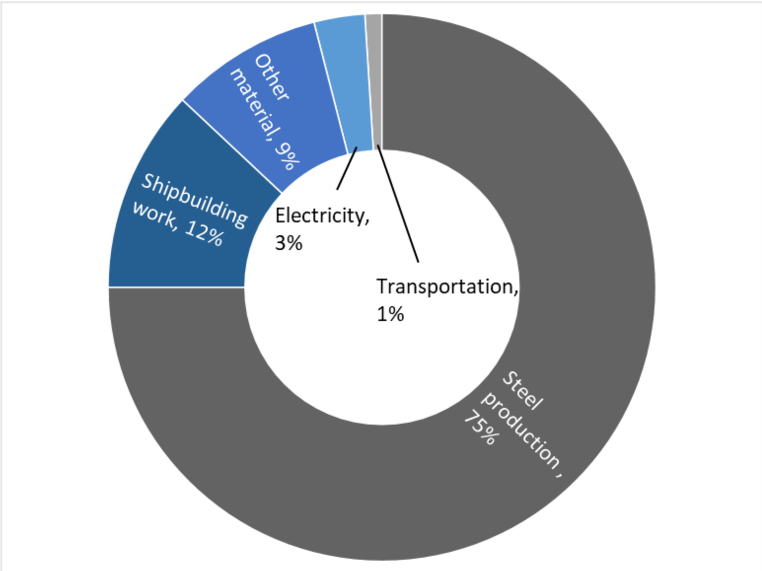

Figure 15: Proportion of environmental impact caused by different shipbuilding processes (Kameyama, M.,et. al. 2018)

With regard to the impact categories, summarised from various literatures (Kameyama, M.,et. al. 2018; Chatzinikolaou, S. and Ventikos, N., 2014; OECD, 2010; Önal, M., et. al. 2020), it was noticed that the most significant ones are greenhouse gas (GHG) emissions (i.e. global warming), resource consumption and photochemical oxidant creation. Figure 16 shows a representative analysis result regarding the impact categories and the associated emission inventory of each category using LIME (a life cycle impact assessment method based on endpoint modelling, which converts all impacts to monetary terms for comparison) (Chatzinikolaou, S. and Ventikos, N., 2014). It should be noted that the exact values shown in this figure only apply to the analysed ship model in (Chatzinikolaou, S. and Ventikos, N., 2014), but the importance and proportions of these impact categories (and their inventory) are generally applicable to the shipbuilding process. This can be supported by comparison with equivalent analysis results published in various studies on different ship models (Kameyama, M.,et. al. 2018; Chatzinikolaou, S. and Ventikos, N., 2014; OECD, 2010; Önal, M., et. al. 2020; Shama, M., 2001; Liu, J., et. al. 2020; Favi, C., et. al. 2018).

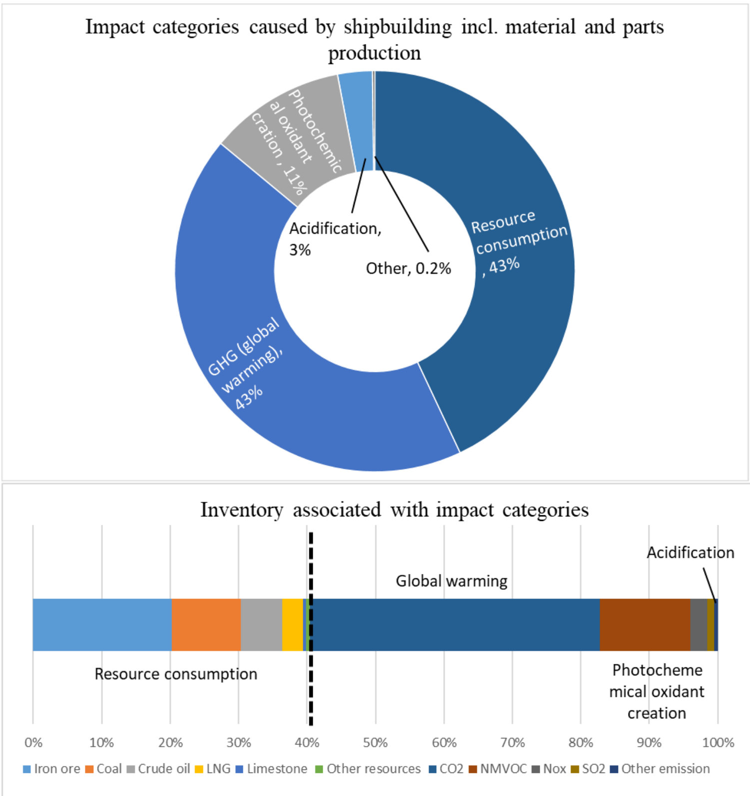

Figure 16: Shipbuilding environmental impact categories and the associated emission inventory of each category based on LIME (Kameyama, M.,et. al. 2018)

It can be summarised from the reviewed environmental impact assessments that impact categories that more relevant to shipbuilding activities are GWP, ADP, POCP and human health.

The scientific approach for quantifying the environmental impacts is named Life Cycle Assessment (LCA). The LCA should be performed following the framework recommended by ISO14040, as illustrated in Figure 17 below (ISO, 2006).

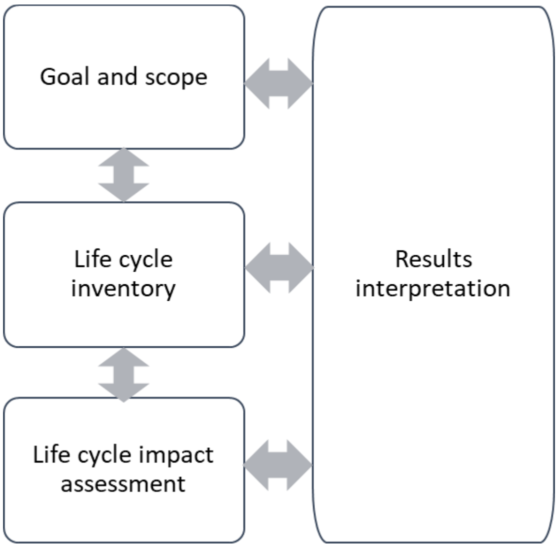

Figure 17: The LCA framework recommended by ISO14040

- **Goal and scope**:
  Confirming the goal and scope is the first step for an LCA. This includes determine the context, the aim and the level of the detail of the study. Other information, such as the selection of LCA software, LCA database or functional unit, etc., will also be defined depending on the specific circumstances of the study context. Besides, in order to assess the effectiveness of the improvement activities, comparative studies will be performed using the actual production parameters and the predicted parameters after implementing the improvement measures.

- **Life cycle inventory**
  Based on the goal and scope, the corresponding life cycle inventory can be developed, which includes data related to material, production parameters, energy consumption as well as tooling and equipment. The source of data can be from both primary (i.e. directly recorded from the project), and secondary (i.e. public databases and literatures) databases.

- **Life cycle impact assessment**
  Based on the goal of the study, specific impact categories will be chosen not only because of their importance to ecology and the environment, but also because of the recognition that they are the main issues arising from the production activities to be studied based on the above-mentioned literature review. Similarly, the choice of LCA method can be determined based on the specific study context.

As discussed in the above, the environmental impact of shipbuilding is mainly from the use of material, the energy consumption and as side product (waste) of the construction activities. Therefore, improvement measures should also focus on these aspects.

Firstly, with regard to energy consumption, the improvement can be achieved through either saving the usage of the energy by improving the energy efficiency of the tool, or, more effectively, choosing to use the energy whenever possible generated from greener resources. For instance, based on the UK government report in 2020, continuous effort has been spent to generate electricity from renewable resources, such as solar, winds, or hydrogen, and UK has enjoyed the longest period of coal-free electricity production in 2020 (DUKES, 2021). However, the shipyard may not have the freedom to choose the source of energy, so that it could be more practical to save energy by improving the efficiency. To do so, shipyard could try to reduce the rate of re-work or duration of the work. This can be achieved by training the workers or using the enhanced production techniques, e.g. automated defect recognition system, or at least ensure the existing machines are maintained and used correctly. For example, if the purity of the oxygen used for cutting is not high enough (99.5% or higher), it will affect the cutting efficiency result in longer cutting time and increased energy consumption (EPA, 2005).

Another direction of effort is to replace steel with more environmentally friendly shipbuilding material, which is an area attracted numerous researches and investments. One possible solution is the development of ultra-light and high-strength steel, which was initiated between steelmakers and automakers. The advancement of such type of steel used in shipbuilding is the considerable weight saving potential and increased corrosion resistance (Worldsteel, 2008). This means less fuel will be consumed during navigation and less maintenance will be required, hence lowing the emissions. As it was also found, the complex design would result in more consumption of the material, hence the effort can be also spent on saving the material from optimising the design. Another attempt is the use of composite material, such as FRP, which is often seen in smaller ships. Advantages for composite ship include more effective weight saving and corrosion resistance. However, as mentioned in the previous section, there is still long way to go for using FRP in large ships, as there are still many technical barriers in it, such as fire resistance, strength, reliability issue, joining and inspection technologies, etc. Moreover, if the base of the composite material is carbon-fibre, its environmental performance may not be as good as expected, because the production of carbon-fibre is extremely energy intensive (Howarth, J., et. al.

2014). The end of life treatment of composites will produce more pollutants than steel that can be 100% recycled. Besides, the shipyard can also consider to switch their supply chain to be greener, meaning acquiring material produced by more environmentally friendly processes, such as steel production by the electric arc furnace that depends mostly on scrap steel, or manufacturer who has implemented new production techniques which can eliminate many of the energy-intensive steps or reduce the need for coke.

Furthermore, employing new and advanced production techniques has also been an option that many shipyards have considered. For example, installing capture (i.e. welding booths, hoods, torch fume extractors, flexible ducts, and portable ducts) and collection (i.e. filters, electrostatic precipitators, particulate scrubbers, and activated carbon filters) system to minimise the welding fumes. The capture and collection system is also useful for reducing pollutant loading during metal grinding processes. For grinding, this system includes vacuum dust extractors, area containment, and area ventilation dust collectors (OECD, 2010). Moreover, many shipyards have installed Regenerative Thermal Oxidisers (RTO) to reduce the discharge of VOCs and other air toxics from surface treatment, by converting them to carbon dioxide and water vapour through high temperature thermal oxidation. In addition to RTO, the impact of surface treatment can be also reduced by introduction of new coating and painting material, such as the TBT (tributyltin) free anti-fouling systems, including rubber coating, organotin-free anti-fouling paints, and biocide-free non-stick coatings or the so called mimicking shark skin as an innovative example of biomimicry (Leahy, S., 2005).

2.2.4. Technical performance evaluation

Production performance from technical perspective is the comprehensive manifestation of multiple aspects, including the advancement of production technology and equipment, the yard capability, the rationality of the plan and its execution, the workers' skill and experience level, as well as the effectiveness of production management strategy, etc. Although each of them can be measured using relevant indicators, it is not an easy task to normalise them into any type of scale for comparison, due to the diverse of their natures. For the same reason, even if any advanced mathematical techniques are used to convert these indicators, the amount of data and calculations required can be huge. Besides, complicated assessment procedure may increase the possibility of errors or uncertainties to be introduced during the normalisation process. Therefore, in order to discover the alternative solution, an FMEA (Failure Modes and Effects Analysis) type analysis based on the literature review has been carried out to identify the characteristics and synergy of the impact from these diverse technical issues during the shipbuilding process.

The analysis result, as per Figure 18, Figure 19, and Figure 20, shows the final consequence of failures due to all technical issues are the delay of the technical deliverables, i.e. the ship. It reflects how efficient the shipyard can manage and provide quick response to the adverse technical issues. As the result, a list of technical issues that most shipyards may face during the production has been identified based on discussion with the collaborative shipyards and literature review (Fernandes, J. and Crispim, J., 2016; Basuki, M., et. al. 2012). Delay of the schedule can happen during any stage of the production, such as design process, procurement or construction including QA/QC stage. In each stage, there are different technical issues causing delay of the schedule, which also varies from one shipyard to the other. As illustrated in Figure 18, the first stage is the design, model test and planning stage, which generally includes activities such as production drawing, yard plan, key plan (general arrangement, mid-ship section plan, construction profile, P&ID), detail arrangement drawing, model test and finish plan, etc. During this stage, revising design is the primary technical issue that will cause the delay of the delivery. The common reasons for revising design are because of the inappropriate equipment size, the problem with integration of various separate designs and requirements from ship owner and Classification that includes corrective actions caused by lack of clarity or misunderstanding during the initial planning stage. Another technical concern during this stage is the problem with new technology transfer. Generally speaking, activities in most shipyards are set by standard operating procedures (SOPs), which can help to manage the production process smoothly but at the same time, it evolves very slowly resulting in a significant barrier to keeping pace with technology. For improving the productivity, shipyards have to upgrade their production technologies, such as new generation of machinery, new building materials or new digital tools, etc. When the new technology is introduced, there will always additional concerns about its adaptability to the existing production system and requirements to manage the changes, such as updating workforce skills, schedule the work in different way, updated risk register incorporating the related new information or concerns on H&S and cyber security, etc. This also requires experiences from the project team to manage the changes. Nonetheless, it was also mentioned by the interviewed shipyards that although these are the common issues happening in most projects, there are rarely delays in the end for two reasons. On the one hand, this is in the early stages of the project and there will be enough time to catch up. On the other hand, due to these so-called frequent technical issues, the project will plan to reserve extra time in advance.

The next stage is to source all the required equipment, machinery, material, labour, workshop allocation, etc. As illustrated in Figure 19, to ensure the effective performance of the procurement process, the purchasing team should follow a well-established and verified procedure and develop a reliable supply chain. Otherwise, the issues such as delay of material in shipbuilding due to inefficient in transport or delay in customs clearance of material or equipment in port, will affect the project delivery. Moreover, in case when there is fast growth of orders, the issues such as financial inability or inability of managing competing projects will cause the delay of purchase order resulting in delay in receiving required resources for the project.

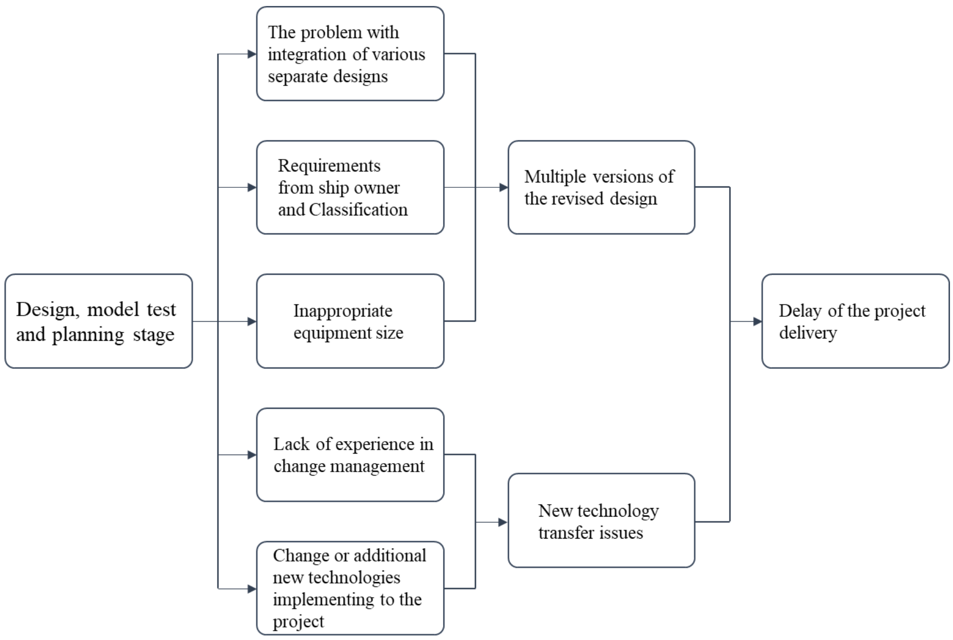

Figure 18: Synthetic model analysing risk of project overdue at design stage

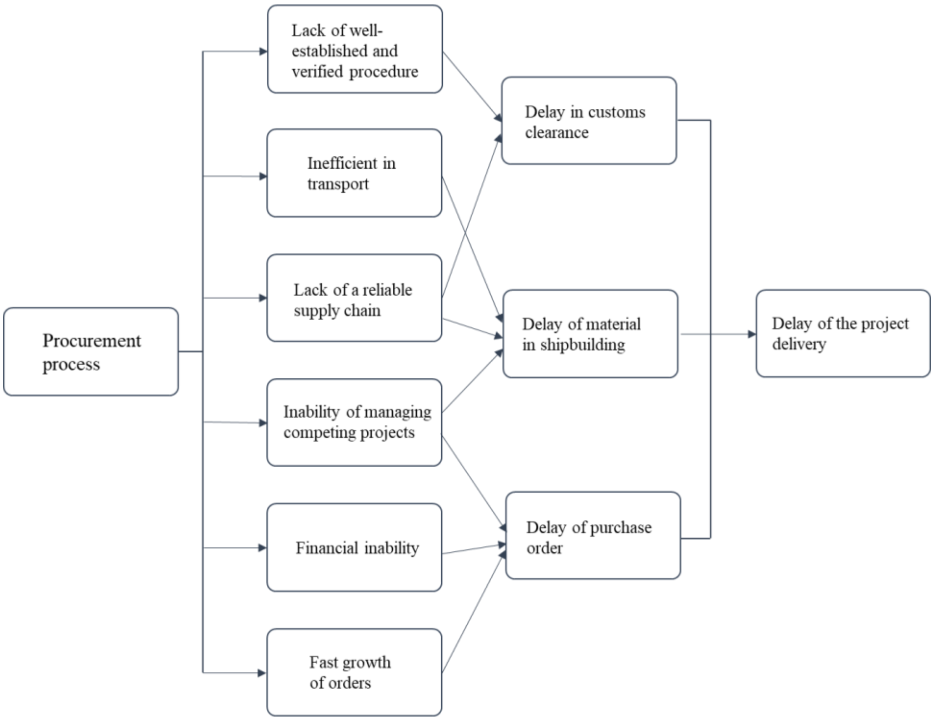

Figure 19: Synthetic model analysing risk of project overdue at procurement stage

The third stage is construction process which includes all the production activities discussed in Section 2.1 above. As illustrated in Figure 20, the common technical concerns during this stage can be categorised as issues from perspectives of labour, planning, and external requirements. Firstly, as a labour intensive industry, the performance of workers and sub-contractors is crucial to the shipbuilding project. Their efficiency and quality of the work are directly linked to the on-time delivery. This will be further discussed in Section 2.2.5 regarding human resources management of the shipyard production. Any mistakes during the construction or poor quality delivery will result in re-work or additional work to be carried out. Another reason of project delay is because of the inappropriate plan, especially when the yard has multiple projects carrying out at the same time. There must be appropriate plan for the usage of workshops, labours or equipment, otherwise conditions such as dock busy with other business may happen. In addition, irresponsible instructions may also lead to the production mistakes, which is related to both labour performance and planning efficiency. Besides, external request to revise the production from ship owners and classifications is another common reason of project overdue. This could be the extra fitting required because of new environmental regulation or change of specification, etc. There also could be lack of communication and involvement between stakeholders, or lack of clarity or misunderstanding of the requirements in the early stage, which may also cause the production mistakes.

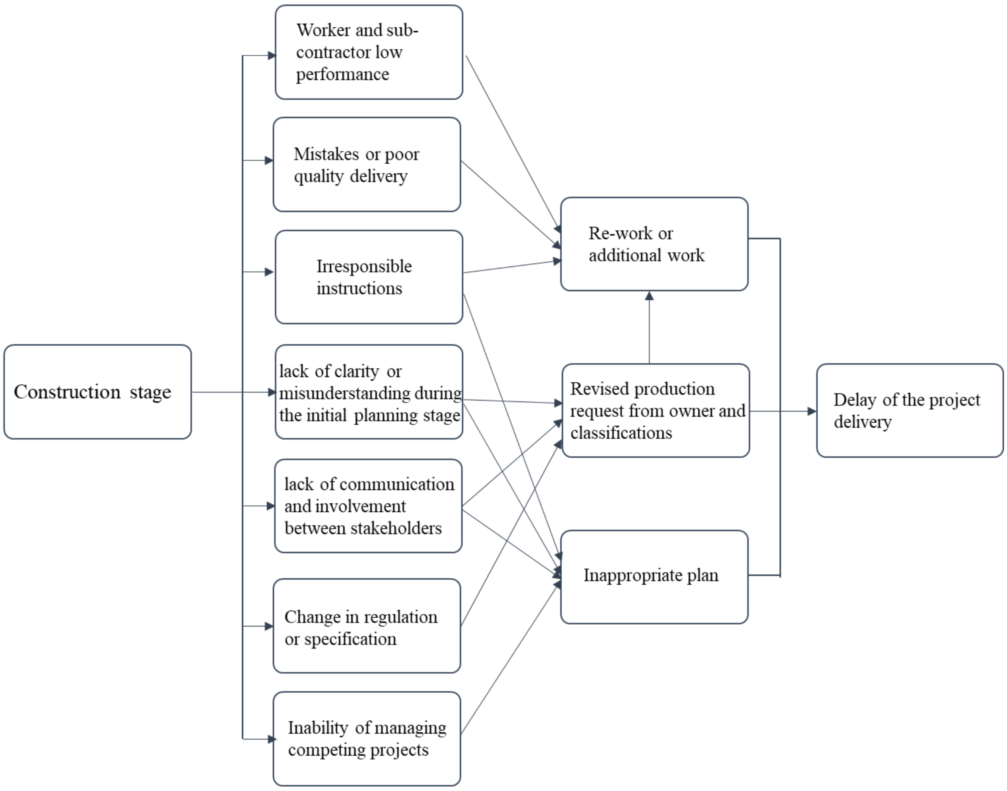

Figure 20: Synthetic model analysing risk of project overdue at construction stage

Focusing on these identified technical issues, to improve the technical performance, the shipyard can consider to enhance their operation from the following aspects. The first option is through reducing the design revisions and optimising the planning. Both design and planning require support from good quality of database and well-understanding of the project requirements. Therefore, this can be related to the topic of communication and information management. One of the widely applied techniques in this field is called digital thread, which is a digital framework allows a connected data flow and integrated view of the physical assets (Singh, V. and Willcox, K., 2018). These data includes but not limited to shipyard arrangement, machine and equipment configurations and availability, material stock information, labour and sub-contractor availability, historical design and production data and so on. The digitalised shipyard can help to provide more precise and up-to-date data for design and planning, especially useful for shipyards that outsource the design task to external consultancies. This also make it possible to optimise the plan through simulation of the production process and resource allocation. Another important factor effecting the quality of the design and production planning is the engineers' experience and knowledge base. This is a subjective matter and hard to quantify, which is relevant to the employee talent management that will be discussed further in Section 2.2.5

The second direction of endeavour is through evolving the shipyard's SOPs by modernising the production strategy and implementing emerging technologies. Along with the fast development of digital technologies, the concept of smart manufacturing has become the new trend across various manufacturing-oriented industries, including shipbuilding (Singh, V. and Willcox, K., 2018). Based on the literature review, there are various digital tools that can be potentially applied to enhance the technical performance of shipbuilding process (Jagusch, K., et. al. 2020). The primary area that can be benefited from such digital tools are the QA/QC system aiming at reducing the defect rate hence reducing the wastage during production. This is also one of the main features in lean manufacturing. Techniques that can be used for this is the embedded sensor and diagnostic connectivity system (Majumder, S. and Deen, M., 2019). In this system, the production process is monitored using connection-enabled sensors, including production parameters such as temperature, pressure, welding speed, or image sensors, etc. Then, the monitoring data can be processed by the powerful data processing tools and analysed using the AI algorithms. Such automatic defect recognition system can help to detect or predict the production defects so that the corrective actions can be taken as early as possible to reduce the amount of re-work or additional work because of the low quality deliveries. In addition, as discussed in the previous session, one of the potential risk agents for project delay is the unclear or irresponsible instruction. Technologies that can be used to assist the work instructions include virtual reality, augmented reality layers, 3D images, and virtual objects on top of the real-world view through mobile tools such as smart glasses or hand-held tablet computers (Pérez F, R. and Alonso, V., 2015; Molina V, D., et. al. 2020). Besides, robots can be another option to improve the production efficiency. Robots can assist production process by handling the assets and performing some of the construction activities, especially useful for inspections in harsh and dangerous environments. These robotics technologies will use cognition, multi-function, imitation, perception and adaptability, and can also acquire new skills or adapt to the environment through learning algorithms. It is worth mentioning that shipyard digitalisation can provide framework to support the smart manufacturing.

Besides, modernising production strategy may also be an option to enhance the technical performance. For example, implementation of modularisation in shipbuilding can help to accelerate the construction because it ensures all blocks will be ready before erection. It also transform the traditional sequence production process to parallel so that the time and resources can be more rationally utilised. However, changing production strategy is not an easy task, which effects the entire shipyards operation and production system, as well as the associated supply chain. It is risky and costly, full consideration regarding the return on investment is needed before making the decision.

Moreover, to ensure the smooth execution of the project, having a reliable, green and cost effective supply chain is crucial. Details about supply chain performance will be discussed later in Session 2.2.7

2.2.5. Human resource performance evaluation

Shipbuilding is a labour intensive industry, Table 9 listed the statistics regarding the number of employees in some major shipbuilding companies and countries published by Statista (Statista, 2021). Having an effective human resource management (HRM) strategy is very important for maintaining the high level of efficiency and sustainability of the business.

Table 9: Survey published by Statista regarding to the number of employees in some major shipbuilding companies and countries

Country	Company/Region	Number of employees	Year of survey
China	China Shipbuilding Industry Corporation (encompassed 46 companies and 28 research institutes)	140,000	2020
South Korea	Gyeongnam (the workplace for 85.8% of all employees at shipbuilding sites in the nation.)	56,800	2019
Italy	Fincantieri Group (one of the world’s largest shipbuilding groups)	10,700	2019
France	Nationwide	21,000	2013
Turkey	Nationwide (Data includes harbor launch and manufacturing location workers)	27,189	2017

The employees at a typical shipyard are normally consisted of front line colleagues with various grades of skills, management at all levels and other business supportive staff. The needs of employees at different positions are various and the HRM development should take into consideration of such diversity. A range of literature review was carried out as the main research method to identify the criteria to evaluate the effectiveness of a shipyard's HRM strategy. Accordingly, it was found that an effective HRM should perform well in the following interrelated aspects:

- Employee retention/ turnover
- Employee quality
- Recruitment effectiveness
- Disciplinary matters

The first point is with regard to employee retention/ turnover. Retention of trained semi-skilled and skilled employees in shipbuilding industry is a priority for most shipyards' HRM practices as per the literature review (Iqbal, M., 2017). It is because the turnover of the employees, in most case, can impact the organisation significantly, but negatively. First of all, losing employees is very costly. Direct cost includes cost of substitute recruitment with the associated training of these new comers and the overtime pay to the co-workers due to the departure of the employees before their replacements are ready to perform the work at the equivalent level (Sutherland, J., 2002). A study carried out in 2000 estimated the cost of hiring and training a replacement employee can be as high as 50% of that worker's annual salary (Johnson, J., et. al. 2000). Research also shows there is a strong link between high rate of employee turnover and the reduction of profitability of the organisation (Hogan, J., 1992; Wasmuth, W. and Davis, S., 1983). Such linkage is caused due to several reasons including the drop in employee morale and company reputation, effects on customer service and satisfaction, loss of institutional knowledge as well as weakening of the corporate culture, and productivity drops due to learning curve involved in getting up to speed (Gustafson, C., 2002; Ongori, H., 2007; Kemal, A., et. al. 2002). Therefore, the employee turnover/ retention should be considered as one of the indicators to track and measure. This will help the shipyard to detect if there is a problem regarding their HRM practices and to compare with their industry peers. Depending on the HRM focus, this criterion can be measured using different metrics such as overall retention (or turnover) rate, voluntary (or involuntary) turnover rate, average length employment, turnover rate by department or manager, and retention rate for star (or low performing) employees.

There is no doubt about the importance of the skilled workforce to the shipyard. However, according to a published survey containing interviews to a number of shipyards worldwide, recruiting and retaining qualified workers is one of the main challenges that all of them are facing today (Ventimiglia, N., 2014). Therefore, it is believed that how efficient the HRM is taking care of this issue to maintain the quality of the workforce should be considered as another criterion in this PPI category. Although skilled employees are important for all positions, it is understandable that the HRM will draw more attention to the technical workforce in a shipyard. Regarding the job roles for shipbuilding, based on the organisational charts reviewed, there are different titles used from one to another. But generally speaking, there are various technical jobs and skills required in common, which can be briefly listed in Table 10 below (Chakraborty, S., 2019).

Table 10: General review of job roles and skills in shipbuilding

Job title	**Description**	**Qualification Certification or other requirements**
Welders	Responsible for welding all the metal structure of the ship, including hull plates, frames, girders, tanks, foundations, pipes, etc.	Professional training and certification are required for this position
Structural fabricators	Responsible for fabricating all the structure of the hull based on technical drawings	The skills of reading technical drawings and carrying out the metal fabrication jobs or handling other building material
Plumbers	Responsible for installation of all pipe works in a ship, along with all kinds of pipe fittings such as valves, flanges, etc.	The skills required is the ability to read and understand isometric piping layout drawings and Piping and Instrumentation drawings (P&IDs), and to carry out the piping installation work.
Electricians	To install all the electric cables in a ship based on the cable routing plan, as well as all the electrical and electronic equipment, navigational equipment in the bridge and radar, lighting, control panels, main electrical control room panels, etc. based on equipment positioning drawings and equipment end drawings	Professional training and certification are required for this position.
Carpenters	To prepare wooden templates for the ship's hull, and to build dock blocks and keel blocks which are important for dry docking and launching of ships from slipways.	The skills of reading technical drawings and relevant professional training are required for this position.
Riggers	To carry out all the rigging work with a shipbuilding yard, including lifting and shifting of heavy structures, scaffolding, and movement of moderate weight structures within the shipyard	Need to be trained for operating various types of cranes with relevant certificates up to date.
Quality control (QC) inspector	QC inspections of shipbuilding includes non-destructive tests on the joints and dimensional control inspections of every major structure after installation.	One of the most skilled task at the shipyard and normally performed by ones with sufficient experience in shipbuilding.
Supervisors	This position is set to supervise other technical staff carrying out their work during every ship construction process	Usually, supervisors are promoted from the most skilled and experienced workforce among welders, fabricators, fitters, electricians, plumbers, etc.

Naval architects and designers	Their main task is designing the ship and carrying out stability calculation, which will determine the safety of the ship during launching.	Relevant qualification, overall and in-depth know-how of the entire shipbuilding process.
Other engineers	There are various types of engineers required to participant in shipbuilding processes, such as mechanical engineers, electrical engineers, piping engineers. In the case when major machinery (e.g. main diesel engine, auxiliary engine, propellers, shafts, etc.) is installed, engineers from multiple fields should be present to participate and supervise the work.	

Another important task for the shipyard HR managers is recruitment. The way to measure recruitment efficiency at a shipyard is similar to which in other industries, with consideration of the specific job requirements and labour market. There are several popular talent acquisition metrics which can be used to access the effectiveness of the recruitment processes, including recruiter efficiency, quality of hire, candidate satisfaction, manager satisfaction, cost per hire, time to fill, retention rates, candidates per hire, employee referrals, fill rate, response rate, qualified candidate per opening, offer acceptance ratio, sourcing channel effectiveness, etc. (Prasad, K., et. al. 2019). All these metrics are good to use for accessing the performance of the recruitment processes from various angles. However, considering the HR requirements of a shipbuilding project as discussed above, two of them are considered to be more crucial than the rest for a shipyard, which are time to fill and quality of hire

Time to hire (T_H) can help to measure the efficiency of the recruiting process including applications, screenings, and interviews. The speed of hiring is crucial for shipyard for two main reasons. Firstly, a faster process can provide company a better chance at attracting and hiring top talent considering the short period that they are available in the labour market. Secondly, the fast hiring process is particularly important when it is to fill the position that is required to start a project or replacing someone who left the ongoing project. Being late in fulfilling such positions within the required timeframe may delay the delivery of the project. However, fast process does not mean to compromise the requirements of the job profile which may, otherwise, end up with recruitment of the inappropriate candidates. For this reason, the quality of hire should also be tracked.

Quality of hire (Q_H) will be calculated based on the unique insights of the process set by different recruiting coordinator. It is normally including appraisals of the new hires regarding their job performance, team fit, retention, engagement and/ or fitness with the company culture. For example, in (Prasad, K., et. al. 2019), a performance appraisal system score/rating using six independent factors and 1 dependent factors was proposed to measure Q_H. It measures the value that new hires can bring to the company. Measuring Q_H can help to keep track on the health of the employee base, hence guiding the company to optimise their recruiting criteria.

Monitoring the Disciplinary matters (DM) related performance is the responsibility with the remit of HRM as well. All employees working at the shipyard are required to follow the company protocols and policies, failure to comply will result in disciplinary action up to termination. This is very important to ensure the safety, security and reliability of the work on-site (Maritime & Coastguard Agency, 2016). The cases that to be considered as breach of discipline are dependent on what are the requirements in the company's own protocols and policies. It would normally include absence from work without approval, cases where drugs or alcohol is abused, charges of criminal offences, cases result in dismissals or logged warnings, and so on.

The overall HR performance can be improved via carrying out activities focusing on improving the four aspects discussed above, which, in fact, are interrelated.

Firstly, with regard to employee retention (or turnover) rate, despite the personal reasons, there are several effective factors that can be taken into account. Some factors are general for all industries, such as job design; recruitment and selection; training and development; succession planning; compensation and reward; performance management; internal communication; involvement; equal opportunities; employment security and prestige, etc. (Ozolina-Ozola, I., 2014). While some of them are more specific for shipbuilding industry, including wage rate, safety at the work, job security, on-job training and career progression, etc. (Iqbal, M., 2017). To minimise the employee turnover, finding the reasons why people, especially the top talents, are leaving is the first step and then enhance the HRM by incorporating the appropriate corresponding actions. Respect, Recognition, and Reward are three important components to be considered for developing and implementing the HRM practice with regard to staff retention (Mathimaran, K. and Ananda K, A., 2017). Accordingly, it is recommended that the activities to be taken for improving KPI rating regarding to shipyard employee retention can be carried out considering the following perspectives:

- Activities that can encourage the employee engagement
  The first action can be taken to improve the employee engagement is to optimise the design of the job ensuring the employee's job involvement, which will influence job satisfaction and increase organizational commitment of the employees (Blau, G. and Boal, K., 1989). Figure 21 is the five core job characteristics identified by Hackman and Oldham (1975, 1980), which can be referred to design the job, including skill variety, task identity, task significance, job autonomy and job feedback (Guimaraes, T., 1997).

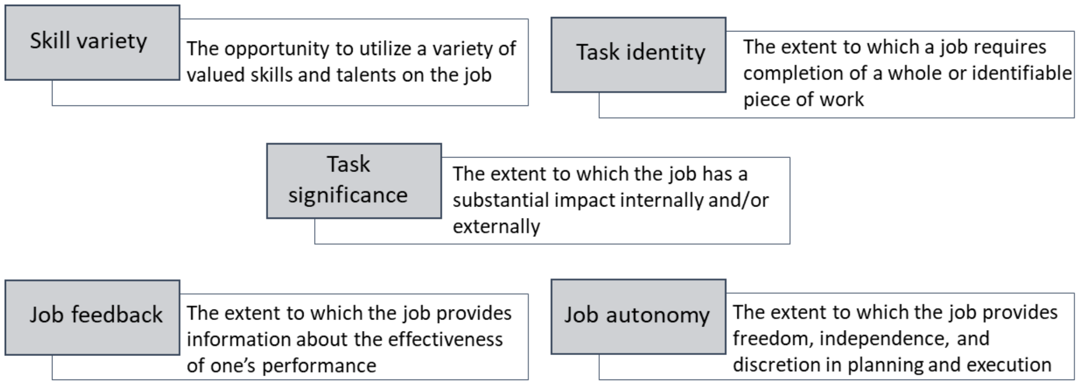

Figure 21: Five core job characteristics identified by Hackman and Oldham (1975, 1980) (Guimaraes, T., 1997)

Secondly, it was also found the information accessibility is also important for employee retention, in terms of employee performance improvement and cooperate culture strengthen (Stovel, M. and Bontis, N., 2002). Therefore, it will be beneficial if the shipyard can set up appropriate mechanism to share knowledge and ideas as well as the smooth channel for communication.

- Activities that help to create the perfect working environment

  In shipyard, particularly, health and safety (H&S) is the most important concern with regard to working environment. Measures to improve this has been discussed in Section 2.2.1.

- Activities to enhance the talent management practices

  Talent management should be concerned with all levels of the organisation, which is to ensure the employees are in the right place where they will be most productive and satisfied, rather than just about the promotion (Naik, S., 2012). In fact, majority people are making decisions based on their own career goals or progression plan, and not based on any factor pertaining solely to the company (Chamberlain, A., 2017). For this reason, the Talent Management practices should be capable to meet the diverse of their requirements, such as competitive wage rate, clear progression path, or relevant on-job training.

- Activities dealing with job security
  Job security is one of the specific issues in shipbuilding industry. Factors such as seasonal fluctuation in demand, or contracts and tenders, etc. were blamed for this issue (Iqbal, M., 2017). As a result, the skilled workers may rotate around shipyards and support industries from time to time, causing loss of talents and repetitive hiring processes every time when there is new project. Monetary incentives for staying or reliable sub-contracting may help in this matter.

Moreover, comparing with staff retention, the strategy to improve the employee quality seems more straightforward. Staff appraisal with specific focus on their own job profile should be performed regularly. Based on the feedbacks, appropriate on-job training can be arranged. In shipyard, particularly, many technical workers (such as welders, fabricators, plumbers, etc.) are recruited from the shipyards' own apprentice programme after obtaining the relevant certificates (Chakraborty, S., 2019). Therefore, it is very important to improve the quality of the apprentice programme and being strict regarding the test and examination. Besides, optimising the recruitment process can also help to improve the employee quality, by filling the vacancy with candidates who are the not only talented but also, more importantly, fit for the purpose. Improving recruitment effectives is another task within the HRM strategy. In order to find the most appropriate candidate, more attention should be given to the criteria for selection and screening. Hiring managers should be trained appropriately to gain the skills of identifying the competitiveness of the interviewees and attracting them. Using powerful recruitment software can also help to improve the efficiency of the hiring process, saving both cost and time.

The last but not the least is about the crew disciplinary. The company should take actions to make sure that the company protocol and polices have been received and interpreted appropriately. This can be done via induction and regular briefing sessions. Cases that breach of discipline should be discussed and informed to the team at appropriate level of confidentiality. Especially for shipyards that depend heavily on sub-contractors, extra effort should be paid for monitoring and inductions. The shipyard can also consider to implement information portal to share the corporate knowledge, news and latest procedures and policies.

2.2.6. Security management performance evaluation

Security management at shipyard is similar to which in other work places. The objective is to develop and implement the effective prevention and protection strategies for the shipyard's tangible and intangible assets. These valuable assets can be human, know-how, real estate, IT assets, digital system, equipment and machineries, etc. Security management is the responsibility of the security department at the shipyard, which generally includes activities such as identifying the security risks and then developing, incorporating and disseminating the best practices, standards and guidelines to monitor and mitigate such risks in compliance with human rights. Consequences from poor security management can be destructive, which can cause the loss of assets, business reputation and potentially regulatory fines and legal action as well as the costs of remediation.

In general, security policies are developed respectively for people, physical assets and digital system (i.e. the Cyber security), with people security and safety being always the most important objective for the organisation, which includes protection for all employees, visitors and contractors, etc. Cyber security is another sophisticated topic that draws much attention from organisations recently due to the increasing reliance on computer systems.

Cyber security, sometimes referred as information technology (IT) security, is technical measures and procedures set for protecting the cyber environment of a user or organisation, to save the integrity of networks, programs and data from unauthorized access. Cyber threats take many forms, and the ones that related to shipyard can be ransom ware, malware, social engineering, phishing, etc. (Seemma, P., et. al. 2018). There was a survey taken by UK government regarding cyber security in 2017, some of the key findings are listed below (Klahr, R. et. al, 2017):

- Senior managers in three-quarters (73%) of micro/small businesses and Senior managers in the overwhelming majority of medium/large businesses say that cyber security is a high priority
- 46% of all businesses identified at least one breach or attack in the last year (i.e. 2016), among which the most common types of breaches related to staff receiving fraudulent emails (72%), followed by viruses and malware (33%), people impersonating the organisation online (27%) and ransomware (17%).
- The average cost for a large business is £19,600 and for a small to medium-sized business is £1,570.

It was also noticed from the survey that the breaches were often linked to human factors, highlighting the importance of staff awareness and vigilance. This is not only the case for cyber security, but also the common concern for security management in general. With regard to this, a term ‘Personnel & People Security’ has been used by UK government’s National Technical Authority for physical and personnel protective security, CPNI (Centre for the Protection of National Infrastructure), to represent a set of policies, procedures, interventions and effects which seek to enhance an organisation or site’s protective security by (CPNI, 2021a):

- Mitigating the risk of workers (insiders) exploiting their legitimate access to an organisation's assets for unauthorised purposes,
- Optimising the use of the workforce (and, where appropriate, the public) to be a force multiplier in helping to prevent, detect and deter security threats,
- Detecting, deterring and disrupting external hostile actors during the reconnaissance phase.

Specifically for shipyard where more contractors, sub-contractors and suppliers involved in the daily operation and production activities, such effective policies and procedures must be in place and implemented appropriately. It is because the intensive third party involvement in shipyard operation increases the risk of security matters and make it more difficult to manage. During the site visit to one of the shipyards studied in this project, it was mentioned, there were several occasions that unauthorised personnel was found in the dock or inside the ship under construction. It is extremely dangerous not only to the shipyard, but also to the intruders. It is because shipbuilding often involves operation of heavy machineries that requires all staff remain within the assigned safe region. As the result of such incidents, the shipyard normal operation might be interrupted, leading to delay of the project delivery or even legal disputes

Being one of the essential department in most organisations, best practices and principles for security management can be found from numerous literatures. In general, different organisations will adopt their own protective and preventive procedures from such practices and principles to protect themselves against security threats using a combination of physical, personnel and people, and cyber security measures. Considering the proposed KPIs above, the recommendations on improvement activities that shipyard can be benefited are proposed from the following aspects.

The primary and most straightforward activity for improvement is to improve the security equipment installed at the shipyard. The basic functions for security equipment at shipyard are for access control, barriers, detection and tracking, as well as digital solutions for cyber security, etc. Most of these equipment can be purchased as commercially available off-the-shelf products. To maintain the good security performance, shipyard should carry out inspection or self-assessment regularly to identify the area that new equipment or replacement is required. Then compare the quality and price to decide the most suitable product to install. However, having the right equipment installed is just the start, appropriate utilisation is the key step. For this reason, the shipyard should develop appropriate policy and procedures that all staff should be trained and follow. For example, using swipe-card and PIN is one of the most widely used access control system, however, it may not be as secured as expected if inadequate checks on authorisation or if the system can be remotely accessed or bypass.

This concern triggers another direction of effort for improving security efficiency, which is the activities that help to create the effective security culture at the shipyard. According to CPNI, security culture is the set of values shared by all staff regarding to the expectations how to think about and approach security, which will help to a security conscious and responsible workforce, and promote the desired security behaviours. Other benefits an effective security culture can bring to the shipyard include increased compliance with security measures and awareness of security threats, and reduced insider incidents. Activities that can support the development of the security culture can include proper training on people about the security measures, self-assessment regarding their security culture, and having the dedicated, motivated and professional security staff employed, etc.

Security officers are important for creating the positive security culture as they are often the first point of contact when anyone entering the organisation’s premises, and their behaviour sets the example how the organisation prioritises security (CPNI, 2021b).

The improvement can be also supported by implementing appropriate incident management practices, which will help to ensure a swift and effective recovery. The incident management practices should be well planned and rehearsed by everyone involved. The primary objective should be to save the lives if attack occurred. The focus of such practices is to highlight the immediate actions as soon as an incident occurs. There are several practices recommended by different professional authority or consortium in security management. For instance, Figure 22 below shows a phased approach to identify incidents and its associated remediation target, recommended by CPNI (CPNI, 2021c). Figure 23 is the seven step cycle that is abstracted from CISSP (Certified Information Systems Security Professional) (Faithfull, M., 2022; Whitman, M. and Mattord, H., 2006).

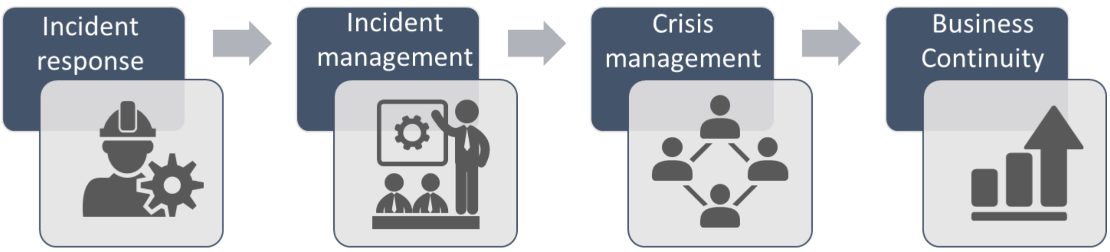

Figure 22: Phased approach to identify incidents and its associated remediation target, recommended by CPNI

Figure 23: The seven step cycle that is abstracted from CISSP objectives

As can be seen, though the individual element is different, the fundamental principles for managing the incidents are consistent. Accordingly, shipyard could manage their security guided by such flowchart, in terms of installing security equipment, training staff and developing policies and procedures. To summarise, firstly, shipyard should have the arrangement for response preparation of potential risks that is predicted based on their experience, historical record, or consultancy with the security professionals. Such preparation, on the one hand, includes installing monitoring equipment such as Intrusion Detection Systems deployed to monitor network activity, on the other hand, the security practices should be tested and rehearsed regularly such as Fire Evacuation Drill once or twice a year to ensure everyone knows what to do when fire accident occurs. Furthermore, the shipyard should have appropriate plan of responses. There are several levels of responses, including the responses to immediate impact, how to manage the consequences of the business interruption, and arrangements to manage strategic, complex and unprecedented events. It should be made clear about who is in charge, how to keep stakeholders informed, escalation processes, coordination of resources, etc. (CPNI, 2021c).

Finally, activities should be taken to recover the business, or at least to maintain critical and urgent business activities to a pre-determined level. To do so, the security management team should collaborate with all other departments at the shipyard to understand what impacts that could disrupt the business, including unavailability of building (e.g. dock), people (e.g. colleagues or suppliers) or equipment (e.g. machineries or IT). Then plan how to continue critical parts or priorities the resources for business recovery during and after disruption.

2.2.7. Supply chain management performance evaluation

The scope of supply chain management (SCM) includes all management and planning activities related to collaboration with channel partners, sourcing and procurement, as well as logistics management that plans, implements and controls the flow and storage of material, information and service between the origin and consumption points (Ramirez-Peña, M., et. al. 2020). In shipyard, it is normally responsible by purchase manager and sometimes, quality manager, includes inventory control and distribution of drawing, material, assemblies, machineries, equipment and labour.

SCM plays a vital role to ensure the production to go on smoothly. Nowadays, outsourcing the non-core activities is the common operation at the shipyards so that they can focus on the activities where they could remain competitive (Mello, M. and Strandhagen, J., 2011). Statistics shows nearly 60-80% of the ship value is outsourced, with considerable coordination between all stakeholders involved in the design, engineering, and production. As outsourcing can cover almost every phase that use to perform in the shipyard traditionally, there is a trend to transform the so-called ‘full shipyard’ to ‘assembly shipyard’

(Held, T., 2010), such as the modular production model in shipbuilding as discussed in Section 2.1. Failure in efficient and effective SCM may cause delay of the project delivery and overspent to the project.

The backward industries that supply to the shipbuilding include machinery, electronic parts, steel and other general marine supplies (Ferreira, F., et. al. 2018). It is a typical engineer-to-order (ETO) type of industry. As illustrated in Figure 24 where the customer order decoupling point (CODP) is used as a buffer between upstream and downstream partners in the supply chain, comparing with other types of operation, the ETO operations requires lower level of stock with less driven by forecast and longer delivery time depending on the demands from downstream (Hoekstra, S. and Romme, J., 1992). This is because of the characteristics of the shipbuilding that is highly customised to meet individual customer requirements, and has deep and complex product structures with levels of assembly process. In general, the storage capability of the yard is limited as ETO operation does not require massive storage of the raw material. It is also because there is very low chance the old stock can be commonly used for the diverse design of the highly customised products. Therefore, delivery on time (i.e. not too early and not lagging behind) is the primary requirement for the successful SCM in shipbuilding. For the same reason, implementation of the lean concept becomes more and more popular in shipbuilding aiming at minimising the defect rate via techniques such as condition monitoring of the production process. Moreover, the high level of customisation and complicity will usually increase cost, risks and longer lead time which raises the requirement of suppliers' active involvement during design and planning stage to reduce the probability of misunderstanding or miscommunication. As there will always be certain level of difference between each project resulting in the requirements being constantly changing, the SCM must be agile enough to adapt to these changes and to give responses as quick as possible. Besides, due to the highly dependency to its supply chain, the shipyard must have a proper QA/QC procedure to ensure the quality of the received deliveries. The shipyard will normally allow certain days for the QA/QC to be performed to the newly received deliveries before transferring to the production site. In addition to the quality control, integration is another major concern for the shipyard SCM because of the involvement of multiple suppliers.

As can be summarised from the discussion above, the success of SCM is the result of collaboration between multiple links and multi-functional stakeholders from diverse backgrounds. Although it is a sophisticated research topic, its performance evaluation is straightforward. Regardless of the type of the supply chain or the context of the business, the common objective of SCM is to ensure the reliable supply chain that can deliver services, material or information on time, with low cost and good quality. It can be further refined into the performance measurement of suppliers and logistics.

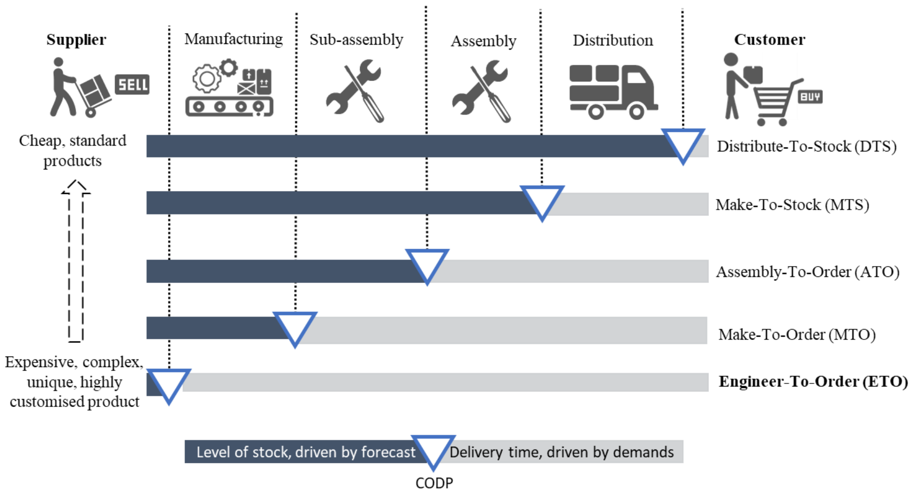

Figure 24: The different types of operations according to CODP (adapted from (Hoekstra, S. and Romme, J., 1992; Ognyan, A. and Tanya, P., 2013))

Based on review of the researches regarding supply chain in shipbuilding industry, it was found the key to improve the performance of SCM is to develop an effective integration and knowledge acquisition mechanism that can securely, accurately and timely share the information between shipyards and their suppliers. The successful implementation of such mechanism can benefit all parties within the supply chain mutually. On one hand, this can help suppliers with better understanding of the shipyard's demand and requirement, as well as avoidance of any miscommunication and conflicts. On the other hand, the shipyard will need to understand the capability of the suppliers such as capability to produce high quality output, capability to keep schedules, capability for rapid deliveries with short notice and availability of capacity, etc. (Ruuska, I., et. al. 2013). In addition, selection of the supplier, sometimes, is not the sole decision by the shipyard, it may be the requirement from the ship owners that they will only offer the project if certain components are from designated suppliers. Therefore, it is important that the shipyard should have good knowledge regarding the capability of their supply chain and maintain efficient partnership with their suppliers especially such designated ones.

The target is to develop the culture of trust with the suppliers. Traditionally, this is achieved through repeated collaboration, review of the experiences from the previous projects and taking time for meetings to get acquainted with each other, which will be useful to gain important knowledge on each other and build common ground needed for future projects (Beach, R., et. al. 2013). Nowadays, the fast development of the advanced ICT (Information Communication Technology) tools that facilitate the communication and information flow among the supply chain has made this target easier to achieve. One of the most popular concept in this context is the application of Industry 4.0 techniques in SCM.

The term Industry 4.0, aka the Fourth Industrial Revolution, first appeared in a high-tech strategical report for the German government describing the expectation of using modern smart technology for automation of traditional manufacturing and industrial practices. According to the Boston Consulting Group, there are nine technologies used in manufacturing, as the foundation for the necessary adaptation to fully integrate the flows of information (Rüßmann, M., et. al. 2020):

- Big data and analytics.
- Autonomous and collaborative robots.
- Simulation, allowing managing data in time through virtual models.
- Horizontal and vertical integration.
- The Industrial Internet of Things (IoT).
- Cyber security.
- The Cloud.
- Additive manufacturing.
- Augmented reality.

The feasibility of individual technique applying to shipyard SCM is dependent on the type of supply chain adopted by the shipyard, i.e. lean, agile, resilient or green. With assistance of these advanced digital technologies, the efficiency and effectiveness of the SCM can be greatly improved. Firstly, the SCM in shipbuilding involves management of large quantity of the inventory data which requires an effective big data analysis and database management tools, which also includes the cloud based techniques that can improve reaction times and enabling more data driven services for production system and information flow among the entire supply chain. The simulation functions can allow data management in time through virtual models of products, materials and production processes with all its components, workers, machinery, and final product (Ramirez-Peña, M., et. al. 2020) so that the order demands can be appropriately predicted. Secondly, for a digitalised shipyard, the horizontal and vertical integration strategy can support the internal integration of various functional departments horizontally and vertically integrated with other players in the supply chain. In addition, the automation system with robots and sensors can also help with the sorting, distribution and quality control of the received deliveries. Besides, the cyber security must be taken into account when implementing the Industry 4.0 techniques. More details about cyber security has been discussed in Section 2.2.6.

2.3. Performance measurement and management

Performance measurement and management has long history, as early as 221AD during Wei Dynasty in China, a 9 grade system for evaluating royal performance has been created and successfully implemented, which is believed to be the first report in this subject (Mangipudi, M., et. al. 2020). There have been numerous well-established theories and models implemented to support business development (Altiok, T., 1997). Performance can be defined as anything from efficiency, to robustness or profitability or numerous definitions that never fully specified. It is a planning and control cycle that captures performance data, enables feedbacks, and influence the work behaviour, which is the potential for future successful implementation of actions in order to achieve the goals (Lebas, M., 1995; Simons, R., 1990). In simple word, performance management supports the development of strategic plans, evaluates the achievement of objectives and can be employed as a channel for continuous learning and improvement. As mentioned in Chapter 1, the scope of SPPM focuses on two elements within the performance management framework: the performance measurement and improvement. The improvement includes activity plans and optimisation of its associated budgets. The literature regarding these topics in the context of SPPM can be found in Section 2.2 and 2.4. In the following sections, the research and development of performance measurement will be reviewed.

2.3.1. Performance measurement frameworks

Performance assessment is part of performance management process. Figure 25 illustrate the general process of performance measurement (Osmani, F. and Maliqi, G., 2012). As stated by (Bititci, U., et. al. 1997), 'performance measurement is the information system which is at the heart of the performance management process and it is of critical importance to the effective and efficient functioning of the performance management system'.

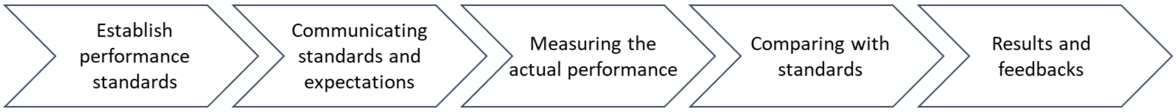

Figure 25: Performance measurement process (Osmani, F. and Maliqi, G., 2012).

The first step is to establish the performance standards which will be used as criteria for comparison. This step is crucial for a successful performance assessment as all follow-on activities are based on these standards. These standards must be clear, understandable and measurable. More importantly, it must fit for the nature of the business with alignment of environment, strategic intent and what to be measured (Franco-Santos, M., et. al. 2012). In the other word, these standard is the interpretation of the firm's objectives. The next step is to communicate these standards to all relevant individuals so that they can understand their role and responsibility in organisation. This can be done through various metrics or assessment forms. The third step is to measure the actual performance and then compare with the standards in order to evaluate the deviation between standards and the performance. The comparison results will be communicated with all relevant individuals and feedbacks, such as rewards, solution to problems, improvement plans, etc. will be provided. Finally, the output from such measurement will become necessary input to the decision making and planning for corrective actions.

The performance measurement framework employed in SPPM is KPI, the detailed review of this model will be given in the next section. The decision regarding the application of KPI is based on review of several alternative models. The following paragraphs will explain what have been compared.

The first framework compared with KPI is OKR, stands for Objectives and Key Results. Objectives in the OKR is the qualitative definition about what to improve and key results means quantitative assessment to confirm if the objectives are achieved. Similar to KPI, OKR is also an outcome-oriented method, but the focuses and assessment detail level of these two metrics are different. KPIs are business metrics that reflect performance, OKR is a goal-setting method for organisation growth and improvement (Zhou, H. and He, Y., 2018). For SPPM, the focus of Module 1 is the performance benchmarking will be at a very detailed level so that it can cover all essential elements during the shipbuilding processes. The goal-setting step in OKR can be viewed as the task to be performed after KPI in SPPM, which is out the scope of SPPM. Moreover, there is another similar framework named Management by Objective (MBO) which is a process where goals of an organisation is defined and conveyed by management to the responsible individuals. This framework was created earlier than KPI and OKR and sometimes was considered as the origin of these two, however, it contains several shortcomings that have now been improved by KPI and OKR. The most critical limitation for MBO is the ignorance of existing ethos and working conditions, it often does not consider the context wherein the goals are set and sometimes over-emphasise the importance of target setting for succeed, rather than solving the operational issues (CFI, 2022). For this reason, although the underline logic for both models are similar, KPI would be more preferable as it will be more adjusted to fit the context of the assessment.

Another group of frameworks reviewed is the so-called business-oriented metrics. The representative models within this group is AARRR or BARRA. AARRR stands for Acquisition, Activation, Retention, Referral, and Revenue, while BARRA stands for Retention, Activation, Referral, Revenue and Acquisition, Both methods are aiming at monitoring how you lose your customers along the whole customer lifecycle, so that the product team can focus on providing good values to customers before spending much money on marketing (Ratcliffe, J., 2017). These models focus on company growth and more suitable for start-ups. Comparing with KPI, these models are not very suitable for the potential users of SPPM.

The third type of framework for performance measurement is based on customer's experiences, such as Persona-based models or Customer Experience Index (CX Index) (Lidwell, W., et. al. 2010). These models look into all aspects of a product to measure customer loyalty and how it influence the revenue. These models often focus more on the product quality and after sale service rather than the production process. The data collected for analysis is mainly from customer feedbacks. Hence, it is more suitable for the fast consuming goods or digital products which is not the target user for SPPM. For the same reason, models such as Xavier Blanc's REAN (Reach, Engage, Activate, Nurture) (Shannak, R. and Qasrawi, N., 2011) and Dave Chaffey's RACE (Reach, Act, Convert, and Engage) (Sestino, A., et. al. 2021), which assessing the performance from life cycle perspectives rather than focusing on production activities cannot be used. The review has also included some social metrics such as STEEP (societal, technological, environmental, economic and political) or Ethical OS toolkit (Lilley, M., et. al. 2020). Some of the indicators that can be incorporated in SPPM but still cannot the fit for the full purpose, especially these are proposed to support designers rather than focusing on production stage.

Consequently, considering the requirement on level of detail, assessment focuses (production activities), fitness of business nature (shipbuilding), flexibility (various elements to be integrated), and potential users (shipyard), etc. the KPI framework is believed the most suitable model for SPPM. More detailed information about KPI to support this choice can be found in the next paragraph.

2.3.2. The KPI based approach

With development of techniques used for modern accounting, scientific operational management and modern measurement, the value based framework becomes more and more popular. In 1990s, the introduction of Balanced Scorecard (BSC) was anticipated by Eccles to be the revolution of performance management (Eccles, R., 1991). BSC was introduced by Kaplan and Norton as a performance measurement tool, which now commonly used by companies to track KPIs as part of their strategic business management to ensure the alignment of the operational performance with the long-term strategic objectives (Kaplan, R. and Norton, D., 1992). At strategic level, performance management as a discipline has established since the 20th century, mainly driven by strategic management and organisational behaviour practitioners, such as Peter Drucker and his famous publication “Concept of the Corporation” (Drucker, P., 1946) which was evaluated as the turning point in the evolution of strategic performance management (Bieńkowska, J., 2016). The KPI BSC is designed for both financial and non-financial goal management, related to strategic objectives and categorised as cause and effect. The development of KPI based techniques is continuous, as for now, the KPI models are calibrated with industry performance data so that the company can anytime know about their performance and come up with recommendations on what to improve.

As part of a holistic management framework, Key Performance Indicators (KPIs) are the critical indicators of progress towards an intended goal. It provides an analytical basis for strategy execution including strategic and operational improvement, supporting the decision making and identifying the hotspots driving the performance of a process. However, there is a serious weak point when using the KPI models, which is the possibility of ignorance of certain tasks that are not measured by KPIs. Therefore, setting the appropriate KPIs is the key to a successful performance measurement and management system. The balanced scorecard institute has defined the basic perspectives that the KPI should cover four categories (Sushil, 2008):

- **Financial**: also known as Stewardship in public sector, views organisation's financial performance and resources usage
- **Customer/Stakeholder**: satisfactions to customers and stakeholders
- **Internal Process**: views the internal operational goals, such as quality and efficiency related to product or services or other business processes, etc.
- **Organisational Capacity**: also known as Learning and Growth previously, covers the performance related to human capital, infrastructure, technology, culture, training, information systems, etc.

The logic insights of these four viewpoints are interdependent and hierarchical (Cooper, D. and Ezzamel, M., 2016). As shown in Figure 26, the organisational capacity growth requires constant learning and innovation which will lead to the refinement of their internal process. Improved internal process will encourage the increment of operating efficiency and service (or product) quality, which can help in achieving higher customer/ stakeholder satisfaction, gaining better market reputation, attracting loyal customers and repeat business. Eventually, this will increase the financial performance of the business. This means, there will be sufficient financial investment available to support the organisational capacity growth.

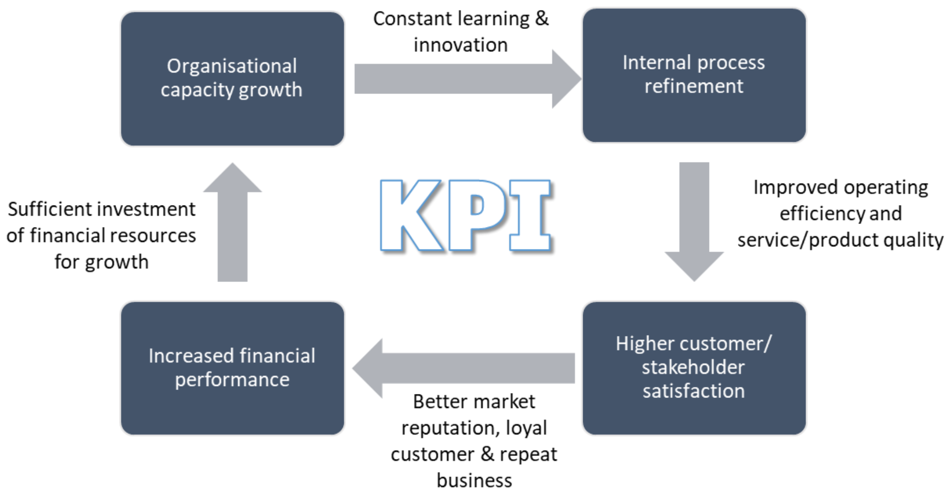

Figure 26: The links among KPI BSC perspectives

The interpretation of the KPI varies dependent on the business nature, linking to its operational strategy and a solid framework to map any company's progress towards success (Armitage, H. and Scholey, C., 2006). To design the KPI template for a given decision context, the first step is to set the goal which is the desired level of performance, then identify the way of measurement and tracking the progress. Indicators are sometimes categorised as cause and effects (or lead and lag). Improving leading indicators can drive the lagging benefits which shows how successful the organisation is achieving their performance goal. The good KPI template should be able to measure all intended indicators and balanced between leading and lagging indicators that can support a better decision making, including efficiency, effectiveness, quality, timeliness, governance, compliance, behaviours, economics, project performance, personnel performance or resource utilisation, etc. It will be beneficial if the KPI template can work dynamically, meaning the comparative study can be performed to gauge the degree of performance change over time.

Regarding the challenges when using the KPI method, knowing what can or cannot measure would be the most the most influential one. This can be effected by data availability, the reporting level requirement or the alignment with organisations strategy and external environment, etc. More specifically, some well-established techniques can help to select and design the specification of the KPIs, such as the ‘SMART’ principle. ‘SMART’ is a well-established tool used to plan and achieve objectives, first used by George T. Doran in 1981(Doran, G., 1981). While there are a number of interpretations of the acronym's meaning, the one used in this research is Specific, Measurable, Attainable, Relevant, and Time-bound. More detailed interpretation will be given in Chapter 3. The decision in employing SMART is based on a comparison of several popular alternative goal making principles, and SMART is believed to be most suitable to fit the nature of KPI framework as it can clearly and straightforwardly describe each KPI at any required level of detail and easy to integrate with any business (Doran, G., 1981). The comparison of these reviewed alternative principles can be found in Table 11 below.

Table 11: Comparison of different goal setting principles

Acronym	Full definition	Advantages	Disadvantages	References
SMART	Specific, Measurable, Attainable,	Provide clear direction of the objectives,	It can create pressure and demotivate user	(Doran, G., 1981)

	Relevant, Time-bound	motivate user to focus on the desire results and get out of the comfort zone, it supports monitoring of the progress so that the satisfaction can be obtained from continuous work towards the goal.	when the set goals cannot be met. It is very outcome oriented so that the user may not able to share their effort in other non-goal-oriented areas	
CLEAR	Collaborative, Limited, Emotional, Appreciable, Refinable	Good for working with large group. Very clearly describe the details of the goal and the route to achieve the goal	It takes extra effort in setting the goal as extensive instruction will be included at this stage. There is less flexibility for the user when process the work.	(Project Manager Success, 2019
PACT	Purposeful, Actionable, Continuous, Trackable	Output focused, aiming at continuous growth for long-term, ambitious goals.	Not suitable for pursuing short and medium term well-defined achievements	(Cunff, A., 2022)
FAST	Frequently discussed, Ambitious, Specific, Transparent	Good for holding yourself accountable to others	Many not suitable to set goals for a team and business purpose because of the transparency of the progress to others	(Project Manager Success, 2019)
DUMB	Dream-driven, Uplifting, Method-friendly, Behaviour-driven,	It is rather a mission statement, good for grounding the ambitions	Usually not used as standalone method to set the goal	(Smartschan, A., 2022)
WISE	Written, Integrated, Synergistic, Expansive	Suitable for setting multiple goals	Less focused on individual goal itself	(Pell, A., 2020)

2.3.3. Development on performance management in shipbuilding industry

Production performance analysis, or performance management, is a common practice widely applied by businesses in manufacturing dominated industries. However, in practice, customisation of the analysis models is necessary when apply to different business fields, such as shipbuilding, to fit the nature of such business. Without such a fit, there will not be good alignment between what is being measured and what is actually important to the firm, which is very crucial to the business (Venkatraman, N., 1989). Particularly for shipbuilding, there have been several research works and publications reviewed to understand the state-of-the-art for this topic. In this section, the findings from literature review will be introduced followed by discussion on the research expectation for SPPM accordingly to fill the research gaps which is re-emphasised from discussion in Chapter 1 Section 1.2.

The primary observation from the literature review of other researches in shipbuilding performance analysis is that most of them have focused on a particular angle of the production performance rather than developing global metrics. For instance, in the research carried out by P Floriano, et.al. (2009), a model has been developed to benchmark the shipbuilding efficiency based on their performance in terms of productivity, building time and quality (Jr., F., Lamb, T. and Souza, C., 2009). This paper represented the mainstream of most similar studies which focused more on the technical perspectives. A similar example is a research by B Omer, et.al (2007) which measures the performance by the different production processes (i.e. hull, outfitting and painting) (Saracoglu, B. and Sitki, G., 2007), and research by S Myung (2018) who has proposed several KPIs combining viewpoints from technical and project management activities (Myung, S., 2018). While there are also models developed with a different focus, for example, in another research by D Gavalas, et. al. (2021), more non-technical KPIs were selected, such as finance, customer satisfaction, internal process, learnings and growth (Gavalas, D., et. al. 2021). The researchers have all mentioned in their publications why such factors are important to support the efficiency of the production. When analysing all the literature together, it can be concluded that the performance should be measured from multiple dimensions, including both technical and non-technical perspectives. On the other hand, some of the authors have also mentioned the restrictions of the work resulting in excluding some of the important indicators. There could be two main reasons, firstly, this is dependent on the diverse research interest as the researchers are from different backgrounds. The second reason is the scope and objectives of the original research project, especially the level of engagement with shipyards. Shipbuilding is a sophisticated process, which can be influenced by numerous factors such as human, market, regulation, environment, internal process, supply chain, technology development, and so on. It will take considerable effort to develop a holistic model that could provide decision-makers with the overall picture of their production performance.

The ultimate goal for performance management is to develop a strategy for maintenance and improvement. An effective, accurate, and exhaustive performance measurement model builds the foundation for decision-makers to make fair judgements when planning for the improvement activities. Another observation from the literature review is about the level of computation detail of the models. Most reviewed publications as listed above have proposed indicators without providing detailed calculation procedures, which may affect the practicality of the models for users to implement. Therefore, developing a comprehensive performance measurement model with a detailed computation procedure becomes the primary requirement for this PhD research.

After a detailed performance measurement, the improvement activities can be proposed focusing on the aspects that are considered as ‘hotspots’. This step has been excluded from most above listed researches focusing on performance measurement which is another observation from the literature review. There have been various researches aiming at proposing technologies that could improve the production performance, such as (Park, J., et. al. 2014; Shahsavar, A., et. al. 2021; Sender, J., et. al. 2020; Zhang, Y. and Tao, F., 2017), and many other publications which has been discussed in Section 2.2 in detail. However, these researches are normally carried out separately without linking to the performance evaluation. The decision-maker would need to evaluate the effectiveness of such technologies from various angles. For example, if a shipyard considers introducing robotics to assist the production, then the central management needs to evaluate the effectiveness of this improvement activity from multiple perspectives. The advantage of the robot is the improved productivity and quality, it may also save cost from labour and reduce wastage. However, the user may also need to consider the associated effort of change management required for this, such as a modified production line, new H&S (Health and Safety) and cyber security measures, employee upskill training, and new supply chain, etc. There might also be other hidden factors that could affect the usefulness of this improvement trail, which the decision-makers would need to refer to the professional decision support tools specifically designed for such decision context for more information. To make the right decision all these pros and cons should be considered and compared, which requires a holistic model to be developed that covers all essential figures and have integrated all factors to make the measurements comparable. In addition, the performance management strategy is not only about selecting the useful technology, but also optimising the budget for the improvement. This is not often seen in publications in the context of shipbuilding performance management, although there is a good number of studies of budget optimisation in other applications. More details about these studies and relevant theoretical models will be discussed in the later sections of this Chapter.

There has been also noticed during the initial study that in the shipyard, the data generated every day is innumerable with a great deal of variety, especially for the shipyards that are equipped with advanced digital techniques. However, the data from different parts of the shipyard are normally managed by different people but might be required to use by others, which may cause issues with misinterpretations of the data and waste of resources. For this reason, it will be beneficial that SPPM can also serve as a centralised performance data management system, which allows quick access to the consistent information related to performance management reported from various departments. These data can be either input parameters required for performance measurement or the outputs from SPPM recorded for continuous monitoring.

2.3.4. Performance measurement in other manufacturing industries

Production performance analysis, or performance management, is a common practice widely applied by businesses in manufacturing dominated industries. As discussed above, performance measurement as the core part of performance management is critical for the organisation to be successfully achieve their strategic goals. To do so, any organisation needs to determine suitable performance indicators and subsequently measurement metrics and improvement plan that are strategically relevant to its respective situation (Mapes, J., et. al. 1997). According to ISO 22400 ("relevant measurements for use in the formula of a key performance indicator"), the basic KPIs can be mainly divided into three categories: time, quality and logistical (including quantity and inventory management). Considering the business nature of manufacturing industries, the following indicators were found commonly used in general from literatures:

- Quality: This indicator has been focused by most organisations because this is the basic promises they have provided to the customers (Heckl, D. and Moormann, J., 2010). It can be further measured from several dimensions, such as features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality (White, G., 1996).
- Flexibility: this indicators shows the ability of the organizations to perform multiple tasks at given level of resources (Zhang, Q., et. al. 2002).
- Time: This indicator could be measured as lead time, delivery lead time, due date performance, frequency of delivery or rate of production introductions, etc. (Neely, A., et. al. 2005). It is very important for a company to achieve competitive advantage over its competitors.
- Safety: Safety is the most important factor ensuring the sustainability of the business. In turn, it is believed that to ensure the safety, work structures as well as technical arrangements should be well managed (Mearns, K., et. al. 2003).
- Financial performance: This is the traditional metric for measuring what businesses care about most. It can be the physical values of sales and profits or percentage return on equity and assets (Ishaq B, M., et. al. 2014).

- Employee's satisfaction: This indicator is very important especially for the labour intensive industries, which is the case for most manufacturing industries (Ishaq B, M., et. al. 2014).
- Learning and growth: This is the metric measuring the future of a business.
- Environment/social performance: With the research and development of CSR, the social and environmental impact has been widely recognised as the important part for the business to be sustainable (Singh, C., et. al. 2021).
- Customer satisfaction: There is no doubt about the importance of customer to the business, but it can be effected by various factors such as on time delivery, product quality, after sale services and user friendly trading system, etc. (Ishaq B, M., et. al. 2014).

It is worth mentioning these indicators are not necessary to be used for all industries because each industry will have its own characteristics. For example, in construction industry which has very similar core business of shipbuilding, i.e. generating new buildings or refurbishing existing ones for a variety of clients. Traditionally, cost, quality and time have been used to for performance measurement. However, it now has been recognised that although these three measures can indicate the success or failure of a project, it cannot provide a balanced view the overall performance in isolation. For this reason, more construction companies now consider to develop their KPI BSC from financial, internal business process and customer perspectives (Kagioglou, M., et. al. 2001). More particularly, in 1999, the UK best practice programme launched the KPIs for construction (KPI Working Group, 2000), which is still available:

- Client satisfaction – product
- Client satisfaction – service
- Defects
- Predictability – cost

- Predictability – time
- Profitability
- Productivity
- Safety
- Construction cost
- Construction time

The benefit of having KPIs for whole industry is that an organisation can benchmark their performance against the national performance of the industry and identify the area for improvement.

The review has also included the process industry which is in the different object-type of shipbuilding. Process industry is defined 'as the industry in which the raw material undergoes conversion during a continuous process in order to become finished products' (Zhu, L., et. al. 2017). Specific KPIs proposed for process industry as observed from literatures can be categorised as basic measurement elements, equipment, energy and process KPIs. Table 12 below is the list of some of the commonly applied metrics for measuring these KPIs in process industry (Zhu, L., et. al. 2017).

Furthermore, with development of emerging technologies in the manufacturing industry, more different KPIs have now been applied to address the changes and new challenges in the field. For instance, manufacturing companies are confronted with more complex and individual technical systems and at the same time with less time to plan and develop, increasing requirements on quality and flexibility as well as reduction in cost of production (Gottmann, J., 2016). Industry 4.0 or rather digitalization has now been considered as a solution to the most current challenges in production and at the same time the next development step in manufacturing (Reinhart, G., 2017). Therefore, there should be KPIs linked to Industry 4.0-related changes in production, which means the above reviewed common KPIs should be adjusted and more IT related KPIs can be developed. Besides, green and lean manufacturing is another concept becomes popular for the industry recently. Based on the review of researches in this topic, the performance regarding green-lean manufacturing is normally measured from following aspects (Singh, C., et. al. 2021):

- Environmental parameters, such as emission, resource usage, wastage.
- Economic/ operational parameters, such as product quality, operating cost, time, flexibility.
- Social parameters, such as OHS, employee satisfaction, customer experience, community satisfaction, suppliers commitments and certification.

Table 12: List of some commonly applied KPIs in process industry (Zhu, L., et. al. 2017)

Category	**Metrics**
Time element	Planned operation time, actual busy time (sum of actual production time and actual down time)
Quantity element	Input quantity (sum of raw material quantity and energy medium quantity) Output quantity (sum of Desired product quantity, By-product quantity and Scrap quantity)
Equipment KPIs	Allocation ratio, Utilization efficiency, Equipment load ratio
Process KPIs	Production rate, Technical efficiency, Quality ratio, Actual to planned scrap ratio, Scrap ratio, Finished goods ratio
Energy process KPIs	Energy consumption

The observations from the above literature review regarding performance measurement in different manufacturing industries will be considered regarding its suitability of transferring such best practice into shipbuilding industry, in particular, to support the selection of KPIs in SPPM.

2.4. Budget Optimisation Models

In this section, the models to support the budget optimisation for performance improvement is reviewed. To summarise, the optimisation has two directions – the performance based budgeting (PBB) defining the activity plan and total budget required with its allocation and budget allocation optimisation (BAO) when total available funding is restricted.

Research regarding achieving optimisation in various context has a long history. As early as 1744, Leonhard Euler mentioned that "Nothing in the world takes place without optimization, and there is no doubt that all aspects of the world that have a rational basis can be explained by optimisation methods" (William A. et. al. 1933). For every business, budget optimisation is always the important part of its development strategy. Budget is often defined as a financial plan for a given period, which can be used to express strategic plans of business activities in measureable terms (CIMA, 2005). In the context of SPPM, the budget optimisation model will support shipyard to plan for the funding and associated activities aiming at achieving the effective performance improvement. The function is not only just a cost or cost allocation estimation, but also an opportunity for decision maker to review their production performance and the effectiveness of the planned activities for improvement. The two directions of optimisation build on research conducted at TWI in the context of optimisation of inventory management where spares are stocked based on either minimising risk (measured in money terms) of a stock out within a given budget or minimising budget given a threshold for the risk of stock out (Bharadwaj, U.,et. al. 2011).

2.4.1. Performance Based Budgeting (PBB)

Performance based budgeting (PBB) is the practice that develops budget based on the relationship between allocated fund and the expected achievements from investing such fund. Comparing with the traditional budgeting approach, the most notable difference in PBB is its ‘Results’ oriented planning and budgeting framework.

Traditionally, to plan for the budget, the organisation will first make a long-term plan, and then break the plan to annual budget accordingly. At the end of each year, based on the variance-comparison between the actual spend and the budget, revise the monetary amount for the next year and start the next planning and budgeting cycle (Carter, K., 1994; William A. et. al. 1933). Though this approach is easy to implement, its drawbacks are also significant. Firstly, the framework is based on long-term goals rather than short-term and intermediate objectives. This means there could be lack of clear guidance resulting in subjective judgement on next-year’s spending and inaccurate representation of the business strategy. Moreover, as the traditional budgets use the previous period’s budgets as the base, when there is undetected error in the previous budgets, it can be carried over to the next period. Until the time it comes to notice, unrealistic standards might have been created for the business already.

To overcome these disadvantages, various enhanced budgeting models were developed, among which PBB is believed that fits for purpose of SPPM. When using PBB, the resources will be allocated to achieve specific objectives, based on program goals and measured results (Carter, K., 1994). PBB is a sub-set of what is known as ‘outcomes systems’ that is defined as any systems designed to identify, measure, attribute and/or hold parties to account for outcomes (Duignan, P., 2009). Developed by Paul Duigran, the outcomes theory builds the conceptual basis for working with outcomes systems of any type, such as strategic plan, management by results, outcome-focused management system, accountability system, evidence –based practice system, and so on. The core of outcomes theory can be explained using Duignan's Outcomes System Diagram, as shown in Figure 27, which shows the seven different building blocks that an outcomes system should include.

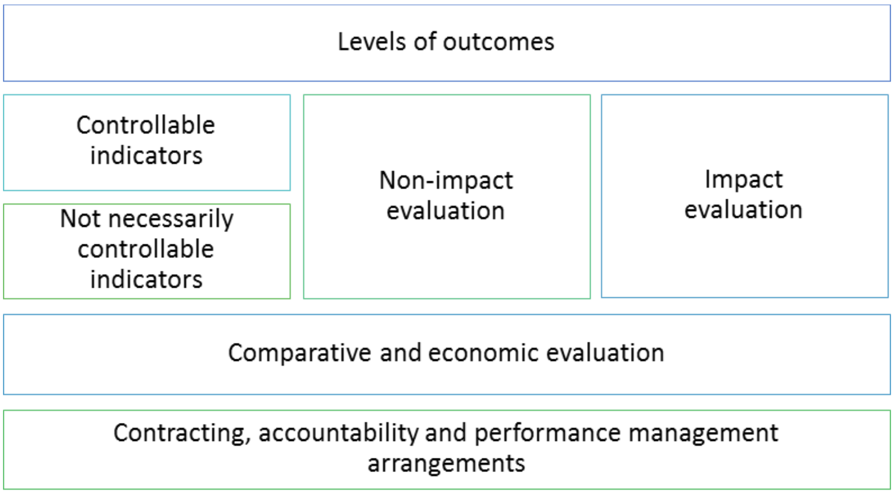

Figure 27: The seven building blocks of outcomes systems adapted from Duignan's Outcomes System Diagram

To start, the levels of expected outcomes should be defined, which also includes the route planned to achieve such outcomes, supportive evidence for the plan, priorities and evaluation whether the current activities are in line with such priorities. Then, the controllable and not-necessarily controllable indicators are selected based on which the information are collected. Controllable indicators are those their mere measurement is proof that they have been caused by the project, organization or intervention that they are controlled by. They are often used as accountability measures, such as the KPIs which measures the achievement of identified goals or Key control indicators (KCIs) for measurement of effectiveness of controls that are put in place. On the contrary, the measurement of not-necessarily controllable indicators does not say anything about what has caused them. To continuously improve the system, impact and non-impact evaluation are performed. The former makes judgement whether the intervention (e.g. project activities carried out) has caused the high-level outcomes to occur, while the latter focuses on improving lower level routes within the outcome model such as the implementation evaluation that aims to explain how complex interventions work. The impact evaluation involves counterfactual analysis: "a comparison between what actually happened and what would have happened in the absence of the intervention."(White, H., 2006) The next step is to determine the best course of action by comparing the benefits obtained from alternative interventions based on the outputs from other blocks. Finally, the arrangement will be in place, which includes but not limited to typical clauses such as what information will be collected regarding the above mentioned six blocks and what parties will be held to account for, and rewarded and punished for, etc.

As a sub-set system of the outcome systems, PBB focuses on planning and budgeting aspects and is required to comply with outcomes theory. The model is built on the basis of the link between the rationales for specific activities and the results. Therefore, the PBB should include three essential elements (Segal, G. and Summers, A., 2002):

- The results, i.e. the expected final outcomes
- The strategy, i.e. different routes to achieve the final outcomes
- The activities, i.e. what is actually done to achieve the final outcomes

Figure 28 shows the PBB general process framework based on which the fund can be budgeted (Young, R., 2003). The system is framed in accordance to the abovementioned outcomes theory. On the top of this budget system, linkages are built between causes and effects in a tree model to define the context in which the general PBB framework can be adapted to. The model will be then integrated with the transition system so that the finance, procurement, or sales, etc. are tracked. This aspect is out of the scope of the current research.

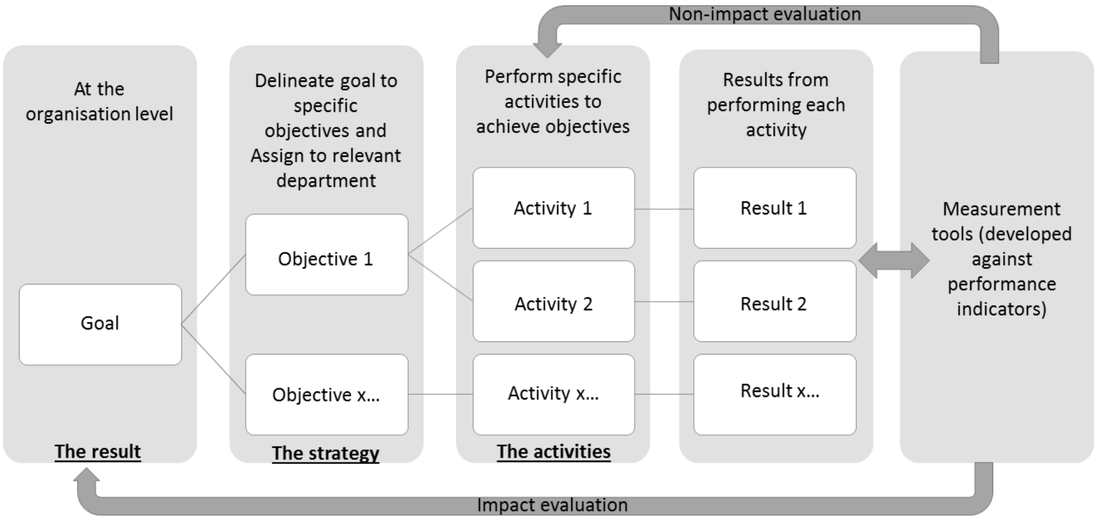

Figure 28: General process of PBB framework to determine the optimised activity plan

As can be seen from Figure 28, to develop a PBB system, the organisation should identify the strategic goal first, which is the expected results that the organisation would like to achieve using this fund. Next step is to design the strategy how to achieve the goal, based on which the goal will be delineated to specific objectives and assigned to relevant department for the detailed activities to be carried out. The effectiveness of each activity will be evaluated using the pre-defined measurement tools, such as the KPIs. Both non-impact and impact evaluation will be carried out at this stage to understand the effectiveness of the current strategy in achieving the goal. This step can help to improve the future design of the strategy or select the optimised strategy when there are alternative routes. Once the optimised activity plan is confirmed through the above process, the associated budget can be calculated and allocated accordingly.

PBB was initially developed for using in public sector, as this model is particularly powerful to deal with the organisation that operated with sophisticated processes. In general, the public bodies need to go through many processes before moving into the budget execution phase and post-execution analyses and involves the collaboration of different bodies throughout the government. It can be used not only for budget preparation, negotiation and approval processes, but also for the spending approval after the whole budget allocation is finalised. As there is increasing recognition regarding the advantages of PBB and various successful implementations in public sectors (Surianti, M. and Dalimunthe, A., 2017), the adoption to private entities has also started. One of the widely accepted ways of adoption is via using Cooperate Performance Management (CPM).

CPM is also known as Business Performance Management, Enterprise Performance Management or Financial Performance Management. According to the term and concept of CPM devised by Gartner Research in 2001(Mihok, J. and Vidová, J., 2006), it is a term describing various processes and methodologies involved to relate organisation’s strategies and goals to its plans and executions. Typically, CPM includes processes such as budgeting, scenario analysis, financial planning, forecasting and data reporting, which will be supported by a suite of analytical applications. For instance, the balanced scorecard, six sigma, and the European Foundation of Quality Management (EFQM) excellence model are the popular strategic frameworks and management methods used in CPM. This approach can help organisation to reduce operational costs, improve alignment of KPIs and strategies. It can be also used to remodel the budget and upgrade financial planning processes. One of the important elements within CPM is the CPM metrics, also known as KPIs, which provides measureable values revealing how a company has progressed in relation to its strategic goals (Frolick, M. and Ariyachandra, T., 2006). As can be seen from this definition, CPM metrics builds the basis that the PBB approach can be adopted to private sector. Via CPM, the adopted PBB approach can be carried out following the process shown in Figure 29.

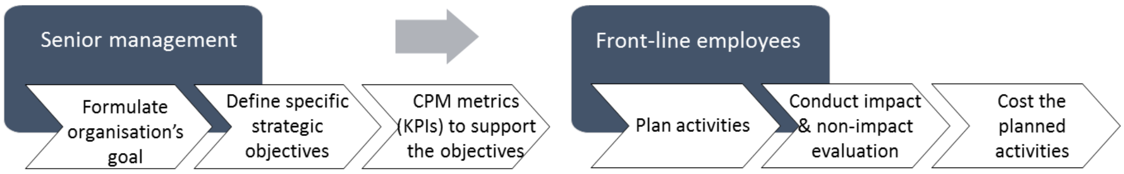

Figure 29: The process flowchart of applying PBB via CPM

Firstly, the senior management will formulate the organisation's goal and define specific strategic objectives towards the goal. At the same time, the CPM metrics addressing financial and non-financial KPIs will be developed to support these objectives and to evaluate the effectiveness of the activities to be planned and executed by front-line employees. Through impact and non-impact evaluation against the CPM metrics, the optimised activity plan can be confirmed. Then the cost associated with each activity is calculated to complete the budgeting process. However, activity cost estimation is not a straightforward task, which requires consideration of both direct and indirect costs. As observed from the literature review, many entities failed to relate costs and outcomes accurately is primarily because of the problems with indirect cost allocation. To overcome this difficulty, one of the costing models that many organisations have implemented is the activity based costing (ABC) framework to help coordinate the operational and financial planning. According to Chartered Institute of Management Accountants, ABC is defined as "an approach to the costing and monitoring of activities which involves tracing resource consumption and costing final outputs. Resources are assigned to activities, and activities to cost objects based on consumption estimates. The latter utilize cost drivers to attach activity costs to outputs" (Edwards, S., 2008).

2.4.2. Budget allocation optimisation (BAO)

The target of a BAO analysis is to find out the optimal solution to allocate the restricted funds for maximum profitability. There are various models that have been used by organisations in different scenarios. Based on the literature reviewed, these models can be broadly categorised as BAO through multi-criteria decision analysis (MCDA), BAO through utility theory, and BAO through mathematical programming.

2.4.2.1. The MCDA-based approach

MCDA is a sub-discipline of operations research that supporting decision-making via explicitly evaluating multiple conflicting criteria. In the simple words, MCDA supports decision making via comprehensive comparison among alternatives based on various predefined criteria.

The earliest known reference of using MCDA can be traced back to Benjamin Franklin (1706-1790)(MacCrimmon, K., 1973) who, in his letter to Joseph Priestley (1733-1804)(Franklin, B., 1975), described his method to make important decisions, which is now called as 'Ben Franklin method'(Ullman, D., 2006). His method involves making two columns listing pros and cons, estimating the importance of each one, and then strike off items from each list of roughly equal importance until one column is dominant. Despite the weakness of this rough-and-ready approach that may mislead people into falsely believing rationalisations that do not accurately reflect their true motivations or predict their future behaviour (Wilson, T., 2002), it is still considered as the early use of a decisional balance sheet. The term decisional balance sheet was first phrased by Irving Janis and Leon Mann in 1959, and used as a way to decision-making (Janis, I., 1959). The principle of decisional balance sheet is to support decision-maker what to do in a certain circumstance by tabulating the advantages and disadvantages of different choices. In fact, the fundamental aim of MCDA is to achieve the optimised solution for a problem with multiple objectives. In this context, Charnes, Cooper, and Ferguson published an article in 1955 that contained an extension or generalisation of linear programming to handle multiple, normally conflicting objective measures (Charnes, A., et. al. 1955). This method was later named as goal programming in their book published in 1961(Charnes, A. and Cooper, W., 1961). Goal programming is a branch of MCDA and is considered as a mainstay of management science and operations research. Stimulated by Charnes and Coopers work, the further outstanding development regarding multi-criteria problem was the formation of 'Zionts-Wallenius method' by Stan Zionts and Jyrki Wallenius (Zionts, S. and Wallenius, J., 1976). The Zionts–Wallenius method is an interactive method used to find a best solution to a multi-criteria optimisation problem, which can help to solve a linear programming problem having more than one (linear) objective. From another angle related to multi-objective problem, Ron Howard wrote a paper on sequential decision processes with G.E. Kimball and used the term "decision analysis" for the first time during the mid-1960s (Garber, R., 2009). In 1976, Ralph Keeney and Howard Raiffa published an important book that established the theory of multi-attribute value theory (including utility theory) as a discipline (Howard, R., 1968; Keeney, R., et. al. 2003). It became a standard reference for many generations of study in the area of decision analysis such as MCDA.

As the theoretical background of MCDA getting stronger, numerous computational models and tools have been developed to power the process of multi-criteria decision-making in different and specific circumstances. Figure 30 illustrates the generic decision-making framework that should be followed by all computational models to conduct the MCDA.

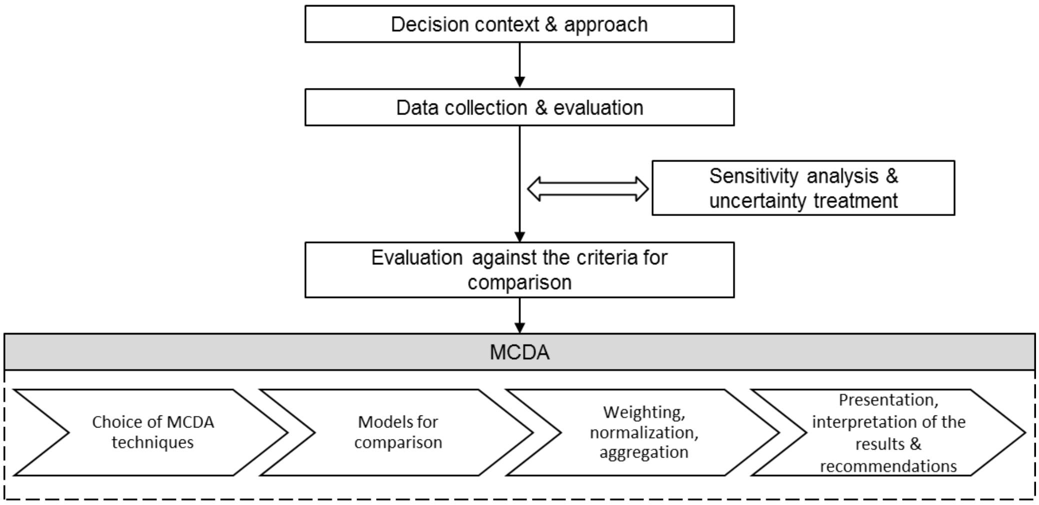

Figure 30: Generic decision-making framework (Cui X, et. al. 2017)

The first step in a decision-making structure is to **define the decision context and approach**. This step is important as it has the direct impact on the justifiability of the decision. The decisions will be judged relative to the context in which they are made. The decision context, in general, includes decision domain and decision situations (Motahari Farimani, N., 2018). More specifically, clarifying decision context involves identifying:

- Decision domain:
  - what are the alternatives for comparison.

    - what are the criteria for evaluating the alternatives.
- Decision situations:
    - what decision is being made and why.
    - its relationship to other decisions previously made or anticipated.
    - the roles and their responsibilities involved in this decision making process.
    - scope and constraints.
    - performance evaluation models.
    - baseline and level of details required.
    - assumptions and preferences.
    - risk assessment and risk mitigation strategy.

In addition, it is also required to define what the expected output from this decision making process, for instance, the output can be the plan for an action, or it can be the selection of an optimised option among various alternatives. When there are dependencies among a series of decisions, this information is very important. In most cases, the factor of time-dependency needs to be considered when defining the decision context. It is because not only the details of the above listed factors can change over the time, but also it is necessary to predict the situation in the future when the effects of the decision are brought to bear. (Motahari Farimani, N., 2018) There are several techniques can be used to define the decision context, such as consultation to experts using the checklist, holding a brainstorming session using ‘Mind Map' or a 'Creative Pattern' approach, or referring the past experience to guide deliberations about the future and make considered judgements, etc. Understanding context is an early pre-requisite toward a rational decision.

Based on the decision context, **data collection** will be carried out which is the process of gathering information for decision-making. The types of data can be either qualitative or quantitative, as required by the performance evaluation models defined in the previous step. The data needs to be processed to predefined format, and labelled with the description of the dataset, such as source, accuracy, validity, condition, and confidence of the dataset as well as any other specific details about the dataset (Cui X, et. al. 2017; Motahari Farimani, N., 2018). Such information will help decision maker with a better understanding of the evaluation results. This will also be used for uncertainty treatment and sensitivity analysis. Though output metrics is unknown at this stage, it is necessary to plan for its format in accordance to the requirement of different decision-making approaches. Popular data collection methods include literature and database review, stakeholder interview, extraction from previous experience and historical records, and so on (Li, T., et. al. 2022).

The collected data will be then applied to **evaluate the performance against the criteria for comparison** using the pre-designed performance evaluation models that are specific to the decision context. Output from this step will be then fed into the **MCDA** process.

The MCDA process starts from selection of the suitable computation model that fits the decision context. As introduced by (Linkov, I. and Moberg, E., 2012), these models are classified into three basic categories (Cui X, et. al. 2017):

- **Multi-Attribute Utility Theory (MAUT)**, where the disparate units will be resolved into comparable utility or value.
- **Analytical Hierarchy Process (AHP)**, where the pairwise comparisons between each criterion are used instead of using direct weights or value functions.
- **Outranking**, where the alternatives will be ordered by finding ones that outperform or dominate. There are many different models included in the outranking methods family such as ELECTRE, PROMETHEE, and GAIA etc. The underline approach for outranking is to make comparisons based on decision maker’s preference. This makes

it more judgement-based as opposite to an optimisation algorithm that presents an optimal solution. In the other word, the decision maker is in charge of the control regarding the definitions of what precisely constitutes outranking and the threshold parameters that are set. Although this mechanism gives maximum flexibility to the decision maker for incorporating their requirements, it may result in a rather arbitrary decision (Dodgson, J., 2009). Therefore, outranking method normally requires user to be an expert in the decision theory and have good understanding of the techniques behind the model so that the appropriate preference function and thresholds can be identified to ensure the rational decision to be made.

Considering target user of SPPM who are not expected to be expert in decision theories, outranking methods may not be suitable to be applied in SPPM. For this reason, in this project, the MAUT and AHP methods were selected for PBB and BAO respectively. Each of them has pros and cons. In the following paragraphs, these two models will be reviewed in detail.

1) MAUT

MAUT is a label for a family of decision analysis methods that aims at attaining a conjoint measure of the attractiveness (utility) of each outcome of a set of alternatives. The research history of MAUT has been over a period of decades. The earliest reference with regard to the background and history of MAUT are publications from Fishburn (1965,1970) as well as Keeney(1969,1971,1973) and Raiffa (1969) (Dyer, J., 2005.). The other important contributors in this field include Debreu (1960), Luce and Tukey (1964), Krantz (1964), Pollak (1967), Keeney (1968), and so on (Jansen, S., et. al. 2011; Greco, S., et. al. 2016). As one of the MCDA models, MAUT satisfies the framework shown in Figure 30, more specifically, Figure 31 illustrates the common procedure that all MAUT methods are following in general (Greco, S.,et. al. 2016; Winterfeldt, D. and Edwards, W., 1986).

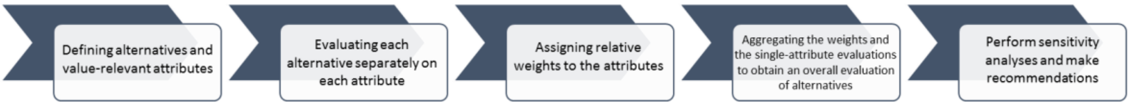

Figure 31: General procedure of MAUT methods

Firstly, after the alternatives are defined, the decision maker's preference on their attributes will be presented by constructing a utility function, U, to measure their desirability or performance (Keeney, R. and Raiffa, H., 1976). The utility function is composed of various criteria corresponding to each attribute. The next step is to evaluate each alternative on their attributes using the criteria defined by utility function. For each criterion, a so-called marginal utility score will be given as evaluation outcome on the corresponded attribute. Then, the marginal utility scores of all criteria can be aggregated to obtain the global utility score, which will be used to rank the performance of these alternatives (Ishizaka, A. and Nemery, P., 2013). Usually, for alternatives a and b defined for decision context D, evaluating their attributes on the basis of utility function U and obtaining the global utility score $\mathrm{U(a)}$ and $\mathrm{U(b)}$, then, the preference and indifference relations between these alternatives can be denoted as (Ishizaka, A. and Nemery, P., 2013):

$$\forall \mathrm{a}, \mathrm{b} \in \mathrm{D}: \mathrm{a}\mathbf{P}\mathrm{b} \Leftrightarrow \mathrm{U(a)} > \mathrm{U(b)}: \text{a is preferred to b} \quad (4).$$

$$\forall \mathrm{a}, \mathrm{b} \in \mathrm{D}: \mathrm{a}\mathbf{I}\mathrm{b} \Leftrightarrow \mathrm{U(a)} = \mathrm{U(b)}: \text{a and b are indifferent} \quad (5).$$

In the context of MAUT, the utility function U can be defined in various ways, among which, the additive model was selected to use in this project. Equation (6) is the general additive utility function:

$$\forall a_i \in D: U(a_i) = U\left(f_1(a_i), \cdots, f_q(a_i)\right) = \sum_{j=1}^{q} U_j\left(f_j(a_i)\right) \cdot w_j \quad (6).$$

where $f_j(a_i)$ is the evaluation of the alternative a_i against criterion j ($j = 1, \cdots, q$) on the corresponded attribute. This evaluation is then transformed into marginal utility score of $U_j\left(f_j(a_i)\right)$ and aggregated with a weighted sum or addition. w_j is the weight of criterion j, which satisfies the normalisation constraint:

$$\sum_{j=1}^{q} w_j = 1 \quad (7).$$

The weights represent the preference of decision maker. By applying weights, the decision maker can trade on one criterion in order to gain certain amount of units on another criterion.

Moreover, there are several characteristics related to MAUT that are worth mentioning. Firstly, the preference and indifference relations (i.e. Equation (4) and (5)) on alternatives based on utility scores is transitive. This means if alternative a**P**b and b**P**c, then it can be concluded that a**P**c; while if alternative a**I**b and b**I**c, then a**I**c. Secondly, when using the additive function, there is a condition that the preferential independence between the criteria needs to be respected (Keeney, R. and Raiffa, H., 1976; Vincke, P., 1992). Besides, the shape of utility function is determined by the decision maker, which not only reflects the decision context, but also represents the decision maker's attitude with regard to risks (Doumpos, M. and

Zopounidis, C., 2002). Figure 32 summarises typical types of the utility function. The straight line corresponds to a risk neutral attitude, who is making decisions regardless of the risk. This is different from risk averse, i.e. the concave shape, who always chooses less risky options. The third one with convex shape represents the attitude of risk taker (Concina, L., 2014). MAUT provides clear choice criteria, which is mostly used in the cases where a wide range of perspectives and decision alternatives are under consideration. However, achieving the consensus of utility scores on various attributes may be complicated and time consuming (Cui X, et. al. 2017; Cresswell, A., et. al. 2000).

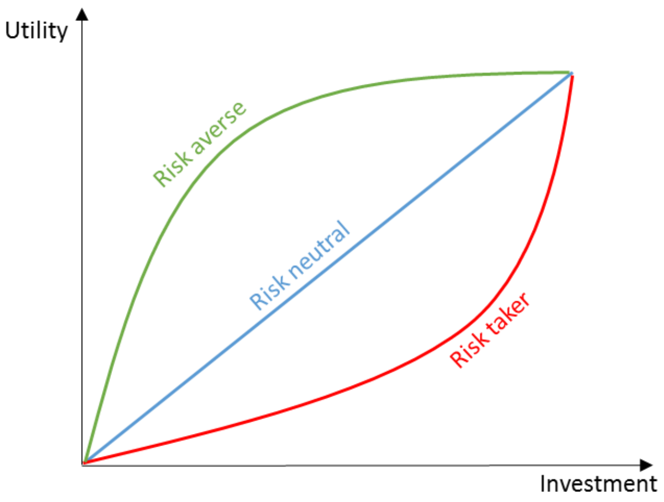

Figure 32: The curvatures of the utility function corresponding to different attitudes with regard to risk

2) AHP

The AHP method was introduced by Thomas Saaty in the 1970s. It is a structured technique and accurate approach for organising and analysing complex decisions through estimating relative magnitudes of factors using pair-wise comparisons (Forman, E. and Gass, S., 2001). AHP is a widely accepted method and employed by numerous corporations listed in Fortune 500 (Palmer, B., 1999). The other important contributors in development of AHP include Saaty's co-authors and colleagues Ernest Forman and Luis Vargas.

The hierarchy in AHP is composed of 'Goal', 'Criteria', and 'Alternatives'(Saaty, T., 1980). Figure 33 illustrates how the hierarchy is constructed.

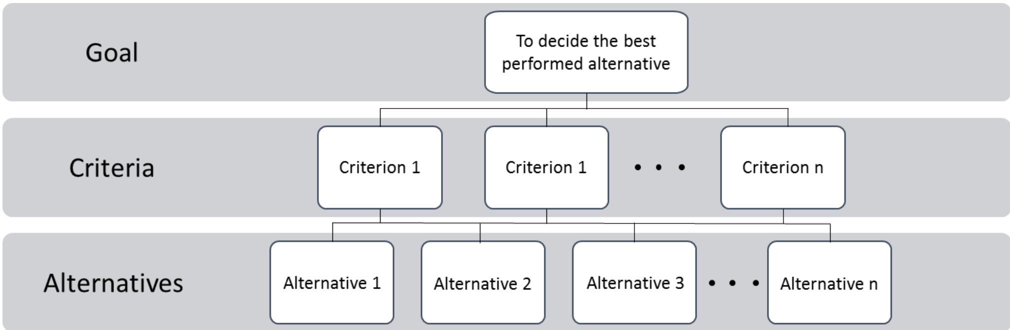

Figure 33: Illustration of AHP hierarchy

	Alternative 1	Alternative 2	⋯	Alternative n
Alternative 1	1	$\frac{f_j(a_1)}{f_j(a_2)}$	⋯	$\frac{f_j(a_1)}{f_j(a_n)}$
Alternative 2	$\frac{f_j(a_2)}{f_j(a_1)}$	1	⋯	$\frac{f_j(a_2)}{f_j(a_n)}$
⋮	⋮	⋮	1	⋮
Alternative n	$\frac{f_j(a_n)}{f_j(a_1)}$	$\frac{f_j(a_n)}{f_j(a_2)}$	⋯	1

Figure 34: Template of a typical pairwise comparison matrix

Based on the constructed hierarchy, every alternative is contrasted straightforwardly with another alternative with regard to each criterion and the decision makers can make a relative judgement between the two. Then plot this information into a pairwise comparison matrix. Figure 34 is the template of a typical pairwise comparison matrix for one criterion. Where $f_j(a_i)$ is the evaluation of the alternative a_i $(i = 1,2,\cdots n)$ against criteria j $(j = 1,\cdots,q)$ assuming there are n alternatives under consideration. When evaluating qualitative criteria, the recommended scale as shown in Table 13 can be used. Then, from each matrix, a priority vector, v_k^j , can be calculated for k^{th} $(k = 1,\cdots,n)$ alternative on criterion j $(j = 1,\cdots,q)$ using Equation (8).

$$v_k^j = \frac{1}{n}\sum_i\left(\frac{\frac{f_j(a_k)}{f_j(a_i)}}{\sum_i\frac{f_j(a_i)}{f_j(a_k)}}\right), i = 1,\cdots n \quad (8).$$

Repeat this computation process for all criteria and aggregate all priority vectors using weighting factors, w_j , assigned for each criterion, to obtain the total priority level evaluation for each alternative.

$$P(a_k) = \sum_1^q\left(v_k^j \cdot w_j\right), j = 1,\cdots q \text{ where, } \sum P(a_k) = 1 \quad (9).$$

Finally, decision maker can rank the alternatives based on their $P(a_k)$ and select the best-performed option.

Table 13: The pairwise comparison scale (Saaty, T., 1980.)

Score	Description
1	Both criteria equally important
3	Very slight importance of one criterion over the other
5	Moderate importance of one criterion over the other
7	Demonstrated importance of one criterion over the other
9	Extreme or absolute importance of one criterion over the other

2,4,6,8	Intermediate values between two adjacent judgements

The weighting factors for each criterion can also be estimated using pairwise comparisons. To do so, firstly, construct a pairwise comparison matrix as shown in Figure 35. To fill the matrix, compare one criterion to another and assign the score to each pair of the comparison using the scale in Table 13. In Figure 35, $S_{j:q}$ represents the score when comparing Criterion j to Criterion q. Then the weights for each criterion can be calculated using Equation (10).

	Criterion 1	Criterion 2	$\cdots$	Criterion q
Criterion 1	1	$S_{1:2}$	$\cdots$	$S_{1:q}$
Criterion 2	$S_{2:1} = \frac{1}{S_{1:2}}$	1	$\cdots$	$S_{2:q}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
Criterion q	$S_{q:1} = \frac{1}{S_{1:q}}$	$S_{q:2} = \frac{1}{S_{2:q}}$	$\cdots$	1

Figure 35: Pairwise comparison matrix for weighting factor estimation

$$w_j = \frac{1}{q}\sum_m \frac{S_{j:m}}{\sum_m S_{m:j}}, j = 1 \cdots q, m = 1 \cdots q \quad (10).$$

However, this is not the last step when using AHP. The nature of pairwise comparison may cause the possibility of inconsistency of the original preference ratings. To overcome this shortcoming, the consistency analysis needs to be performed. This is also required for weighting factors if it is estimated using pairwise comparison. Such analysis is done through calculating the so-called consistency indexes (CI) that captures the frequency and level of inconsistency occurrence and is acceptable below 0.1 as permissible (Saaty, T., 1980). Equation (11) to (15) is the procedure of calculating consistency indexes.

$$\lambda_j = \sum_k \left(\sum_i \frac{f_j(a_i)}{f_j(a_k)}\right) \cdot v_k^j \, , i = 1 \cdots n, k = 1 \cdots n \quad (11).$$

$$\lambda_w = \sum_j \left(\sum_m S_{m:j}\right) \cdot w_j \, , j = 1 \cdots q, m = 1 \cdots q \quad (12).$$

$$CI_j = \frac{(\lambda_j - n)}{(n-1) \cdot RI_n} \quad (13).$$

$$CI_w = \frac{(\lambda_w - j)}{(j-1) \cdot RI_q} \quad (14).$$

$$CI_{total} = \frac{CI_w + \sum_j \left(\frac{(\lambda_j - n)}{(n-1)} \cdot w_j\right)}{2 \cdot RI_q}, j = 1 \cdots q \quad (15).$$

Where RI is the random inconsistency indices and can be looked up from Table 14. To pass the consistency check, CI_j, CI_w, CI_{total} should be less than 0.1.

Table 14: The random inconsistency indices look-up table (Saaty, T., 1980)

n (order of the matrix)	1	2	3	4	5	6	7	8	9	10
RI (random inconsistency indices for n)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.46	1.49

In summary, when using AHP, the pairwise comparisons are used rather than using direct weights or value functions. Every criterion is contrasted straightforwardly with another criterion and the decision makers can make a relative judgement between the two (Cui X, et. al. 2017). Comparing with MAUT, AHP has less requirements on the decision maker to be rational, but the paired comparison among criteria or alternatives measured by qualitative criteria is relatively subjective and arbitrary (Han, W., et. al. 2017). One of the shortcomings about the underline pair wise comparison model that applied in AHP is its intransitivity in certain scenarios, which may cause the logical conflict when making the decision (Guadalupe-Lanas, J., et. al. 2020). For example, in the scenario that the difference among two alternatives is above the just noticeable difference, but when comparing with other alternatives in the decision context, all differences are below such level. To avoid errors from such conflict, all assessments should be contingency checked. The consistency indexes capturing the frequency and level of inconsistency occurrence is acceptable below 0.1 as permissible (Saaty, T., 1980). This procedure has been introduced above.

2.4.2.2. The Utility Theory approach

In economics, utility describes an individual's satisfaction level with regard to the service, goods or return on investment they have received or consumed. For convenience, in this thesis, such service, goods or return on investment will be collectively called 'commodity'. For different individuals, it is believed that the preference on utility is different, which influences their behaviour on decision-making. Based on this belief, the so-called utility theory was proposed to model and explain such observed behaviour and choices of each individual, which is a typical kind of positive theory. This concept began playing critical role in economic theory since early 1870s, when several economists have individually put forward a new explanation of exchange value using utility to replace the old way that simply comparing value of two commodities based on the quantity of labour (both direct and indirect labour) involved in production. Economists, such as Menger, C (Menger, C., 1981), Walras, L. (Walras, L., 1954) and Jevons, W. S (Jevons, W., 1871) who have initiated the development of utility theory pointed out that the exchange value of a commodity should be measured by the utility it has to an individual and more precisely, on its marginal utility.

The notion marginal utility quantifies the additional utility when an additional unit of commodity is consumed. Regarding utility, Daniel Bernoulli (1700 - 1782) has raised two important assumptions. Firstly, as can be seen from the example of of an typical utility curve in Figure 36, the utility to an individual will increase when more commodity is consumed, but the increment rates will slow down (Marshall, A., 2012). This is called law of diminishing marginal utility. Secondly, considering the associated risks and uncertainties, the decision-making behaviour of an individual tends to achieve the maximisation of expected utility rather than expected monetary value (Marshall, A., 2012). These assumptions built the basis of most economical models within the utility theory. Specifically in this research, these assumptions made it possible to develop the practical procedure to achieve the utility maximisation.

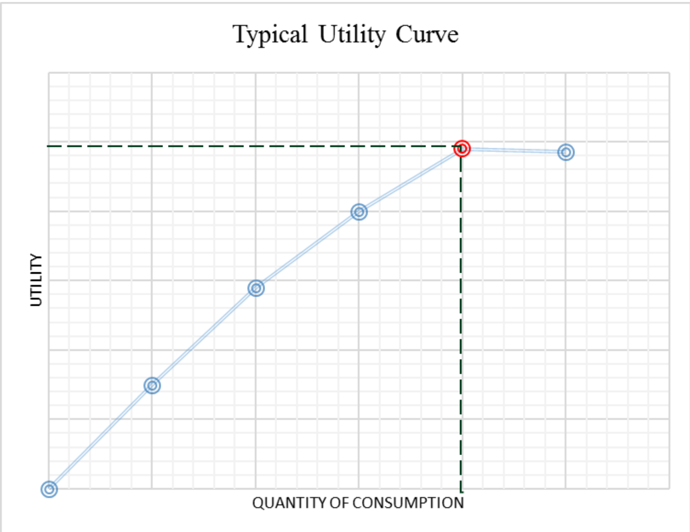

Figure 36: Example of typical utility curve

Before discussing about the utility maximisation, there are several concepts should be introduced. The first one, also one of the key elements in any utility-based model, is utility function, denoted as $U(\mathbf{x})$. The utility function represents the preference ordering of an individual who is facing multiple alternatives. When using utility function, a real number will be assigned to each alternative. If the number assigned to one alternative is greater than another one, this means the individual prefers the former to the latter. The most preferred alternative maximises the associated utility function. Furthermore, according to the abovementioned first assumption regarding law of diminishing marginal utility, the first derivative of a utility function is positive while its second derivative is negative. In practice, defining utility function is not straightforward because measuring utility is often abstract and non-quantifiable, as no one can assign a true numerical value to a consumer's level of satisfaction from a preference or choice. For this reason, there is a condition required when using utility function to represent the preference ordering that the consumer's preferences should be complete, transitive and continuous (Debreu, G., 1954; Jehle, G. and Reny, P., 2011). The way of constructing utility function is various and dependent on the problem formulation. Laid down by Gerard Debreu, the most common mathematical foundations of utility function are quadratic and additive (Debreu, G., 1952). The construction also requires application of both ordinal and cardinal data, including interviewing a decision maker (Tangian, A., 2002). To simplify the calculations, there are various well-behaved, monotonic and quasi-concave alternative utility functions were proposed, such as isoelastic utility, exponential utility, quasilinear utility, homothetic preferences, Stone–Geary utility function, etc.

The second important notion for utility maximisation is an analytical tool namely indifference curves, introduced by Edgeworth, F, Y in 1881(Edgeworth, F., 1994). As can be seen from Figure 37, the indifference curve is a curve with negative slope to the lower right and convex to the origin. It describes the different combinations of commodities that achieve the same utility.

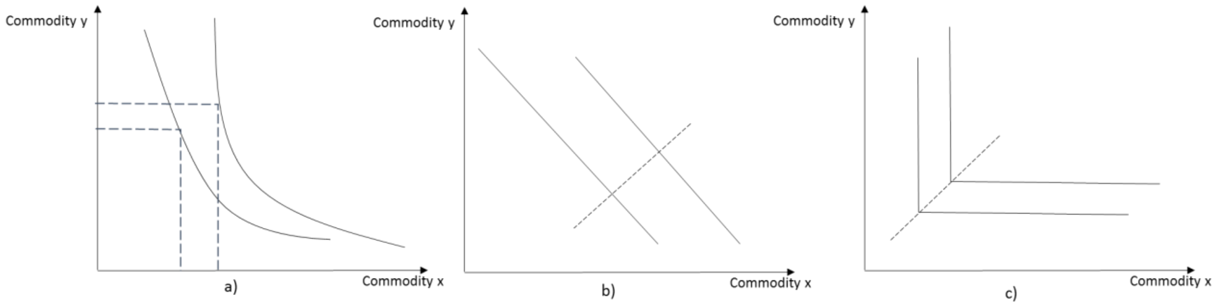

Figure 37: Example of indifference curves: a) indifference map, b) indifference curve where commodities are perfect substitutes, c) indifference curve for perfect complements

The indifference curve shows the willingness of an individual to switch one commodity to another while maintaining the total utility unchanged (i.e. $U(\vec{x}) = \text{constant}$). This means, if consumption of one commodity has increased, the other one should reduce certain amount correspondingly. This willingness is measured by marginal rate of substitution (MRS), which is the slope of the indifference curve:

$$\text{MRS} = -\frac{dy}{dx}, \text{ assuming } U(x, y) \text{ is constant} \quad (16).$$

As stated by Jevons (Jevons, W., 1871), when utility is maximised, the exchange ratio between any two commodities is equal to the ratio of their marginal utilities. Therefore, the relationship between marginal utility and MRS can be derived as (Carvalho C, L. et. al. 2019):

$$MRS = \frac{MU_y}{MU_x}\text{, where } MU_x = \frac{\partial U(x_i)}{\partial x_i} \quad (17).$$

Utility maximisation is one of the important applications of indifference curve. It builds upon a critical assumption in customer theory called substitution assumption that assumes the indifference curves exhibit diminishing MRS. This assumption makes it possible for constrained optimisation because the shape of the curve assures that the first derivative is negative and the second is positive. According to substitution assumption, an individual is willing to trade-off some of one commodity to get more of another at the ratio of MRS, and maintain the level of utility obtained.

In the case where a budget constraint exists, a line can be drawn on the indifference map showing all the possible distributions among commodities. Then, the point of maximum utility is the point where an indifference curve is tangent to the budget line. This is called tangency condition (Board, S., 2009). As shown in Figure 38 for instance, at the point (Qx, Qy), the budget is fully utilised and the maximum utility is obtained.

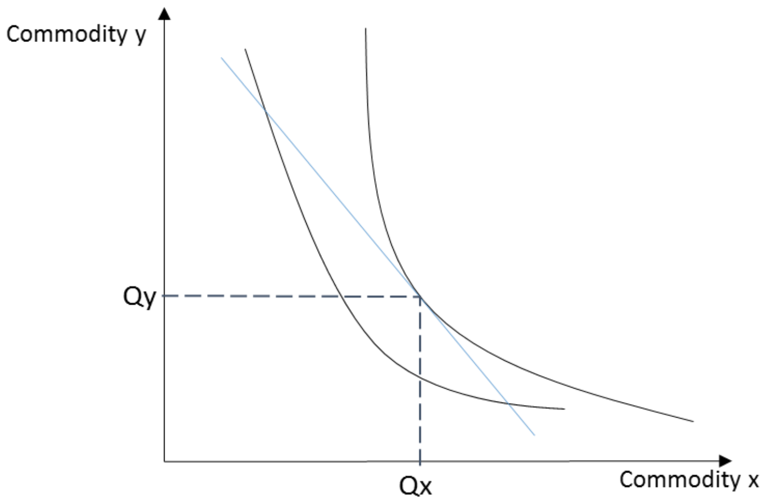

Figure 38: Illustration of utility maximisation when is budget constraints

Assuming there are n commodities, denoted as $x_i, i = 1 \dots n$ and the price of x_i is p_i, the budget constraints (BC) can be then generalised into the equation:

$$\sum_{i=1}^{n} x_i p_i = BC \quad (18).$$

To summarise, the utility maximisation can be achieved via the following steps:

- Step 1: Based on the decision context and problem formulation, define the utility function ($U(x_i)$) and ensure it is complete, monotone and transitive. When these conditions are satisfied, the optimal demand will lie on the budget line. This is called Walras's Law (Levin, J., 2004).
- Step 2: Based on the assumption of tangent condition, derive the mathematical relationship between marginal utility ($MU(x_i)$) and price (p_i) of the commodity from Equation (16) and (17):

  $$\frac{MU(x_i)}{p_i} = \lambda, i = 1 \dots n, \lambda = \text{constant} \quad (19).$$

  Equation (19) can be also used to measure the worth of one's money or exertion.
- Step 3: Apply the budget constraint (Equation (18)) to solve Equation (19) and to find out the optimal distribution of x_i.

- Step 4: Apply final checks. As the validity of all above steps are based on various assumptions and mainly from the mathematical point of view, several checks should be performed to ensure the results in line with the common senses and practical for the predefined decision context. For instance, if the result shows the demand for one commodity is negative, which is not possible in reality, then the quantity for this commodity should be set as zero. Then, repeat the calculation to identify the optimised budget allocation for other commodities in this bundle.

2.4.2.3. The mathematical programming approach

Another proposed approach for BAO is through the employment of mathematical programming (MP). MP is a theoretical tool of management science and economics, which uses mathematical equations to describe the management operations aiming at making the most of limited resources (Britannica, T., 2017). It has been widely recognised as a discipline since 1940s, and in fact, its origins can be traced back much earlier (Orchard-Hays, W., 1984). There were even works from Archimedes and Diophantus that now can be formulated as standard mathematical programs. MP has been continuously developed for several centuries with contributions from numerous precursors, such as André-Louis Cholesky (Brezinski, C. and Tournès, D., 2014), Theodor Motzkin (Motzkin, T., 1936), Lloyd Dines (Dines, L., 1927), Harris Hancock (Hancock, H., 1919), etc. Modem MP has been advanced through engaging with linear algebra and matrix theory significantly, and the application of computer codes made it possible for fast solving the complicated calculations within MP. This theory has been widely used to optimise the operations strategies development and decision-making in various fields, typically about the optimal use of scarce resources, such as aircraft allocation in transportation (Tolstoi, A., 1930; Ferguson, A. and Danzig, G., 1956), agricultural economics (Tintner, G., 1955), defence

(Harris, T. and Ross, F., 1955), manufacturing (Dantzig, G., 1945) and petrochemical industry (Cooper, W. and Charnes, A., 2002) etc.

MP in general has three key elements, including decision variables, objective function, and constraints. The objective function is the function of decision variables whose value is to be optimised in an MP problem. The constraints are equality and/or linear inequality that defines how the values of the variables in a problem are limited. Finding the variables that optimise the objective function while subject to the given constraints is the ultimate goal of a MP problem.

Depending on the properties of objective functions and variables, MP are performed through various models. For instance, if the model incorporated only linear functions, it is called linear programming (LP) otherwise when the function is more general, it would be called nonlinear programming (NLP). Models in which all variables must be integral values is named integer programming (IP), and if IP has both continuous and discrete values then it becomes mixed integer programming (MIP); and there are many other different cases, such as stochastic programming (SP) or dynamic programming (DP). Among which, the most popular one used for optimising budget allocation is the linear programming (LP).

LP is a special case of MP, which aims at optimising a linear objective function that subject to linear equality and/or linear inequality constraints. Its history can be as long as the emergence of MP as a discipline. The early motivator of LP can be traced back to as early as 1940s when the effort was required to achieve the optimal utility under constrained budget in World War II to deal with transportation, scheduling, and allocation of resources, etc. (Orchard-Hays, W., 1984; Britannica, T., 2017). LP can be expressed in canonical form as: The aim of LP is to identify the vector $\vec{x}$ that optimises the objective function, Equation (20), which is subjected to certain constraints, Equation (21).

$$F(\vec{x}) = \vec{c}^{T}\vec{x} \qquad (20).$$

$$\boldsymbol{M}\vec{x} \leq \vec{b}, \text{ and } \vec{x} \geq 0 \qquad (21).$$

The vector $\vec{x}$ is the variables to be identified; the given row vector $\vec{c}$ is the coefficients and used as a single-row matrix (ie. $\vec{c}^{T}$) to form the matrix product; Equation (21) is the constraints specifying a convex polytope over which the objective function $F(\vec{x})$ is to be optimised, in which matrix $\boldsymbol{M}$ and column vector $\vec{b}$ is pre-defined. In addition, the decision variables in LP should always be the non-negative values, which is called non-negativity restriction. Figure 39 is a simple example with three variables to illustrate how LP works: as can be seen, the convex polytope indicates the closed feasible region of the problem with surfaces as planes giving a fixed value of the objective function. The LP problem, therefore, aims at finding a point from this polyhedron that on the plane that gives objective function the highest possible value. There are various techniques that can be used to find out this point. One of these popular techniques is called simplex algorithm. It works by iteratively moving a basic vertex of the feasible region to its adjacent vertices, then improving upon the solution each time until the optimal solution is found. It sounds a long and time consuming process, fortunately, with development of computer technology, this process now is much faster and easier than it was to be in the 1940s when it was originally formulated by George Dantzig (Murty, K., 2000).

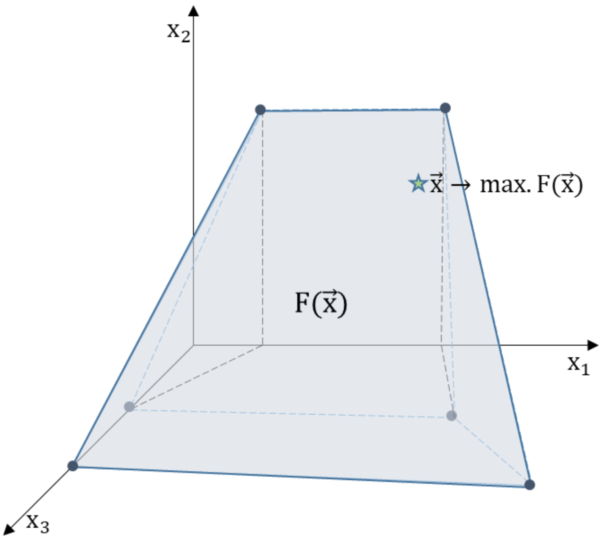

Figure 39: Illustration of a simple LP problem with three variables

With regard to the applicability of LP, there are numerous literatures presenting cases where LP played essential role in supporting the decision making in various areas, specifically, via modelling diverse types of problems in planning, routing, scheduling, assignment, design and resource allocation etc. The most significant advantage of using LP is its mathematical nature that can support user in making less subjective decisions. It can also help to highlight the bottlenecks of the problem. For instance, it can be expected from performing LP in SPPM that some of the PPIs may not be able to improve regardless of how much budget allocated. In addition, LP can be used in a dynamic way meaning when the plan has partly carried out, the allocation can be continuously re-evaluated accordingly. However, the drawbacks of LP is also clear. The model strictly requires the linearity of the objective functions and constraints which may not be possible in reality. For the sake of convenience to the decision maker, appropriate mathematical adjustments should be made to the results of LP. Another condition should be mentioned is that if a problem can be solved by LP, the variables must be quantitatively measurable.

2.5. Remarks

In this chapter, the findings from literature review and consultation with shipbuilding SMEs have been explained, which summarised the work carried out in Task 1. The scope of the review includes the shipbuilding procedure, shipyard organisation, methodologies applied for performance management, details of shipbuilding performance indicators with potential improvement activities and models that can be applied to support the budget optimisation. Literatures reviewed includes scientific and technical publications, public databases, codes and standards, official websites of organisations and government authorities, etc. In addition to the description of the existing research in such abovementioned areas, there have been also discussions to confirm what will be the most suitable theories, approaches and models for the SPPM framework. As the results, based on the review of shipbuilding process and shipyard organisational chart, there have been seven aspects identified to measure the shipyard production performance related to shipbuilding and repair activities. Moreover, based on review of the research and development history of performance management, the KPI based approach is believed to be most suitable for SPPM, which is easy to understand and highly flexible with wide acceptability in various fields. Regarding the support for budget optimisation, it is believed that the adopted PBB model can be applied to provide both budget estimation and activity plan. While in the cases that the total fund is restricted, the three models (i.e. MCDA, utility theory, MP) that have been reviewed can be employed to optimise the fund allocation dependent on the actual condition, optimisation target and the data availability of the scenario.

Chapter 3: Shipyard Production Performance Management (SPPM) Tool

"All's for the best in this best of all possible worlds."

- Voltaire (and Leonard Bernstein), Candide

3.1. SPPM Overview

SPPM has two main modules – production performance evaluation and budget optimisation for improvement. Each module can be performed separately or integrated, depending on the purpose of the assessment. Figure 40 below shows the overall work flow of SPPM.

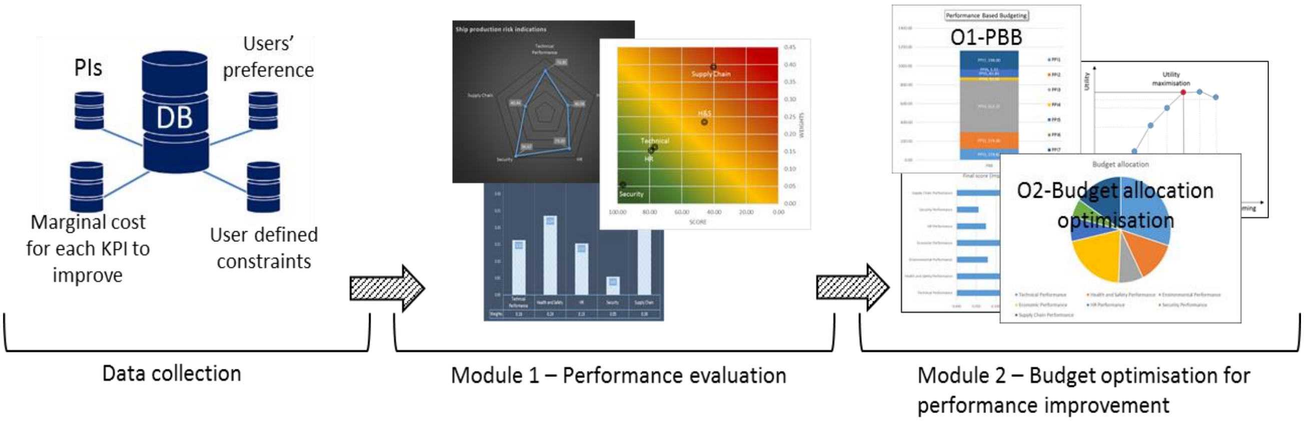

Figure 40: SPPM flow chart illustrating overall assessment process

As illustrated in Figure 40, the assessment begins with data collection, including performance indicators, users' preference, the marginal cost for performance improvement and the user-defined assessment constraints. All these data will be formatted and stored in a centralised database. Details of each data category will be explained in the corresponded chapters of this thesis, including its format, definition, sources, usages, and so on.

After data collection, the Module 1 will be conducted to evaluate the shipyard's production performance related to shipbuilding activities. The model will conduct the evaluation from seven aspects where the level of production performance can be reflected. Based on the results of the evaluation, user can rank the priority among these aspects for the improvement and plan the future performance management strategy accordingly. Then, module 2 will provide user the service to optimise the budget for such performance improvements. The optimisation can be either in forward direction based on performance improvement plan or reverse direction to optimise the fund allocation when the total available budget is limited. The algorithm of SPPM has been implemented using Microsoft Excel.

3.2. The performance evaluation model in SPPM

3.2.1. The PPI hierarchy

The performance evaluation model is built based on the Key Performance Indicator (KPI) model. According to LEXICO online dictionary (powered by Oxford University Press), KPI is "A quantifiable measure used to evaluate the success of an organisation, employee, etc. in meeting objectives for performance" (LEXICO, 2022b). In the context of this research, the KPI concept is applied to measure the success of a shipyard in meeting objectives for production performance related to shipbuilding. For a comprehensive assessment, organisations can use KPIs at multiple levels to evaluate their success at reaching targets (Ishaq Bhatti, et.al. 2014). Therefore, the SPPM module 1 has been designed as an assessment structure of multi-dimensions with multiple hierarchies. Figure 41 shows the hierarchy of the assessment structure and the key formulas.

At the bottom level, the raw data for KPI calculation are collected from shipyard, namely Performance Indications (PIs). These data will be pre-processed and formatted as required by different computation nature of each KPI. This step will be explained in detail in Chapter 3. At the middle level, all KPIs are quantified. The KPIs are categorised into seven groups and each group can be used to evaluate the shipyard production performance of one aspect, namely Production Performance Indications (PPIs) which is at the top level of the hierarchy.

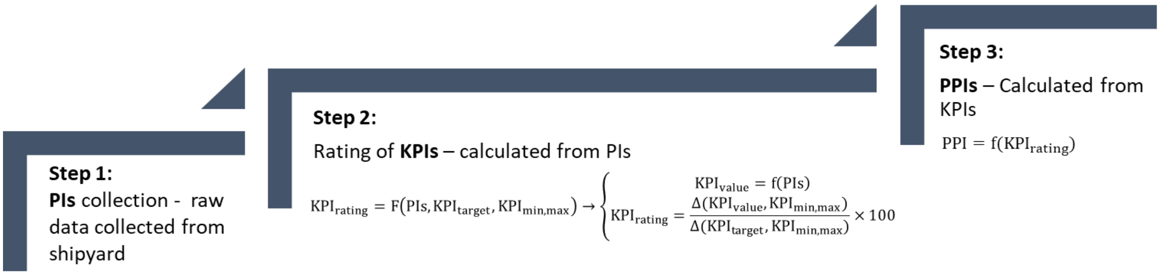

Figure 41: The assessment model overview of Module 1 – the PPI hierarchy and key formulas

For a successful analysis, choosing appropriate KPIs is the primary task. In this project, the ‘SMART’ principle is the employed methodology to select the KPIs. ‘SMART’ is a well-established tool used to plan and achieve objectives, first used by George T. Doran in 1981 (Doran, G. T., 1981). While there are a number of interpretations of the acronym's meaning, the one used in this research is Specific, Measurable, Attainable, Relevant, and Time-bound. Accordingly, the KPIs should be:

- Specific – The KPI should have a clear, highly-specific endpoint
- Measurable – The KPI’s progress should be able to track accurately, so assessor can judge when a goal is met
- Attainable – The KPI should be able to achieve, not too ambitious
- Relevant – The KPI should be pertinent to the production performance, or should benefit shipyard directly
- Time-Bound – Setting a timeframe for the KPI helps to quantify it further, and helps to keep it on track

In total, there are 30 KPIs chosen and assigned to measure seven PPIs. The KPIs associated with each PPI category and their computation methods are explained as follows in detail. All KPIs are defined based on the literature review and consultations with SMEs that have been discussed in Chapter 2. Appendix A is the summary of all KPIs and the template for PI data collection.

3.2.1.1. Health and Safety Performance

The Health and Safety (H&S) performance is a multidisciplinary subject consisted with concerns regarding the safety, health, and welfare of people. The impact and cost associated with consequences due to occupational H&S accidents are enormous, which may include delay of the project delivery, loss of reputation, employee turnover, and even regulatory fines and legal action, etc. Based on the literature review and consultation with SMEs, the KPIs selected to measure H&S performance are in line with the general shipyard occupational H&S policy and procedure, including:

- Risk assessment of incidents, using the Risk Priority Number (RPN) based on the record of incidents at shipyard.

  Shipyards are required to record the number of the OHS incidents, which can be the most straightforward KPI to measure the OHS performance. However, different incidents will have different level of impact to the production and incidents associated with different production activities will have certain contingency. For this reason, it is proposed to use Risk Priority Number (RPN) to take into account these factors in evaluation. The RPN is calculated as (Ozkok, M., 2014):

$$\mathrm{RPN} = \mathrm{P} \times \mathrm{S} \times \mathrm{T} \quad (22).$$

Where,

- P: rank of the probability of failure, i.e. number of injury (e.g. per month) during performing production activity
- S: rank of the severity of failure, i.e. loss of work days due to injury
- T: rank of the adjustment factor, i.e. duration of the production activity (e.g. hours)

The associated RPN table customised for specific shipyard based on their historical record of incidents or accidents, Table 15 below is an example (Ozkok, M., 2014).

Table 15: The example RPN number

Number of injury (e.g. per month)	**P**	**Loss of work days due to injury**	**S**	**Duration of the production activity (e.g. hours)**	**T**
0~0.4	2	0~1	2	0~2	2
0.4~0.8	4	1~3	4	2~4	4
0.8~1.2	6	4~6	6	4~6	6
1.2~1.6	8	6~9	8	6~8	8
1.6~2.0	10	10~	10	8~	10

Besides, the selection of production activities for evaluation is also dependent on different shipyard. For example, in one of the shipyards interviewed in this project, the production activities normally monitored for this purpose are cutting and welding, material handling, mounting, painting, crane movements, and mechanical adjustment, etc. For each activity, the value of P, S, and T can be collected and the RPN associated with such activity can be calculated. Then the average RPN value of incidents from all production activities can be obtained as one of the KPI values for H&S performance. The PI data to be collected from shipyard are "number of injuries during certain activities with a given period", "loss of workdays due to this injury" and "duration of the activity".

This can be also replaced by other industrial standard figure such as lost days of injuries, depending on the usual practice at the shipyard regarding incidents recording.

- Average number of deficiency regarding implementation of safety measures identified during inspection annually
  The shipyards are required to carry out inspections with regard to their safety measures regularly. The inspection could be carried out based on the OHS checklist, which can be modified from the checklist provided by OHS authorities (e.g. HSE COSHH essentials web tool) or created by shipyard OHS team incorporating information from Table 3.

- Average number of deficiency regarding implementation of afterwards corrective actions identified during inspection annually
  The inspection should also include assessment regarding implementation of the afterwards corrective actions in accordance to the incidence investigation report, including the completeness of all relevant paperwork. Two main questions to be answered are whether the action has been taken appropriately as recommended by incident investigation, and how the effectiveness of such actions is. Extra attention should be paid when there are repeated incidents or fatal occupational accidents.

It is worth mentioning that the reason why average number of deficiency regarding implementation of safety measures and corrective actions have been proposed as KPIs in addition to risk assessment or any other industrial standard is because this information can help the shipyard to analyse their performance in detail and identify the areas for improvement. Besides, it is envisaged that the RPN is considered as the direct indicator to examine if the OHS measures have been correctly implemented. However, it may not be able to cover all potential OHS hazards, which means experts are required to ensure all risky production activities are under monitoring and a continues risk register is required.

3.2.1.2. Economic performance

Based on the analysis of the literature review and in consultation with SMEs, the economic performance in the context of shipbuilding is evaluated against two main KPIs: the shipbuilding cost (focusing on budget control) and productivity. Such assessment is normally carried out collaboratively by project manager, financial manager and contract manager. Parameters that are required to carry out this assessment are the PIs in this performance aspect.

Firstly, to calculate the KPI for the shipbuilding cost focusing on budget control (BC), Equation (23) below is proposed:

$$\mathrm{BC} = \frac{\mathrm{Cost_a}}{\mathrm{Cost_e}} \times 100\% \qquad (23).$$

It is proposed that BC is calculated as the ratio between actual cost ($\mathrm{Cost_a}$) of the construction and the estimated cost ($\mathrm{Cost_e}$). Scope of the BC estimation is dependent on the scope of the project that is under evaluation. It is up to the user to choose one typical project for analysis or take the average value (or the worst value for a conservative result) among all projects over the assessment period (e.g. per annual) for the subsequent assessments within SPPM. The latter is more accurate and can help to gain more information about the BC effectiveness of all projects but it is time consuming and requires shipyard to start the exercise since beginning of the assessment period. According to interviews with shipyards, similar to every company, most of them will allocate a margin for overspending when estimating project costs to allow for unexpected interruptions during project execution or inaccuracies in initial cost estimates.

The target value of this KPI should be less than or equal to 1, and ideally as close to 1 as possible. The reason why BC is selected for this KPI instead of directly choosing the cost of the project is because the spending is actually affected by many external factors that beyond the production process, such as the price of the material, inflation, regulation or the price of the energy, etc. For the same reason, BC is more appropriate as BC is directly linked to the production process itself. It is envisaged that this KPI indicates how accurate the cost estimation is and how efficient the finance management of the project is. As per Equation (23), to calculate BC, the spending of the project needs to be recorded to obtain the value of $\mathrm{Cost_a}$ while $\mathrm{Cost_e}$ needs to be estimated prior to the production execution.

As discussed in Chapter 2, depending on the data availability, the shipbuilding cost can be estimated using various models, such as top-down, bottom-up, life cycle costing, feature-based costing or activity-based costing. In general, cost elements that are included in the estimation are material cost (including subcontractors), labour cost, and manufacturing costs. The cost associated with shipyard's general operation or overhead is not included in the costing model, as it is not directly relevant to the production activities, which may mislead the direction of assessment. To improve the accuracy of the assessment, it is important that the shipyard should have effective way of recording the costs occurred during the production. The accurate cost estimation is essential for the project budget control.

Productivity is another important figure reflecting the shipyard's economic performance. If BC reflects the economic performance of shipbuilding processes at the project level, then productivity can be seen as a comprehensive indicator of the shipyard's effectiveness of the resource utilisation, capacity and capital (Krishnan, S., 2012). By definition, the productivity is the ratio between production inputs and outputs. For shipbuilding, the use of labour, capital (productive assets), energy, material and purchased services are inputs, while the output can be measured as compensated gross tonnage (CGT) (Roque, P. and Gordo, J., 2020). Productivity can be calculated partially or systematically depending on the purpose of the assessment. More details about how to calculate the productivity has been introduced in Section 2.2.2.

It is worth mentioning that although partial productivity is easy to calculate, it can only reflect part of the performance in terms of the productivity. Productivity estimation in systematic way can provide the full story but the process is complicated. It normally requires more input information and uses complicated mathematical processes, such as the DEA model reviewed in Chapter 2, which requires special skills from the analyser or specific software to perform the assessment.

3.2.1.3. Environmental performance

Climate change is a topic of global concern, and all walks of life are constantly striving to improve it. Whether it is part of corporate social responsibility or enforcement by the government or authorities, shipyards must pay attention to maintain their performance in terms of environmental impact. The environmental impact at shipyard is mainly generated from the building material, various shipbuilding works and associated energy consumption.

Maintaining the environmental performance is normally the responsibility of the prevention manager and environmental manager at the shipyard. It is measured based on selected categories of environmental impacts evaluated using Life Cycle Assessment (LCA) principles. Based on review of literatures and discussion with SMEs that have been discussed in Section 2.2.3, the following listed environmental impact categories are selected as KPIs for this aspect: Global Warming Potential (GWP), Photochemical oxidant creation potential (POCP), Resource depletion or Abiotic depletion (ADP), and Disability Adjusted Life Years (DALYs). As can be seen from other equivalent researches reviewed in Section 2.2.3, the production activities at shipyard are likely to have more impact on these categories, hence they are selected as the KPIs for environmental performance evaluation. More details of each selected impact category are explained as follows:

- **Global warming potential (GWP, kg-CO2 equivalent)**
  GWP measures the heat absorbed by any GHG in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of CO_2, represented as CO_2 equivalent (i.e. kg-CO2 equivalent). GHG such as carbon dioxide, NOx, SOx and methane cause heat to be trapped within the earth's atmosphere and stop it from moving into the space. This has led to increased temperature of earth and climate change. Global warming is the primary environmental concern for all industries because of the GHG net zero target set by Paris Agreement (United Nations, 2016). During shipbuilding, the source of GHG includes most energy intensive metal working activities, the production of steel and steel parts, and the fuel consumptions during transportation.

- **Photochemical oxidant creation potential (POCP)**

POCP quantifies the relative abilities of VOCs ground level secondary photochemical pollutants such as ozone (O3), which is known to be harmful to human health, vegetation and material (Royal Society, 2008). Therefore, the policies regarding control of photochemical pollutants has been important parts of environmental policies for decades (Jenkin, M., et. al. 2017). It has been widely recognised that the formulation of ozone in situ is through sunlight-initiated VOCs in the presence of NOx (Mellouki, A., et. al. 2015). During shipbuilding, various activities (e.g. welding) will generate NOx and the main source of VOCs is the coating and painting processes.

- **Resource depletion or Abiotic depletion (ADP)**

  ADP measures the natural resource depletion. The ADP is evaluated in two ways, ADP- element (kg- Antimony equivalent) and AD-fossil (MJ). ADP-element refers to the depletion of the total natural reserves of elements, while ADP-fossil is described as the depletion of total natural energy reserve. Such resource consumption is caused by production of the large quantity of material and energy that is used for building the ship.

- **Disability Adjusted Life Years (DALYs)**

  DALYs reflects the damage to human health, which is expressed as the number of year life lost and the number of years lived disabled. This index is also used by the World Bank and the World Health Organisation. During shipbuilding, most production activities will have the negative impact and risk to human health, hence this index should also be considered as one of the environmental KPIs.

The above listed environmental impacts can be evaluated using LCA principles following the framework recommended by ISO14040, as illustrated in Figure 17 (ISO, 2006).

- **Goal and scope**:
  Confirming the goal and scope is the first step for an LCA. In this specific context, the goal is set to analyse the environmental impact of the shipbuilding process at the shipyard, with particular focus on evaluation of GWP, POCP and ADP. A shipyard could choose one typical shipbuilding project to conduct this assessment for a representative value or using the average figures of the year to estimate the average performance of their production activities. According to the literature review of other shipbuilding LCA studies, production processes that have been proven to have a greater impact on the environment will be included in the scope, which can help to improve the efficiency of the evaluation. Figure 42 shows the proposed scope of the assessment with simplified material and energy flow within the scope.

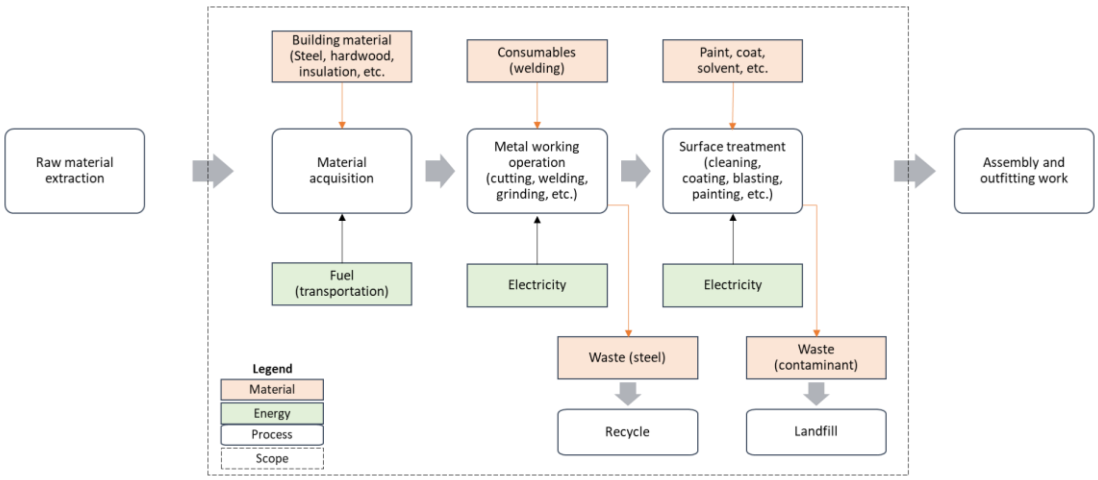

Figure 42: The proposed LCA scope with material and energy flow within the scope

Other information, such as the selection of LCA software, LCA database or functional unit, etc., depends on the specific circumstances of the shipbuilding project that is selected for evaluation. In this case, the functional unit can be considered as“production of one ship at the shipyard”; system boundary is “production process”. The assessment can be done using commercial software such as Gabi, SimaPro, OpenLCA, etc.

Besides, in order to assess the effectiveness of the improvement activities, comparative studies will be performed using the actual production parameters and the predicted parameters after implementing the improvement measures.

- **Life cycle inventory**

  Based on the goal and scope, the corresponding life cycle inventory can be developed, which includes data related to material, production parameters, energy consumption as well as tooling and equipment. The source of data can be from both primary (i.e. directly recorded from the project), and secondary (i.e. public databases and literatures) databases, which can be chosen from any well-known database such as Gabi database, ecoinvent, etc. The production processes and associated material and energy flow illustrated in Figure 42 can be referred for data collection. The life cycle inventory (LCI) data used for performing this LCA are collected as PIs.

- **Life cycle impact assessment**

  It is proposed that this LCA will focus on evaluation of GWP, POCP, DALYs and ADP, which are the measurements of global warming, photochemical oxidant creation human health and resource consumption respectively. These impact categories were chosen not only because of their importance to ecology and the environment, but also because of the recognition that they are the main issues arising from shipbuilding activities based on results of the above-mentioned of literature review. Similarly, the choice of LCA method can be determined based on the specific circumstances of the shipbuilding project that is selected for evaluation.

Although the procedure proposed above can serve the purpose of an approximate LCA estimation that is sufficient for the purpose of SPPM, it is worth mentioning that the detailed environmental impact analysis has never been an easy task, it requires good database, professional software the practitioners.

3.2.1.4. Technical performance

Production performance from technical perspective is the comprehensive manifestation of multiple aspects, including the advancement of production technology and equipment, the yard capability, the rationality of the plan and its execution, the workers' skill and experience level, as well as the effectiveness of production management strategy, etc. This is normally the responsibility of project manager. The direct measure of technical performance is the building time, i.e. the period from signing contract to delivery. Hence, the corresponded KPI is 'delay of schedule due to technical issues', which reflects how efficient the shipyard can manage and provide quick response to the adverse technical issues. This has also been confirmed with the shipyard that the information used for calculating this KPI is available and practical. Delay of the schedule can happen during any stage of the production, such as design process, procurement or construction including QA/QC stage. In each stage, there are different technical issues resulting in delay of the schedule, which also varies from one shipyard to the other. Based on the review of various literatures and discussion with shipyards, a list of typical technical issues, including rework or additional work due to poor quality delivery, has been identified(Basuki, M.,et. al. 2012; Fernandes, J. and Crispim, J., 2016) via conducting an FMEA assessment.

Table 16 is a list of technical issues that most shipyards may face during the production based on discussion with the collaborative shipyards and literature review (Fernandes, J. and Crispim, J., 2016; Basuki, M., et. al. 2012) . If there are any specific technical concerns for the user of SPPM, this list can be extended accordingly. The listed technical issues play the role as PIs in SPPM hierarchy. Accordingly, the values of KPIs for each production stage are calculated as total days of delay due to the associated technical issues during that production stage, as grouped in Table 16. The same issue may repeat a few times during the assessment period, the shipyard is recommended to record each of them into the log book of lessons-learned for future reference. The total days of delay due to each type of technical issue within the assessment period is used for calculating the KPIs. When it is hard to nail down to exact reason of delay because of the complexity of the issue, user could choose to just use the total days of delay during such production stage as the KPIs. However, it is still recommended that the list of common reasons for project delaying should be developed because this can help shipyard to efficiently plan for the improvement activities with more focus on their specific key issues.

Based on discussion with shipyard SMEs, the baggiest challenge of using these KPIs is the interrelationship of these technical issues. It sometimes hard to decide what exactly the reason is causing the delay when many issues happened and some of them may even interconnected. In these cases, the involvement of engineering judgement is unavoidable which may introduce certain level of subjectivity to the assessment.

Table 16: KPIs for technical performance

KPIs	**Technical issues resulting in delay**
Delay (days) during design, model test, planning process– KPI_1^{tech}	Revised design because of equipment size Revised design from owner and Classification New technology transfer problem Revised design due to issue of integration
Delay (days) during procurement – KPI_2^{tech}	Customs clearance of material or equipment in port Delay of material in shipbuilding Delay of purchase order
Delay (days) during construction process – KPI_3^{tech}	Worker performance Inappropriate plan, such as dock busy with other business Sub-contractor performance Mistakes of production; re-work or additional work due to poor quality of delivery Instruction not responsible Revised production request from owner and classifications

3.2.1.5. HR Performance

As a labour intensive industry, having an effective human resource management (HRM) strategy is very important for maintaining the high level of efficiency and sustainability of the business. The Human Resources (HR) performance, normally responsible by HR manager, is measured based on evaluation of crew quality and ethical aspects, including employee retention/ turnover, employee quality, recruitment effectiveness and disciplinary matters. This means the KPIs selected for evaluating PPI in terms of HR should be able to address these focused points. Below listed KPIs for this aspect is built on the basis of literatures and modified in consultation with shipyards SMEs:

- Overall retention rate.
- Involuntary turnover rate.

- Average length of employment.
- Turnover rate considering star employees.
- Employee quality.
- Time to hire.
- Quality of hire.
- Disciplinary matters.

The calculation procedure for these KPIs is suggested as follows:

- **Overall retention rate ($R_{retention}$)**: inverse of the turnover rate, calculated as difference between average number of total employees and the number of leavers divided by the average number of employees:

  $$R_{retention} = \frac{N - N_L}{N} \times 100\% \quad (24).$$

  Where N is the average number of total employees and N_L is the number who have left. This rate indicates the overall competitiveness of the shipyard HRM practices.

- **Involuntary turnover rate (R_{IT})**: this means the employees who are fired, laid off or otherwise terminated. It is calculated as number of involuntary leavers (N_{IT}) divided by the average number of total employees:

  $$R_{IT} = \frac{N_{IT}}{N} \times 100\% \quad (25).$$

  Except the redundancy due to the macroeconomic and geopolitical shifts, the importance of measuring R_{IT} is to identify if there is any issue with the organisation's recruitment process that results in hiring the candidates whose skill not match the job profile. It can be also used to signal shortcomings regarding the on-board management especially in terms of crew disciplinary, which is another important KPI for HRM. In addition, it is also suggested that the organisation should keep record of the involuntary turnover in case they are needed for future litigation (An, S., 2019).

- **Average length of employment** (T_E): calculated as total number of years of employment for all employees (T_{TE}) divided by the total number of employees:

  $$T_E = \frac{T_{TE}}{N} \quad (26).$$

  According to U.S. Bureau of Labour Statistics, in January 2020, the median overall T_E was 4.3 years for men and 3.9 years for women regardless industries.

- **Turnover rate considering star employees (**R_{TS}**)**: calculated similar to overall turnover rate with extra weights (e.g. 200% assuming the productivity if star employees is as twice as the normal employees) to the top employees (N_S):

  $$R_{TS} = \frac{(N_L - N_S) + N_S \times 2}{N} \times 100\% \quad (27).$$

  Contributions to the organisation from top employee who is truly driving an organisation towards its goal is different compare to average- or low-performing employees, and R_{TS} can be used to count for this difference in the evaluation.

The HR performance KPI with regard to **employee quality** can be measured using the ratio (R_{EQ}) between qualified and experienced workers and the total number of employees (Equation (28)), in addition to the abovementioned turnover rate considering star employees (R_{TS}), and the average length of employment (T_E) replacing the total number of employees with the number of experienced employees.

$$R_{EQ} = \frac{N_Q}{N} \times 100\% \quad (28).$$

Moreover, considering the HR requirements of a shipbuilding project as discussed in Chapter 2, two of them are considered to be more crucial than the rest for a shipyard, hence have been selected by the SPPM. These two KPIs are time to fill and quality of hire. However, it is worth mentioning that all these metrics are good to use for accessing the performance of the recruitment processes from various angles. If a specific study required, all of them can be employed for the evaluation. However, considering the context and targeted level of detail in SPPM framework, these two KPIs are believed to be sufficient.

- **Time to hire** (T_H): Calculated as duration from date the candidate enters the ATS (Applicant Tracking System) to the date of hire.

$$T_H = \text{Date of Hire} - \text{Date Candidate Enters ATS} \quad (29).$$

This KPI can help to measure the efficiency of the recruiting process including

- **Quality of hire (Q_H):** can be calculated using the total number of new comers (N_{NH}) to divide the number of new hires who passed their appraisal after probation (N_{PASS}) and then minus the turnover rate of the new hires (R_{NT}):

$$Q_H = \frac{N_{PASS}}{N_{NH}} \times 100\% \quad (30).$$

The number of new hires left the company before completing their probation including both voluntary and involuntary leavers.

Monitoring the Disciplinary matters (DM) related performance is also the responsibility with the remit of HRM. It can be calculated as total number of disciplinary violations (N_{DV}) during the predefined monitoring period (T_M) for assessment:

$$DM = \frac{N_{DV}}{T_M} \quad (31).$$

The cases that to be considered as breach of discipline are dependent on what are the requirements in the company's own protocols and policies. It would normally include absence from work without approval, cases where drugs or alcohol is abused, charges of criminal offences, cases result in dismissals or logged warnings, and so on.

It is believed that the selected matrices can sufficiently measure the effectiveness of the HRM, however, it needs a lot of effort to collect the input data, and especially some of them require long-term tracking. For this reason, some of these KPIs may not be applicable for small shipyards that do not have mature HRM system or for those mainly dependent on sub-contractors to operate hence the responsibility of HRM is unclear. This is out of the scope of SPPM and have not seen in the collaborative shipyards, but it is worth further investigation for the solutions. Hence, it can be included in the future work.

As a summary, Table 17 below is the list of KPIs (and PIs required to collect for this KPI) available in SPPM to evaluate the shipyard HR performance with focus on shipbuilding activities. Depending on data availability and user preferences, this list can be quoted in part or in whole.

Table 17: Summary of proposed KPIs for measuring HR performance in SPPM

KPI	**PI to collect**	**Equation**	**Performance to measure**
Overall retention rate ($R_{retention}$)	N, N_L	(24)	Employee retention/ turnover
Involuntary turnover rate (R_{IT})	N, N_{IT}	(25)	Employee retention/ turnover
Average length of employment (T_E)	T_{TE}, N	(26)	Employee retention/ turnover
Turnover rate considering star employees (R_{TS})	N, N_L, N_S	(27)	Employee retention/ turnover Employee quality
Employee quality (R_{EQ})	N_Q, N	(28)	Employee quality
Time to hire (T_H)	Date of Hire, Date Candidate Enters ATS	(29)	Recruitment effectiveness
Quality of hire (Q_H)	N_{PASS}, N_{NH}	(30)	Recruitment effectiveness
Disciplinary matters (DM)	N_{DV}, T_M	(31)	Disciplinary matters

3.2.1.6. Security performance

Security management at shipyard is similar to which in other work places. The objective is to develop and implement the effective prevention and protection strategies for the shipyard's tangible and intangible assets. The security performance is normally the responsibility of prevention manager (or security manager) and information manager. In general, security policies and measures are developed respectively for people, physical assets and digital system (i.e. the Cyber security), with people security and safety being always the most important objective for the organisation. It includes protection for all employees, visitors and contractors, etc. Therefore, it is proposed that the security performance will be assessed via evaluating the effectiveness of such security policies and measures as well as their implementations.

- Average number of incidents during assessment period (including incidents regarding people, physical assets and Cyber security).
- Average number of deficiency regarding security policies and procedures and its implementation (for purpose of both prevention and remediation) identified during inspections/ audits.
- Average number of deficiency regarding security equipment (for purpose of both prevention and remediation) identified during inspections/ audits.

It was suggested that each shipyard has its own security system, therefore, the details of this section should be customised as appropriate. The abovementioned KPIs is recommended as the ones that are generally applicable. Flexibility of these KPIs has pros and cons. In one hand, it can be adjusted for any security system. However, on the other hand, the effectiveness of the evaluation has to depend on the quality of the security system, as all assessments are based on the review of the pre-defined monitoring scope, procedures, policies and equipment.

3.2.1.7. Supply chain performance

The scope of supply chain management includes all management and planning activities related to collaboration with channel partners, sourcing and procurement, as well as logistics management that plans, implements and controls the flow and storage of material, information and service between the origin and consumption points. In shipyard, it is normally responsible by purchase manager and sometimes, quality manager, including inventory control and distribution of drawing, material, assemblies, machineries, equipment and labour. The success of SCM is the result of collaboration between multiple links and multi-functional stakeholders from diverse backgrounds, with objective to ensure the reliable supply chain that can deliver services, material or information on time, with low cost and good quality. Regarding the cost control, it has been included in the PPI of economic performance, hence exclude from this PPI to avoid the repetition. The following proposed KPIs are mainly focusing on assessing the efficiency and effectiveness of the SCM from schedule and quality control perspectives. These KPIs are selected from literature review and discussion with shipyard SMEs (Dijk, C., 2009).

- Reliability of drawing delivery:

  $$\mathrm{KPI}_1^{\mathrm{sup}} = \frac{\Delta \mathrm{T}_{\mathrm{drawing}}}{\mathrm{N}_{\mathrm{drawing}}} \quad (32).$$

  Where, $\Delta \mathrm{T}_{\mathrm{drawing}}$ is the total days between actual release of drawing and the planned date of release, and $\mathrm{N}_{\mathrm{drawing}}$ is the number of drawings delivered within the assessment period.

- Quality of drawings:

  $$\mathrm{KPI}_2^{\mathrm{sup}} = \frac{\mathrm{N}_{\mathrm{mis}}}{\mathrm{N}_{\mathrm{drawing}}} \quad (33).$$

Where, N_{mis} is the number of drawings containing mistakes that requires supplier for modification within the assessment period.

- Reliability of supplier delivery:

$$KPI_3^{sup} = \frac{\Delta T_{order}}{N_{order}} \quad (34).$$

Where, ΔT_{order} is Total days between actual delivery date from purchase order and the promised date of delivery, and N_{order} is the number of order lines within assessment period.

- Incorrectness of supplier:

$$KPI_4^{sup} = \frac{N_{fm}}{N_{order}} \quad (35).$$

Where N_{fm} is the number of order lines which contains faults or missing parts.

- Quality of supplier:

$$KPI_5^{sup} = \frac{N_{brprts}}{N_{order}} \quad (36).$$

Where, N_{brprts} is the number of order lines containing broken or defective parts.

- Quality of the subcontractors:

$$KPI_6^{sup} = \Delta T_{subcon} \quad (37).$$

Where, ΔT_{subcon} is the total days of delay due to fault from subcontractors within the assessment period.

- Delivery reliability at yard:

$$KPI_7^{sup} = \frac{\Delta T_{yard}}{N_{order}} \quad (38).$$

Where, ΔT_{yard} is the total days between actual arrival date at yard and planned arrival date.

The PIs required for these KPIs is generally with regard to the number of order lines, delay of the delivery, error concurrency, etc.

3.2.2. Description of performance evaluation procedure

The assessment procedure can be briefly described as follows:

- Step 1: Select the PPIs and associated KPIs for assessment from the available list provided by the SPPM, based on user's preference and the purpose of the evaluation. In most cases, the raw data availability also needs to be taken into account for the selection.

- Step 2: Based on the selection from Step 1, the required raw data, i.e. PIs, are collected and processed as per the requirement of its associated KPI(s). The list of required PIs for each KPI and their sources are introduced in Chapter 3.

- Step 3: Rate each KPI by a score between 0 and 100, using Equitation (39) and (40).

$$\mathrm{KPI_{value}} = \mathrm{f(PI_s)} \qquad (39).$$

$$\mathrm{KPI_{rating}} = \frac{\Delta(\mathrm{KPI_{value}}, \mathrm{KPI_{min,max}})}{\Delta(\mathrm{KPI_{target}}, \mathrm{KPI_{min,max}})} \times 100 \qquad (40).$$

  Where, $\mathrm{KPI_{value}}$ is the measurement of actual performance directly calculated from PIs, such as 'days of delay' or 'the ratio between experienced workers and trainees' etc. The calculation procedure of each KPI value has been explained in Section 3.2.1. $\mathrm{KPI_{min,max}}$ is the user defined tolerance limit for each $\mathrm{KPI_{value}}$, which could be the maximum or minimum acceptable $\mathrm{KPI_{value}}$, depending on the nature of such KPI. $\mathrm{KPI_{target}}$ is the ideal value of $\mathrm{KPI_{value}}$, defined by user, representing the perfect condition of such KPI. These values can be derived from literatures or historical record regarding the shipyard's performance and should be reviewed regularly.

- Step 4: Calculate PPIs in each performance aspect equal to the average of the KPI ratings categorised in such aspect. The result will be presented using radar chart (Figure 43 as an example), representing the production performance in different dimensions.

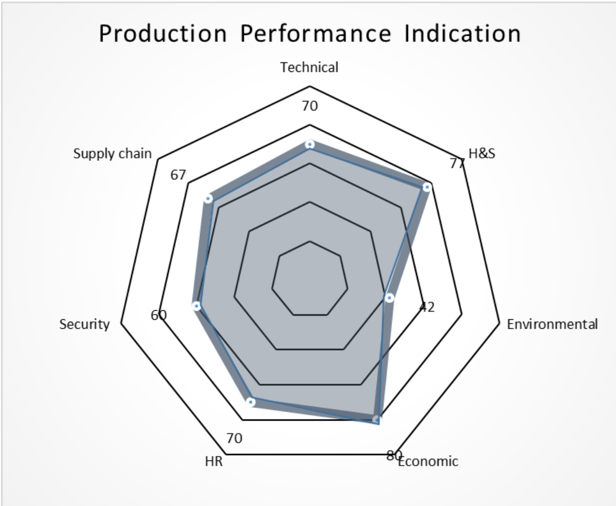

Figure 43: Example of graphical view of the PPI evaluation

By this step, the basic performance evaluation has been completed. For more comprehensive review and to take into account user's preference, additional steps can be carried out:

- Step 5: Conduct a pairwise comparison to rank the importance level of each PPI
The pairwise comparison method is the most often used procedure for estimating criteria weights in multi-criteria decision analysis (MCDA) (Malczewski, J., 2018). The method employs an underlying scale with values from 1 to 9 to rate the preferences with respect to a pair of criteria, as shown in Table 18.

In this step, the seven PPIs are paired with each other and user will be asked to perform the comparison for each pair in the format shown in Figure 44, and referring the description in Table 18 to mark the score for each pair comparison. Then, convert the scores to a 7X7 matrix for normalisation to obtain the final weight of each PPI. An example matrix is shown in

Figure 45, where the H&S performance has the highest weight value means that H&S is most important comparing to other aspects for this assessor. The rank of the weights can be referred to prioritise resources for future performance improvement.

Table 18: The pairwise comparison scale (Saaty, T., 1980)

Score	**Description**
1	Both criteria equally important
3	Very slight importance of one criterion over the other
5	Moderate importance of one criterion over the other
7	Demonstrated importance of one criterion over the other
9	Extreme or absolute importance of one criterion over the other
2,4,6,8	Intermediate values between two adjacent judgements

- Step 6: Plot the results from Step 4 and 5 on a matrix to identify the 'Hot Spots' of the PPI evaluation for improvement that has higher priority but lower score of the performance. Figure 46 is an example illustrating the design of the matrix. It can be also ranked as effort required for improvement, which can be measured as difference between evaluated PPI rating and its targeted value or the cost associated with planned improvement activities.

Technical performance	9	7	5	3	1	3	5	7	9	HR performance
Technical performance	9	7	5	3	1	3	5	7	9	Economic performance
Technical performance	9	7	5	3	1	3	5	7	9	Environmental performance
Technical performance	9	7	5	3	1	3	5	7	9	Security performance
Technical performance	9	7	5	3	1	3	5	7	9	H&S performance
Technical performance	9	7	5	3	1	3	5	7	9	Supply chain performance
HR performance	9	7	5	3	1	3	5	7	9	Economic performance
HR performance	9	7	5	3	1	3	5	7	9	Environmental performance
HR performance	9	7	5	3	1	3	5	7	9	Security performance
HR performance	9	7	5	3	1	3	5	7	9	H&S performance
HR performance	9	7	5	3	1	3	5	7	9	Supply chain performance
Economic performance	9	7	5	3	1	3	5	7	9	Environmental performance
Economic performance	9	7	5	3	1	3	5	7	9	Security performance
Economic performance	9	7	5	3	1	3	5	7	9	H&S performance
Economic performance	9	7	5	3	1	3	5	7	9	Supply chain performance
Environmental performance	9	7	5	3	1	3	5	7	9	Security performance
Environmental performance	9	7	5	3	1	3	5	7	9	H&S performance
Environmental performance	9	7	5	3	1	3	5	7	9	Supply chain performance
Security performance	9	7	5	3	1	3	5	7	9	H&S performance
Security performance	9	7	5	3	1	3	5	7	9	Supply chain performance
H&S performance	9	7	5	3	1	3	5	7	9	Supply chain performance

Figure 44: Scale table for pairwise comparison in SPPM

	Technical performance	HR performance	Economic performance	Environmental performance	Security performance	H&S performance	Supply chain performance	**Weights**
Technical performance	1.00	7.00	1.00	9.00	7.00	0.33	1.00	**0.17**
HR performance	0.14	1.00	0.14	0.33	1.00	0.11	0.14	**0.03**
Economic performance	1.00	7.00	1.00	7.00	7.00	0.20	1.00	**0.15**
Environmental performance	0.11	3.00	0.14	1.00	3.00	0.11	0.14	**0.04**
Security performance	0.14	1.00	0.14	0.33	1.00	0.11	0.14	**0.03**
H&S performance	3.00	9.00	5.00	9.00	9.00	1.00	7.00	**0.43**
Supply chain performance	1.00	7.00	1.00	7.00	7.00	0.14	1.00	**0.15**
	6.40	35.00	8.43	33.67	35.00	2.01	10.43	

Figure 45: Example matrix for calculating PPI weights

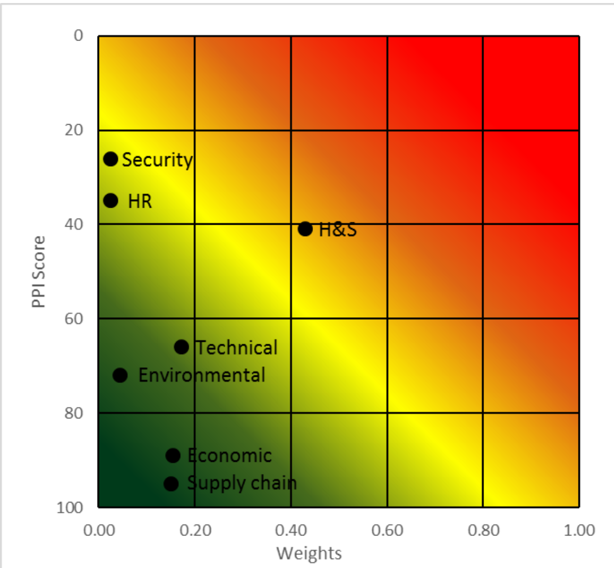

Figure 46: SPPM matrix for 'Hot Spots' identification (an example)

3.3. Budget optimisation support

After the production performance being evaluated, the next task is to make the plan for improvement. As shown in Figure 46, the SPPM matrix can provide user the indication how to priorities which performance aspects to be improved first. However, in fact, most improvement solutions will have cost associated. This means when considering the improvement activities, except the technical barriers, the cost for carrying out such activities should also be taken into account. Therefore, the budget optimisation function has been developed as the second module of SPPM, to support user to plan for the performance improvement in a cost-effective way.

The budget optimisation can be performed in two directions. The first one is called Performance Based Budgeting (PBB), and the other direction is designed to support optimisation of the budget allocation when the total amount of budget is limited. The model is applicable at the global level aiming at PPI improvement or being restricted to a scope including only user-selected KPIs. Detailed assessment procedures and the approach taken to the model development are developed based on the literature review discussed in Chapter 2. In this section, the introduction of the adapted models in SPPM and their functionality is provided as follows.

3.3.1. Performance Based Budgeting (PBB)

In the scenario where the total available fund is not restricted, the PBB approach is considered suitable to apply in SPPM. Firstly, the ultimate benefit of the budget optimisation function in SPPM is to build the linkages between performance improvement and activities to be carried out, which is in line with the principle of PBB. In addition, as discussed in the previous chapter that the entire process of ship production is very sophisticated involving a number of processes and coordination among various internal and external parties. Based on the literature review, PBB shows its capability in dealing with this type of budgeting requirements through the measurement tools and impact evaluation process inbuilt within the approach. Besides, PBB is a model that combines planning and budgeting, which enables user of SPPM to not only optimise the budget, but also identify the most efficient and cost-effective activity plan for performance improvement. PBB is the practice of developing budgets based on the relationship between amount of funding and expected achievements from such funds. PBB is often used to manage more cost-efficient and effective budgeting outlays. In the other word, using PBB to budget for performance improvement means shipyard will need to decide how much they would like to improve in different aspects and how to improve, then calculate the associated cost accordingly.

The PBB in SPPM is used for budget planning when the total available fund is not restricted. For the purpose of optimisation, PBB needs to be performed on the basis of the SPPM matrix (i.e. Figure 46). As discussed, by using the SPPM matrix, user can identify the ‘hot spots’ to rank the priority among various PPIs for improvement that has higher rank of weights but lower score in terms of current performance. In addition, when making the decision, shipyard may also want to consider more factors, such as level of technical difficulty, addition ratio, or fitness for purpose, etc. In this case, a more comprehensive MCDA should be performed against all decision-making criteria, to prioritise the improvement activities and calculate the required budget. The details of this process will be described in the following paragraphs. This also includes the procedures for predicting the plan's effectiveness, which is particularly essential when there are alternative routes to achieve the goal and objectives.

Ideally, the results from PBB assessment will include a calculation of total budget for improvement and cost breakdown for each PPI, Figure 47 is the typical stacked column graph for such results visualisation. When there are alternative improvement plans, the algorithm will also provide a comparative study to identify the most effective and efficient plan.

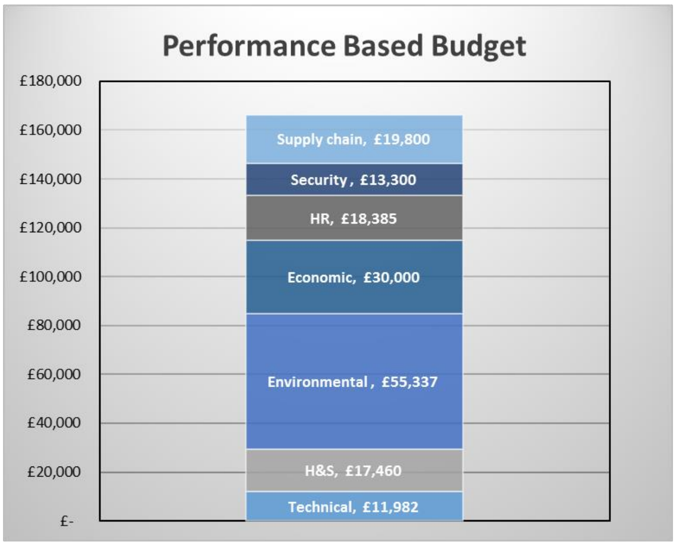

Figure 47: Example of graphical view of the PBB results

The PBB approach, according to the literature review, should follow the framework shown in Figure 28. In general, shipyard is categorised as business in private sector, hence, its PBB process should be adapted from the process given in Figure 29. Figure 48 is the modified process flowchart of applying the adopted PBB principle in SPPM. In the context of SPPM, the organisation's goal is to improve the shipyard production performance, and the specific strategic objectives are improvement target for each PPI category. This can be in the format that the number of PPI ratings to be increased. The senior management will also need to identify the relevant KPIs of each PPI category, i.e. the SPPM metrics, which should fit for the nature of their own business. Accordingly, the corresponded activities for improvement are proposed with estimation of the associated costs.

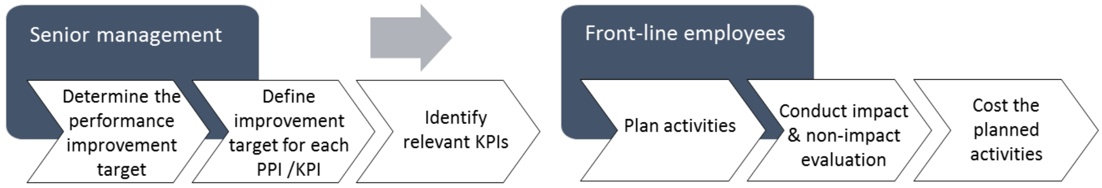

Figure 48: The process flowchart of applying adopted PBB principle in SPPM

The effectiveness of the planned activities can be assessed using the SPPM inbuilt performance evaluation programme. To do so, using the expected results from carrying out the planned activities as input to the Module 1 of SPPM. Then, compare the evaluation results with the current PPI ratings to understand how effective of this plan in terms of performance improvement. If the results shows that, the improvement made by this plan is insufficient, replacement or additional activities may be considered and the associated cost should be recalculated.

The plan's effectiveness prediction is particularly essential when there are alternative routes to achieve the goal and objectives. In such scenario, SPPM will provide a decision support function that the alternative plans to be compared comprehensively. The comparison will be performed through the multi-criteria decision analysis (MCDA) approach, considering the effectiveness of the activities, the associated costs and the priority of each PPI category. Numerically, the effectiveness of the plan will be presented as expected average increment of the PPI ratings from carrying out the planned activities in the format of percentage (%). When there is preference from user regarding the priority of each PPI category, the weighting factor will be incorporated and the weighted average value will be used for comparison. The method employed by SPPM for calculating the weighting factors has been introduced in Chapter 2. The procedure to calculate effectiveness is expressed by Equation (41) and (42).

$$\Delta \mathrm{PPI_i} = \frac{\mathrm{PPI_i'} - \mathrm{PPI_i}}{\mathrm{PPI_i}} \times 100\%, \mathrm{i} = 1,2 \ldots 7 \quad (41).$$

$$\overline{\Delta \mathrm{PPI}} = \begin{cases} \sum_\mathrm{i} (\Delta \mathrm{PPI_i} \times \mathrm{w_i}), & \text{when weighting factors applied} \\ \frac{1}{7} \sum_\mathrm{i} \Delta \mathrm{PPI_i}\,, & \text{no weighting factors applied} \end{cases} \quad (42).$$

Where, $\Delta \mathrm{PPI_i}$ is the percentage of the PPI rating increment for the ith PPI category, calculated by comparing the expected PPI rating after improvement ($\mathrm{PPI_i'}$) and the original PPI rating ($\mathrm{PPI_i}$). $\overline{\Delta \mathrm{PPI}}$ is the average value among $\Delta \mathrm{PPI_i}$ of all categories. When there is weighting factors defined by user, this value is calculated as weighted arithmetic mean; otherwise, it is the arithmetic mean of $\Delta \mathrm{PPI_i}$.

The other criterion to support the selection among alternative activity plans is their associated costs. To certain extend, this figure could reflect the difficulty level and the effort required for the performance improvement if such activities took place. As per the literature review regarding the MCDA in Chapter 2, the Multi-Attribute Utility Theory (MAUT) was selected for the comparison. The concept of MAUT method is to resolve the disparate units into utility or value so that they can be comparable (Cresswell, A., et. al. 2000). MAUT was selected because its sufficient capability in dealing with wide range of perspectives and decision alternatives. Besides, in this case, it is relatively easy to achieve the consensus on the attributes so that the drawbacks discussed in Section 2.4.2.1 can be ignored.

In this decision context, the criteria for comparison are improvement of average PPI rating ($\overline{\Delta PPI}$) as the result of carrying out the planned activities and the associated costs. The alternative with more average PPI rating increment and lower cost will be ranked higher and considered as the preferred option. To perform the MAUT assessment, the first step is to construct a $2 \times n$ matrix, A, assuming there are n alternative plans, as shown below:

$$A = \begin{vmatrix} \overline{\Delta PPI_1} & Cost_1 \\ \overline{\Delta PPI_2} & Cost_2 \\ . & . \\ . & . \\ . & . \\ \overline{\Delta PPI_n} & Cost_n \end{vmatrix} \quad (43).$$

Then, perform linear normalisation and obtain a new matrix, A*:

$$A^* = \begin{vmatrix} \overline{\Delta PPI_1}^* & {Cost_1}^* \\ \overline{\Delta PPI_2}^* & {Cost_2}^* \\ . & . \\ . & . \\ . & . \\ \overline{\Delta PPI_n}^* & {Cost_n}^* \end{vmatrix} = \begin{vmatrix} \frac{\overline{\Delta PPI_1}}{\sum \overline{\Delta PPI_n}} & \frac{Cost_1}{\sum Cost_n} \\ \frac{\overline{\Delta PPI_2}}{\sum \overline{\Delta PPI_n}} & \frac{Cost_2}{\sum Cost_n} \\ . & . \\ . & . \\ . & . \\ \frac{\overline{\Delta PPI_n}}{\sum \overline{\Delta PPI_n}} & \frac{Cost_n}{\sum Cost_n} \end{vmatrix} \quad (44).$$

Finally, the MAUT score can be calculated from matrix A* using Equation (45):

$$S_{\overline{\Delta PPI},i} = \overline{\Delta PPI_i}^* - {Cost_i}^*, i = 1.2 \ldots n \quad (45).$$

The alternative with higher MAUT score is believed as more efficient and cost effective option that the shipyard can consider for future performance improvement. When there is concern of priority level between PPI increment and cost, the weighting factor can be applied. Weighted MAUT score is calculated as:

$$WS_{\overline{\Delta PPI},i} = \overline{\Delta PPI_i}^* \cdot w_{PPI} - Cost_i^* \cdot w_{Cost}, i = 1.2 \dots n \quad (46).$$

3.3.2. Budget allocation optimisation (BAO)

In the cases when the total budget approved for performance improvement is pre-defined, the decision maker would need to decide how to allocate the fund among different KPIs or PPIs to maximise the benefit. With SPPM, user can perform this assessment using several different models developed based on three different fundamental theories. The detailed assessment procedure is described as follows and the approach towards the model development can be found in Chapter 2.

3.3.2.1. Marginal Cost

The term “marginal cost (MC)” in SPPM means the cost required to improve each unit of PPI rating. This is an important parameter that will be used in some of the BAO models hence, it is worth to provide the explanation of this concept before introducing the detailed procedure of BAO models. Ideally, considering the total cost of improvement is a function of increment of PPI rating, the marginal cost should be calculated as the derivative of a cost function with respect to the quantity of improvement, i.e. its partial derivative:

$$\text{Marginal cost} = \frac{\text{Change in total cost(TC)}}{\text{Change in PPI rating(q)}} = \frac{\partial TC}{\partial q} \quad (47).$$

Then, the task becomes identifying the mathematical relationship between TC and q. Total cost means the cost required to improve each PPI from its current rating to the target condition. To increase the rating of PPI, specific actions should be taken to its corresponded KPIs. For each PPI, the way of estimation will be different, because different actions needs to be taken for improvement. For example, if the KPI was to improve the employee quality by recruiting more experienced staff, the cost will be the cost associated with recruitment. While if the KPI was reliability of drawing by changing the supplier, then cost associated with the management of change activities should be counted.

The concept of MC is introduced in this research to assist the development of BAO models mathematically. It reflects the effort required for the improvement in different PPIs. However, it is not a straightforward task for the user to define the function between TC and q in most cases; typically, such inputs have to be tailored to the shipyard requirements making necessary assumptions and approximations. One way of constructing the cost function could be through the implementation of PBB. To estimate the MC via PBB, the procedure shown in Figure 48 can be followed. Firstly, based on the evaluation of the current performance rating and the improvement target, the decision maker could plan for the activities at the PPI level for the improvement. Impact analysis can be performed in case there are alternative routes. Then calculate the cost associated with these activities to obtain the TC function for each PPI category and derive the MC from the cost function. To simplify the calculation, a linear relationship can be assumed between TC and q. Due to the dependency among KPIs, i.e. same activity may help to improve multiple KPIs, necessary judgement may require to allocate such effect from the investment to different

KPIs mathematically. This is not an issue for PBB or MCDA-based BAO, but will be a critical step when using utility theory or mathematical programming for BAO. This concern will be further discussed in Section 3.3.3of this chapter.

3.3.2.2. The MCDA-based BAO model in SPPM

The first type of model is developed based on the MCDA theory. MCDA is the set of tools and methods providing the mathematical methodology that incorporates the judgement of decision makers and stakeholders as well as technical information to select the best solution for problems and to make more logical and scientifically defensible decision (Linkov, I. and Moberg, E., 2012). In the simple word, the MCDA-based approach optimises the budget allocation via comprehensive comparison among PPIs against various predefined criteria. There are various mathematical models can be used to perform the MCDA. After a detailed comparison based on literature review, the Analytic Hierarchy Process (AHP) model using pair-wise comparison is believed to be the most suitable method to use in this context. The AHP method was developed by Thomas L. Saaty in the 1970s (Saaty, T., 1980) and has been refined since then. It contains three parts: the goal, the alternatives, and the criteria. In this case, the goal is to allocate the limited improvement budget to different PPIs based on their AHP ranking. These PPIs are the alternatives for comparison. In terms of criteria, as a conclusion from literature review and discussion with shipyard SMEs, it was suggested that the suitable criteria are importance level and the effort required for improvement.

The MCDA-based approach for budget optimisation is actually a step further from SPPM matrix. As the result from AHP, the PPIs can be ranked with scores/ rates which can be referred to allocate the fund. The cost allocation for each PPI will be presented using a pie chart, e.g. Figure 49.

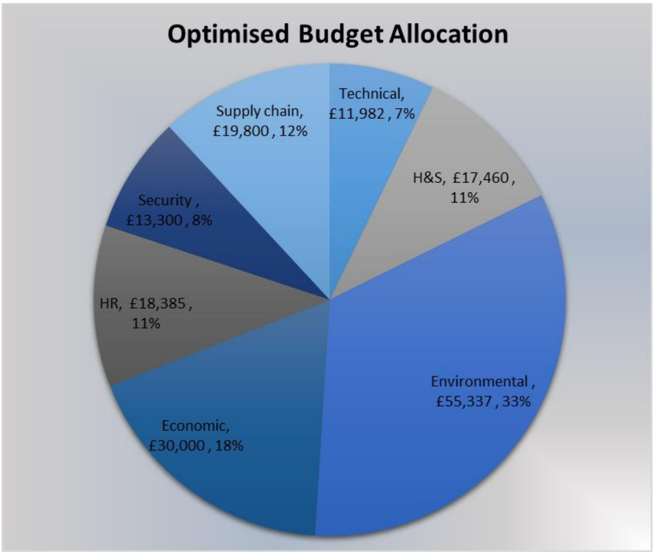

Figure 49: Example of graphical view of the budget allocation optimisation using MCDA-based approach

MCDA played an important role in SPPM. The MAUT method has been used in supporting decision making in selection of the optimised PBB route and analysing the performance evaluation results. The detailed computation procedure can be found in previous sections.

On the other hand, the AHP method has been adopted for developing one of the BAO models in SPPM. The objective in this decision context is to rank the seven PPIs in SPPM using their priority vectors and then convert this rank to the budget allocation. The criteria for comparison are each PPI's level of importance to the decision maker and the level of effort required for improvement. Accordingly, the AHP hierarchy can be constructed as shown in Figure 50 below. The measurement of importance level is from the expert's judgement using the scale in Table 13. With regard to effort required for improvement, it can be measured by the amount of PPI rating to improve, i.e. the difference between estimated PPI rating and the ideal PPI rating for each PPI category. It can be also measured by estimating the fund required for improving such PPI from the present status to the targeted condition using PBB concept. The pairwise comparison matrix for each criteria can be then developed as shown in Figure 51 and Figure 52.

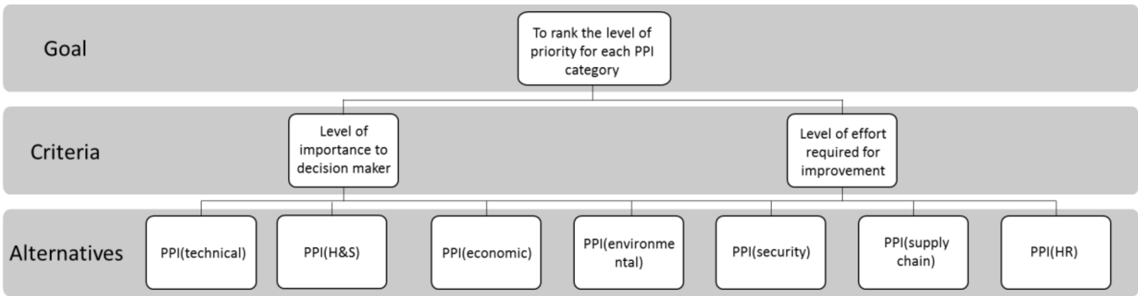

Figure 50: AHP hierarchy of the MCDA-based BAO in SPPM

	Technical PPI	H&S PPI	Economic PPI	Environmental PPI	Security PPI	Supply Chain PPI	HR PPI
Technical PPI	1	$S_{tech:H\&S}$	$S_{tech:eco}$	$S_{tech:env}$	$S_{tech:sec}$	$S_{tech:sup}$	$S_{tech:HR}$
H&S PPI	$S_{H\&S:tech} = \frac{1}{S_{tech:H\&S}}$	1	$S_{H\&S:eco}$	$S_{H\&S:env}$	$S_{H\&S:sec}$	$S_{H\&S:sup}$	$S_{H\&S:HR}$
Economic PPI	$S_{eco:tech} = \frac{1}{S_{tech:eco}}$	$S_{eco:H\&S} = \frac{1}{S_{H\&S:eco}}$	1	$S_{eco:env}$	$S_{eco:sec}$	$S_{eco:sup}$	$S_{eco:HR}$
Environmental PPI	$S_{env:tech} = \frac{1}{S_{tech:env}}$	$S_{env:H\&S} = \frac{1}{S_{H\&S:env}}$	$S_{env:eco} = \frac{1}{S_{eco:env}}$	1	$S_{env:sec}$	$S_{env:sup}$	$S_{env:HR}$
Security PPI	$S_{sec:tech} = \frac{1}{S_{tech:sec}}$	$S_{sec:H\&S} = \frac{1}{S_{H\&S:sec}}$	$S_{sec:eco} = \frac{1}{S_{eco:sec}}$	$S_{sec:env} = \frac{1}{S_{env:sec}}$	1	$S_{sec:sup}$	$S_{sec:HR}$
Supply Chain PPI	$S_{sup:tech} = \frac{1}{S_{tech:sup}}$	$S_{sup:H\&S} = \frac{1}{S_{H\&S:sup}}$	$S_{sup:eco} = \frac{1}{S_{eco:sup}}$	$S_{sup:env} = \frac{1}{S_{env:sup}}$	$S_{sup:sec} = \frac{1}{S_{sec:sup}}$	1	$S_{sup:HR}$
HR PPI	$S_{HR:tech} = \frac{1}{S_{tech:HR}}$	$S_{HR:H\&S} = \frac{1}{S_{H\&S:HR}}$	$S_{HR:eco} = \frac{1}{S_{eco:HR}}$	$S_{HR:env} = \frac{1}{S_{env:HR}}$	$S_{HR:sec} = \frac{1}{S_{sec:HR}}$	$S_{HR:sup} = \frac{1}{S_{sup:HR}}$	1

Figure 51: Pairwise comparison matrix for evaluating priority vectors of importance level

	Technical PPI	H&S PPI	Economic PPI	Environmental PPI	Security PPI	Supply Chain PPI	HR PPI
Technical PPI	1	$\frac{E(PPI_{tech})}{E(PPI_{H\&S})}$	$\frac{E(PPI_{tech})}{E(PPI_{eco})}$	$\frac{E(PPI_{tech})}{E(PPI_{env})}$	$\frac{E(PPI_{tech})}{E(PPI_{sec})}$	$\frac{E(PPI_{tech})}{E(PPI_{sup})}$	$\frac{E(PPI_{tech})}{E(PPI_{HR})}$
H&S PPI	$\frac{E(PPI_{H\&S})}{E(PPI_{tech})}$	1	$\frac{E(PPI_{H\&S})}{E(PPI_{eco})}$	$\frac{E(PPI_{H\&S})}{E(PPI_{env})}$	$\frac{E(PPI_{H\&S})}{E(PPI_{sec})}$	$\frac{E(PPI_{H\&S})}{E(PPI_{sup})}$	$\frac{E(PPI_{H\&S})}{E(PPI_{HR})}$
Economic PPI	$\frac{E(PPI_{eco})}{E(PPI_{tech})}$	$\frac{E(PPI_{eco})}{E(PPI_{H\&S})}$	1	$\frac{E(PPI_{eco})}{E(PPI_{env})}$	$\frac{E(PPI_{eco})}{E(PPI_{sec})}$	$\frac{E(PPI_{eco})}{E(PPI_{sup})}$	$\frac{E(PPI_{eco})}{E(PPI_{HR})}$
Environmental PPI	$\frac{E(PPI_{env})}{E(PPI_{tech})}$	$\frac{E(PPI_{env})}{E(PPI_{H\&S})}$	$\frac{E(PPI_{env})}{E(PPI_{eco})}$	1	$\frac{E(PPI_{env})}{E(PPI_{sec})}$	$\frac{E(PPI_{env})}{E(PPI_{sup})}$	$\frac{E(PPI_{env})}{E(PPI_{HR})}$
Security PPI	$\frac{E(PPI_{sec})}{E(PPI_{tech})}$	$\frac{E(PPI_{sec})}{E(PPI_{H\&S})}$	$\frac{E(PPI_{sec})}{E(PPI_{eco})}$	$\frac{E(PPI_{sec})}{E(PPI_{env})}$	1	$\frac{E(PPI_{sec})}{E(PPI_{sup})}$	$\frac{E(PPI_{sec})}{E(PPI_{HR})}$
Supply Chain PPI	$\frac{E(PPI_{sup})}{E(PPI_{tech})}$	$\frac{E(PPI_{sup})}{E(PPI_{H\&S})}$	$\frac{E(PPI_{sup})}{E(PPI_{eco})}$	$\frac{E(PPI_{sup})}{E(PPI_{env})}$	$\frac{E(PPI_{sup})}{E(PPI_{sec})}$	1	$\frac{E(PPI_{sup})}{E(PPI_{HR})}$
HR PPI	$\frac{E(PPI_{HR})}{E(PPI_{tech})}$	$\frac{E(PPI_{HR})}{E(PPI_{H\&S})}$	$\frac{E(PPI_{HR})}{E(PPI_{eco})}$	$\frac{E(PPI_{HR})}{E(PPI_{env})}$	$\frac{E(PPI_{HR})}{E(PPI_{sec})}$	$\frac{E(PPI_{HR})}{E(PPI_{sup})}$	1

Figure 52: Pairwise comparison matrix for evaluating priority vectors of effort required for improvement

Where in Figure 52, $E(PPI_i)$ is the evaluation of the effort required for different PPI category, which can be expressed using Equation (48) (i.e. the fund required for improving such PPI from the present status to the targeted condition) or Equation (49) (i.e. the difference between estimated PPI rating and the ideal PPI rating).

$$E(PPI_i) = \frac{PPI_{i,target} - PPI_{i,present}}{PPI_{i,present}} \times 100\%, \text{ or} \qquad (48).$$

$$E(PPI_i) = PBB(PPI_i) \qquad (49).$$

Then apply Equation (8) to Equation (15) to obtain the value of $P(PPI_i)$ and rank the priority level of each PPI category, including the consistency check. Assuming the restricted total budget is TB, and then the budget to be allocated to each category, BA_i can be calculated as:

$$BA_i = P(PPI_i) \times TB \quad (50).$$

3.3.2.3. The Utility Theory based BAO model in SPPM

The second approach developed for budget allocation is based on the utility theory. The term 'Utility', by definition, is a measure of pleasure or satisfaction for an individual regarding the consumption or investment that one has conducted. It follows the concept of "law of diminishing marginal utility (MU)" (also known as Gossen's First Law) (Polleit, T., 2011), which assumes the utility will increase when the consumption increases, however, the rate of the increment will decrease. Therefore, there will be one point that the utility will not increase even when more consumption is observed. Figure 36 is the typical utility curve that shows the relationship between quantity of the consumption and the utility, which follows the Gossen's First Law.

Suppose if the amount of KPI (or PPI) increment is equivalent to the quantity of consumption, then according to the Gossen's First Law, there will be one point that the utility will achieve its maximisation even when more investment is allocated to such KPI (or PPI). The process of identifying this Stationary Point of the utility curve is called Utility Maximisation. The utility maximisation rule says: to obtain the greatest utility the consumer should allocate the money incomes so that the last dollar spent on each good or service yields the same marginal utility (Curwen, P., 1976). This builds the fundamental assumption of the algorithm in SPPM for the utility theory based BAO approach. The assessment is based on optimisation of the user defined utility function to optimise the fund allocation so that the user's utility will be maximised.

As introduced above, the objective of BAO function in SPPM is to optimise the allocation of the restricted budget for improvement among different PPI categories that would maximise the satisfaction of the decision maker's expectation. This statement can be rephrased using the context of utility theory: The target of utility-based BAO in SPPM is to achieve the utility maximisation via optimising the distribution of spending on improving the PPI ratings for each PPI category subject to a given budget constraint. Therefore, this can be viewed as a utility maximisation problem and the procedure introduced in literature review above can be followed to solve it.

The first task is to define the utility function representing the decision maker's preference ordering among alternative distributions of budget granting to each PPI category. According to the literature review, the utility function is dependent on the problem formulation, i.e. the decision maker's expectation from the result of such investment. In SPPM, the PPI rating to be improved can be viewed as quantity of the commodity to purchase and the associated marginal cost is the price of each unit of such commodity. The utility function should be able to measure the effectiveness or efficiency of the planned activities for performance improvement. Definition of effectiveness or efficiency is determined by SPPM users considering their own requirements, hence there will not be any specific format for the utility function. It could be the algebraic mean (Equation (51)) or geometric mean (Equation (52)) of the PPI rating increment percentage (Equation (41)). It also could be derived from some well-established common utility models that suit for certain circumstances, such as the so-called quasilinear utility. Quasilinear utility model uses rating of one PPI category, called numeraire, to measure the utility. If the consumption of numeraire increases, the indifference curves will shift outward without changing their slope. Using quasilinear utility to measure the effectiveness of the mechanism design of the performance improvement strategy ensures the compensation among agents with side payments while their compensating variation, equivalent variation, and consumer surplus are algebraically equivalent (Varian, H., 1992). The utility function is written as (assuming $\mathrm{i} = 1 \ldots 7$, representing seven PPI categories):

$$\mathrm{U}(\Delta\mathrm{PPI_i}) = \frac{1}{7}\sum_{1}^{7}\Delta\mathrm{PPI_i} \quad (51).$$

$$\mathrm{U}(\Delta\mathrm{PPI_i}) = \sqrt[7]{\prod_{1}^{7}\Delta\mathrm{PPI_i}} \quad (52).$$

$$\mathrm{U}(\Delta\mathrm{PPI_i}) = \Delta\mathrm{PPI_1} + \theta(\Delta\mathrm{PPI_2}, \ldots, \Delta\mathrm{PPI_7}) \quad (53).$$

Where in Equation (53), $\theta()$ is an arbitrary function that is strictly concave.

The next step is to calculate the marginal utility from the utility function as:

$$\mathrm{MU}(\Delta\mathrm{PPI_i}) = \frac{\partial\mathrm{U}(\Delta\mathrm{PPI_i})}{\partial\Delta\mathrm{PPI_I}} \quad (54).$$

Then, based on Equation (19), construct the relationship among marginal utility and the cost of PPI rating increments:

$$\frac{\mathrm{MU}(\Delta\mathrm{PPI}_1)}{\mathrm{MC}_1} = \cdots = \frac{\mathrm{MU}(\Delta\mathrm{PPI}_7)}{\mathrm{MC}_7} \quad (55).$$

On the other hand, if there is priority preference among each PPI category, then weighting factors can apply:

$$\frac{\mathrm{MU}(\Delta\mathrm{PPI}_1)}{\mathrm{MC}_1 \cdot \mathrm{w}_1} = \cdots = \frac{\mathrm{MU}(\Delta\mathrm{PPI}_7)}{\mathrm{MC}_7 \cdot \mathrm{w}_7} \quad (56).$$

Finally, apply the budget constraint (TB) and yield the Equation (54) to Equation (57) to optimise the budget allocations.

$$\sum_{\mathrm{i}=1}^{7} \Delta\mathrm{PPI}_\mathrm{i}\mathrm{MC}_\mathrm{i} = \mathrm{BC} \quad (57).$$

3.3.2.4. The mathematical programming BAO model in SPPM

Mathematical programming (or mathematical optimisation) is commonly used to schedule a plan of activities, which is a tool of the broad discipline known as management science. Dantzig and Thapa (Jain, S. and Singh, V., 2003) defined it as *"branch of mathematics dealing with techniques for maximizing or minimizing an objective function subject to linear, non-linear, and integer constraints on the variables"*. This technique finds the optimal solution that can minimise or maximise a function in a given domain. This means, it is possible to apply mathematical programming to obtain the optimised solution that achieves the maximum benefits under certain given assumptions and restrictions. Accordingly, in SPPM, a model has been developed employing mathematical programming technique to optimise the budget allocation.

To apply mathematical programming for budget allocation, user will need to define an objective function that best describes the purpose of the assessment, it can be any user preferred utility function or financial performance indicators. In this research, it is proposed that the concept of return on investment (ROI) can be adopted here to create the objective function, assuming the net income is the amount of PPI rating increment benefited from financial investment to achieve such increments. This is similar to the cost-effectiveness analysis. The constraints for this mathematical programming problem include the total available budget is limited, the allocated fund for each PPI should not be negative, the PPI rating after improvement should be less than 100, and any other specific restrictions required by the shipyard.

Considering the decision context of BAO in SPPM, LP could be a good option. The variables to be defined is the budget allocated to each PPI category for improvement. The optimisation target in this LP problem is to identify the variables that maximise the total increment of the PPI ratings.

To do so, the first task is to identify the objective function, which can be any type of user defined utility function or financial performance indicators. In this research, it is proposed that the concept of return on investment (ROI) can be adopted here to create the objective function. In business, ROI is defined as the ratio between net income and the cost associated with such income (Zamfir, M., et. al. 2016). Equivalently, assuming the net income is the amount of PPI rating increment, then the adopted ROI can be calculated as:

$$\mathrm{ROI^*}_\mathrm{i} = \frac{\Delta \mathrm{PPI_i} \cdot \mathrm{PPI_i}}{\mathrm{PBB}(\Delta \mathrm{PPI_i})} = \frac{1}{\mathrm{MC_i}}, \mathrm{i} = 1,2 \ldots 7 \quad (58).$$

$\mathrm{PBB}(\Delta \mathrm{PPI_i})$ $(\mathrm{i} = 1,2 \dots 7$ representing seven PPI categories$)$ is the function of calculating the cost associated with improving the PPI from its current status to the ideal solution using the PBB approach introduced in Section 3.3.1 Equation (41). This method is similar to the concept of cost-effectiveness analysis or cost-utility analysis. Mathematically, ROI^* is the multiplicative inverse of the marginal cost for improving PPI rating to target value, which reflects the effectiveness of the investment. Therefore, the expected improvement from given investment, $\mathrm{BA_i}$ of each PPI category can be calculated as:

$$\Delta \mathrm{PPI_i} = \frac{\mathrm{ROI^*}_\mathrm{i} \times \mathrm{BA_i}}{\mathrm{PPI_i}}, \ \mathrm{i} = 1,2 \dots 7 \quad (59).$$

Accordingly, the objective function can be defined as:

$$\mathrm{F(BA_i)} = \sum \frac{\mathrm{ROI^*}_\mathrm{i} \times \mathrm{BA_i}}{\mathrm{PPI_i}}, \ \mathrm{i} = 1,2 \dots 7 \quad (60).$$

Weighting factor can be also applied to indicate user’s preferences:

$$\mathrm{F(BA_i)} = \sum \frac{\mathrm{ROI^*}_\mathrm{i} \times \mathrm{BA_i}}{\mathrm{PPI_i}} \times \mathrm{w_i}, \ \mathrm{i} = 1,2 \dots 7 \quad (61).$$

The constraints in this LP problem includes the total available budget is limited and the PPI rating after improvement should be less than 100, i.e.

$$\sum \mathrm{BA_i} \leq \mathrm{TB}, \mathrm{i} = 1 \dots 7 \quad (62).$$

$$\frac{\mathrm{ROI^*}_\mathrm{i} \times \mathrm{BA_i}}{\mathrm{PPI_i}} + \mathrm{PPI_i} \leq 100, \mathrm{i} = 1 \dots 7 \quad (63).$$

$$BA_i \geq 0, i = 1 \ldots 7 \quad (64).$$

As the number of constraints is less comparing with the number of variables mathematically, the result may be arbitrary. Therefore, it is suggested that user could introduce more constraints to the variables considering their own requirements. There could be other constraints, such as the budget given to certain PPI category is restricted or there could be minimum funding awarded to certain PPI categories, etc., which is dependent on the specific requirements from shipyard.

There are various computer software such as Matlab, Python or R, etc. that can be used to solve this LP problem.

Besides, when there is appropriate historical data, the model that calculating the production efficiency can be also adopted for this purpose. The input is assumed as budget allocated to each PPI category, and output is the increment of each PPI ratings. To solve this problem, other advanced MP models, such as the DEA model introduced in Chapter 2 can be considered. In addition to the optimised budget allocation, the assessment will also provide other information to support the decision making, such as radial movement, slack movement, recommended amount of inputs, etc. The results from this assessment can be presented using the similar pie chart as shown in Figure 49 with all additional information available to decision makers.

3.3.3. Budgeting model capability and limitation discussions

To improve the production performance, activities should be planned in a strategical view that must include estimation of the associated cost, i.e. a plan of budgeting. However, due to the diverse nature of different business, the way to achieve the optimised budget plan should be flexible and fit for the purpose of different scenario. Therefore, four different models have been adopted to form the budget optimisation function in SPPM.

The first model is developed based on the concept of PBB approach and adopted for SPPM via CPM. This method provides a 'Result' oriented planning and budgeting framework, suitable for shipyard's long term development strategy. Among all the advantages of PBB that has already been discussed in Section 3.3.1, the most valuable outcome from using PBB in SPPM is the optimised performance improvement strategy which includes both activity planning and cost estimation. The PBB model can be also used to conduct the marginal analysis to estimate the marginal cost, which is an important parameter for BAO. However, the drawbacks of this PBB based budgeting model is also obvious. This method is time consuming and requires involvement of experts' experience from various departments, including engineering, finance, management, operations, etc. For this reason, PBB is relatively subjective comparing with other math-intensive methods. Besides, this model is more suitable when there is no restriction of the total available funding so that the decision maker can focus more on the effectiveness of the plan rather than cost saving. At the same time, if there are alternative improvements routes, the decision maker can make the judgement based on the comparison among the alternatives based on their effectiveness and cost. The one with higher effectiveness and lower cost will be the preferred option. It is also suggested that the improvement plan should be reviewed at both

KPI and PPI level, so that the dependency among different KPIs (i.e. improvement of multiple KPIs can be active by conducting same activity) can be addressed, and to avoid the repetition of fund awarding.

In the case that the fund granted for performance management is restricted, the decision maker will need a model to optimise the allocation of such fund among different aspects of the production performance, i.e. the PPIs. There are three BAO methods implemented in SPPM which are derived from different theoretical models. The first one is based on the concept of MCDA. This model is relatively easy to understand and operate. However, it cannot handle complicated scenarios when there are predefined additional constraints or conditions that need to be factored into the assessment. In the case of such scenario, the model built upon utility theory or MP would be suitable. These models are math-intensive so that the results would be less subjective but the solving process could be sophisticated and often requiring assistance of computer technology. Appropriate utility function or objective function is the key for a successful BAO via utility theory or MP. This is not a straightforward task, which requires analysis of specific condition of each scenario and able to reflect user’s own objective and preference.

In SPPM, the BAO function works through reviewing the effort required, the cost effectiveness, and the priority level of each PPI to decide how much funding should be allocated. This includes considerations of both subjective and objective factors. For MCDA model, this is shown as the criteria for comparison, for utility theory based model, this is reflected through utility function and for MP based model, these conditions are implemented as objective function and constraints. The main difference between the based

MP method and utility theory is that the choice of utility function for the latter can be more flexible but also more subjective and sometimes, more difficult to solve.

Unlike the PBB model, output from BAO does not include a detailed activity plan, its focus is to provide decision makers with quantitative recommendations on how to allocate the restricted budget among different PPIs. Such recommendations can be rather viewed as a kind of mathematical concepts. However, in reality, the direct results calculated from these models may not be able to implement straightway without necessary fine-tuning and interpretations. Three types of results can be expected directly from the assessment. The ideal condition is when the result is practical and can be implemented directly. However, in some cases, it can be expected that the fund allocated to some of the PPIs may be too less to carry out sufficient activities. In such case, decision maker could consider to use the fund to improve the PPI as much as possible or invest it to other categories. The third possibility is some PPIs may be granted with too much fund result in its PPI rating exceeds upper limit with underspend of the allocated budget. If this happened, the extra fund can be transferred to other categories. One of the reasons causing such complexity of the results is the interrelationship among KPIs which may affect the MC estimation. Certain assumptions may need to be made at this stage to continue the calculation process, but such intervention from user may also introduce the subjective opinions into the results. The dynamic nature of the developed BAO models will take these information into account for future assessment to enhance its practicality. Besides, as this is a mathematical optimisation, it is suggested that the analyser should first review the PPI evaluation with consideration of their specific condition to customise the subsequent steps, such as the assumption of MC or the constraint functions. For instance, one PPI could be improved to the target by purchasing one piece of equipment, i.e. it is a yes / no decision for budgeting, hence should exclude this PPI and the cost of such equipment from the assessment and amend the constraint functions accordingly.

Besides, there are specific challenges for using utility theory and MP based BAO models. Firstly, for utility theory, defining utility function is the fundamental in this model which is normally based on users' own preference. It may introduce certain level of subjectivity. In terms of MP based model, the main issue here is the number of constraints. If it is too less, considering there are more variables need to be defined, the result may be arbitrary. Therefore, when using this method, user is suggested to introduce more constraints to each PPI category or conduct 'manual' fine-turning afterwards.

In practice, the biggest challenge for utility theory or MP based BAO is to accurately estimate the MC which is the key to ensure the confidence and reliability of the assessment. This is because the entire BAO algorithm developed in this project is based on a basic hypothesis that PPI rating is viewed as a kind of commodity and the MC is the unit price of this commodity, so that the BAO can be conducted to achieve the maximum value for money. The recommended general approach to estimate MC has been introduced in Section 3.3.2.1, but the specific procedure will be required to satisfy the requirements of different shipyards.

3.4. SPPM advantages and limitation discussions

The primary objective of SPPM is to provide decision support for performance management, including the evaluation of current performance and plan for the future improvement. The MCDA nature behind the model can be also used for comparative study to determine the optimised performance management strategy, or to compare the performance between different shipyards. The model is flexible so that, depending on the specific condition of the shipyard, user can choose the appropriate KPIs for analyses. The customisation will not affect the computation algorithm of the tool. This also means, by replacing KPIs, the algorithm can be applied to different industries. However, this feature has its pros and cons. If too much subjectivity involved in the selection of the KPIs, the evaluation and subsequent assessments may become unfair and not able to reflect the actual production performance of the shipyard. For this reason, it is suggested that the KPIs introduced in this research should be applied to the maximum, as it is believed to cover majority of the essential information that indicates the level of shipyard's production

Another benefit this tool can provide is the function that allows centralised performance data management. One of the feedbacks received from interviewing shipyards was that it is necessary to develop such centralised database. This is because the data generated from shipyard every day is innumerable with a great deal of variety. In addition, the data from different part of the shipyard are normally managed by different people but might be required to use by others, which may cause issues with misinterpretations of the data and waste of resources. The unified data model allows user to establish a single repository where they can quickly access consistent information related to performance management reported from various departments, easily move between reporting the past and projecting the future, and drill to detailed information.

However, this programme also has limitations and shortcomings. Firstly, in order to carry out the budget optimisation mathematically, there has been an assumption that the marginal cost is assumed to be able to be subdivided infinitely. Similarly, there are assumptions involved in various numerical models for KPI evaluation. As these assumptions may not be practical in reality, user has to take one more step in the end to make the fine-tuning of the results. This additional step depends on the experts' judgement in most cases, which may cause a degree of subjectivity. Fortunately, it is expected that such fine tuning will not change the overall results massively. It will mainly focus on modifying the exact numbers rather than the overall trend of the results. Moreover, like all decision support techniques, the quality of this assessment will depend on the quality and availability of the raw PI data. In some cases, when there is insufficient PI data or the data quality is not to standard, adjustments have to be made to the programme. Because of such adjustments, some KPIs may have to be skipped which will affect the subsequent steps, such as comparisons or budget optimisation. The tolerance and target value of KPI is user's decision which means it can be influenced by user's subjective opinion. In most cases, these values are derived from publications or shipyard historical record and should be reviewed periodically. Besides, as the programme is an integration of various numerical models, there will be unavoidable limitations or shortcomings from the model itself. Regarding this point, the details has been discussed in the relevant sections where such models are applied.

3.5. Remarks

This chapter introduced the functionality and assessment procedure of SPPM. SPPM is a strategic tool that can support the shipyards to measure their production performance as well as supporting the shipyard to budget the future investment for performance improvement. The underline approach that SPPM has employed for performance measurement is the KPI based model. In total there have been 30 KPIs identified based on the literature review and consultation with shipyard SMEs. These KPIs are assigned to measure 7 PPIs, which are health and safety, economic, environmental, technical, HR, security and supply chain. This function will benchmark shipyard's production performance and identify the 'hot spots' so that the priority for performance improvement can be determined. The result of performance measurement will then be used to support the shipyard plan for improvement budget. The knowledge repository embedded in SPPM has also provided suggestions in potential improvement activities that can be considered when planning for the improvement. SPPM provided four models for this purpose. The first one is called PBB that defines the total budget required with its allocation and activity plan. The other three models are designed for the purpose of budget allocation optimisation (BAO) when total available funding is restricted. These three models are developed based on MCDA, utility theory and MP. Advantages and limitations for each model as well as their suitability in different decision contexts have been discussed in this chapter as well.

Chapter 4: Model Verification and Demonstrative Case Study

"The supreme misfortune is when theory outstrips performance."

- Leonardo da Vinci

4.1. SPPM Model verification

In this section, the efforts made to ensure the validity of the research are discussed. The verification is mainly based on the review of two aspects – the quality and reliability of the data and theory used in this project; and the applicability and feasibility of the developed model in practice.

Firstly, as introduced in Chapter 1, a data, information and knowledge repository related to shipyard production performance and budget optimisation has been delivered as part of the project, and is included within this thesis in the appropriate context by way of references, tables and visit reports from interviews held. This repository provides the theoretical supports to the development of SPPM, which is the cornerstone of the model and ensures that the whole algorithm is well-founded. The primary knowledge source for the repository is the literatures that have been reviewed including secondary databases, relevant publications, industrial best practice, codes and standards, etc. The literatures and secondary databases applied in this project have been listed as *References* with citations throughout the thesis. As can be seen from Figure 53, in total, there are 270 references used to support the development of this thesis. Among these references, 77% from peer-reviewed publications, books or thesis, 7% from government report, industrial best practice, codes and standards published and approved by relevant authorities, and 2% are secondary databases. For the credibility of this research, specific effort has been made to ensure all critical steps and arguments are supported by references from trustable sources.

In addition, the repository has also included recommendations from shipyards' SMEs which are the essence extracted from practice. The collaborative shipyards are located widely in Europe, including Denmark, Spain, the United Kingdom, Greece, France and Bulgaria, who are the members of the SHIPLYS and FIBRESHIP project consortiums. The support from shipyards for this research is crucial, which enhanced the practicality of the model. For example, there was an opportunity to review the cost estimation sheets that are actually used by a shipyard in reality. It provided practical information on how shipyards estimate the cost and control the budgets, which helped this research to gain deeper understanding of the pros and cons of theoretical models in textbooks. Moreover, there were opportunities to visit various shipyards, and to intuitively understand how on-site production activities are carried out. Much of the valuable knowledge was obtained from discussions with the experts working on the frontline of the production during the site visits. These expert opinions have been incorporated into model development as well as the design of the demonstrative case study, and specific citations are made where applicable.

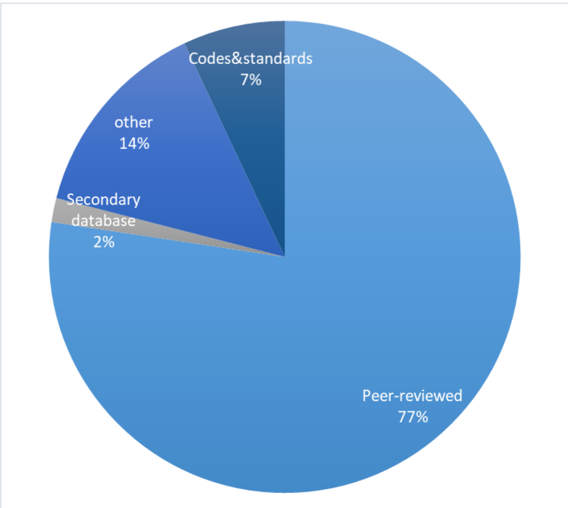

Figure 53: Statistics of the references in in this thesis

Besides, during the model development, there were numerous iterative discussions with various shipyards to ensure the feasibility of the model and to confirm the input data availability for using the model. The final version of SPPM algorithm has been presented to all collaborative shipyards, and positive comments about its practicality have been received. In addition, the SPPM has also been presented at the workshop held by SHIPLYS project. The audience were from various backgrounds within the shipping and shipbuilding industries, including university, research and technology organisations, shipyards and ship-owners, etc. Valuable feedbacks were received and incorporated to enhance the algorithm afterwards. Moreover, for the purpose of completion, detailed discussions regarding the limitation, capability and eligibility of the developed SPPM algorithm have been included in Chapter 2 and Chapter 3.

4.2. Demonstrative case study

4.2.1. Purpose of the case study

This is a demonstrative case study, which is designed based on the developed data, information and knowledge repository. It also contains a number of assumptions where the direct data are not available. All data sources and assumptions have been mentioned and explained where required in the next section.

The primary purpose of this case study is to demonstrate the complete process of using SPPM to support shipyard production performance management, from input data collection to result interpretation. All the theoretical models that have been reviewed and developed in this research will be applied to this case study. It is expected that through such demonstration, the capability of the SPPM algorithm can be presented. It not only can visually show what specific support to be expected from using SPPM, but also serve as a detailed instruction of its evaluation procedure.

The second purpose for conducting this case study is to enhance the applicability and feasibility of the developed algorithm. One of the key factors in this is to ensure the availability of input parameters, i.e. the PIs listed in Appendix A. For confidentiality considerations, external personnel may not be able to access some of these parameters for research, but they should be available for internal use by the shipyard for their own purposes. Therefore, this case study can be viewed as a platform to directly work with shipyards to understand the availability of such data, where to find them and who is responsible for such information, etc. In short, this activity helps to improve the adaptability of theoretical models to industrial reality. Besides, this has also provided opportunities to discuss with shipyards about the difficulties or additional work required if they would like to incorporate SPPM into their performance management strategy. Although this topic is beyond the scope of current research, it can still provide valuable informative support for the future development focus and exploitation potential of SPPM.

Furthermore, this case study, actually, has not included all budget optimisation models and KPIs listed in Appendix A, which is mainly because of the data availability. Most of the input data were provided by shipyards, together with some data collected from secondary database and reviewed by shipyards. However, because of the confidentiality concerns, some data, such as cost-related parameters, exist but cannot be shared externally, nor can it be found from any public resources. For this reason, it was decided to exclude the KPIs that require these data as input from the case study rather than using an assumed value. Excluding some of the KPIs will not affect the completion of SPPM assessment, because of the algorithm flexibility that has potential for adapting the high degree of customisation. In practice, the choice of KPIs and budget optimisation models is the user's decision and preference, so it is important that the model should be developed with sufficient flexibility. Through this case study, the ability of the developed algorithm in this respect can be partially validated.

4.2.2. Case study design

4.2.2.1. Introduction

As introduced in Chapter 1, this case study is not the actual case of any specific shipyard, but is designed aiming at simulating the actual situation of the shipyard to the greatest extent possible. Performance improvement plan will be proposed based on the recommended activities reviewed in Task 2. The effectiveness of such improvement activities will be analysed in the context of the case study.

The case shipyard is the hypothesis simulated from a typical small and medium sized shipyard located in the Europe, with shipbuilding and ship repair as the main business area. Most of the data used as input parameters (i.e. the PIs) were provided by collaborative shipyards. This dataset is the combination of data collected from similar shipyards in Demark, Spain and France. Appendix B is the sample questionnaire that was used for collecting the data from shipyards, which is made anonymous as per the requirement of confidentiality. Moreover, due to the confidentiality requirement, it was also mentioned by the shipyards who provided these data that some of the exact numbers provided may not be the actual value at their shipyard but it represents the typical values of the shipyards in this type. The rest was collected from literatures and reviewed by these shipyards. More specifically, all input parameters used in this case study can be categorised into four types based on the source of the data:

- Category A: Data that are directly provided or recorded by shipyards. Uncertainty level: low
- Category B: Data that are collected or extracted from literatures (e.g. publications, standards, databases, etc.) and reviewed by shipyards. Uncertainty level: low-median
- Category C: Assumed value for confidential parameters. Due to confidentiality requirements, some parameters can be only accessed internally. For this category, the data availability has been confirmed by shipyards, but only assumed value was suggested to use for the case study. Uncertainty level: low-median
- Category D: There are two types of data considered in this category. First one is the data that are collected or extracted from literatures (e.g. publications, standards, databases, etc.) but not have been reviewed by shipyards. The other type is the assumed values for completing the assessment procedures. The availability of these data is confirmed but the value was not reviewed by SMEs. Uncertainty level: high

In the next section, the category of the each input parameter will also be presented.

4.2.2.2. Input parameters

Input parameters required for the case study includes PIs, user defined tolerance and target KPI rating, as well as the improvement activities with associated cost information.

1) Input for H&S performance evaluation

This includes the PIs (Table 19) as well as tolerance and target value of KPIs (Table 20) The shipyard which has provided the above data have mentioned that, at their shipyard, the way to categorise the production activities for recording injuries are grinding, welding, cutting, mounting, crane movement and material handling.

Table 19: List of PIs collected and used for evaluating H&S performance

The list of PIs	PI Values	Category	Data source or notes
Number of injury per month during grinding, converted to rank of P in RPN table	1	A	
Loss of work days during grinding, converted to rank of S in RPN table	3	A	
Duration of grinding, converted to rank of T in RPN table	5	A	
Number of injury per month during welding, converted to rank of P in RPN table	2	B	
Loss of work days during welding, converted to rank of S in RPN table	2	B	Ozkok, M., 2014
Duration of welding, converted to rank of T in RPN table	10	B	
Number of injury per month during cutting, converted to rank of P in RPN table	1	A	
Loss of work days during cutting, converted to rank of S in RPN table	2	A	
Duration of cutting, converted to rank of T in RPN table	5	A	
Number of injury per month during mounting, converted to rank of P in RPN table	2	A	
Loss of work days during mounting, converted to rank of S in RPN table	3	A	
Duration of mounting, converted to rank of T in RPN table	5	A	
Number of injury per month during crane movement, converted to rank of P in RPN table	1	A	
Loss of work days during crane movement, converted to rank of S in RPN table	2	A	

Duration of crane movement, converted to rank of T in RPN table	2	A	
Number of injury per month during worker material handling , converted to rank of P in RPN table	2	A	
Loss of work days during worker material handling , converted to rank of S in RPN table	3	A	
Duration of worker material handling , converted to rank of T in RPN table	3	A	
Number of deficiency regarding implementation of safety measures identified by each inspection	30	C	
Number of inspections annually	12	C	
Number of deficiency regarding implementation of afterwards corrective actions identified by each inspection	10	C	
Number of inspections annually	12	C	

The shipyard which has provided the above data have mentioned that, at their shipyard, the way to categorise the production activities for recording injuries are grinding, welding, cutting, mounting, crane movement and material handling.

Table 20: the tolerance limit and target value of KPI

KPIs	**Description**	**KPI value max.**	**KPI value target**	**Category**	**Data source or notes**
$KPI_1^{H\&S}$	Risk assessment of incidents during production	38	1	A	
$KPI_2^{H\&S}$	Average number of deficiency regarding implementation of safety measures identified during inspection annually	9	0	C	
$KPI_3^{H\&S}$	Average number of deficiency regarding implementation of afterwards corrective actions identified during inspection annually	3	0	C	

2) Input for economic performance evaluation

This includes the PIs (Table 21) as well as tolerance and target value of KPIs (Table 22).

Table 21: List of PIs collected and used for evaluating economic performance

The list of PIs	PI Values	Category	Data source or notes
Estimated cost of ship construction, £m	4.5	A	FIBRESHIP consortium, 2020; Umair, S., 2006
Actual spent, £m	4.4	A	
Number of employees involved in production activities	40	A	
CGT	8840	A+B	

The value of CGT was calculated from a sample Ro Pax ship designed as part of FIBRESHIP project using Equation (3) and the number of employees involved in production activities was estimated for this ship. The data provided is related to a sample ship, which means the associated KPI value will be calculated using one typical ship to represent instead of the annual overall productivity.

Table 22: the tolerance limit and target value of KPI for economic performance

KPIs	Description	KPI value max.	KPI value target	Category	Data source or notes
KPI_1^{ec}	Budget control	1	1	A	Lamb, T., 2007
KPI_2^{ec}	Productivity	0.0072	0.0043	B	

The tolerance and target value of KPIs is estimated based on the survey published regarding the global shipbuilding productivities (Lamb, T., 2007), which has been mentioned in Chapter 2.

3) Input for environmental performance evaluation

The PIs in this aspect are the data required for carrying out the LCA assessment of the sample ship, which were derived from the deliverables of FIBRESHIP project and relevant publications(FIBRESHIP consortium, 2020; Umair, S., 2006). All PI data, except otherwise mentioned, are categorised as Category B.

The scope and simplified production process is shown in Figure 54, and the input production data is listed in Table 23 below. The assessment was performed using the SimaPro and the database used was ecoinvent. Considering the data availability, the LCA has been simplified and only performed for the superstructure of the ship. The functional unit is the production of the superstructure with 75m long, 29m wide and 13m high.

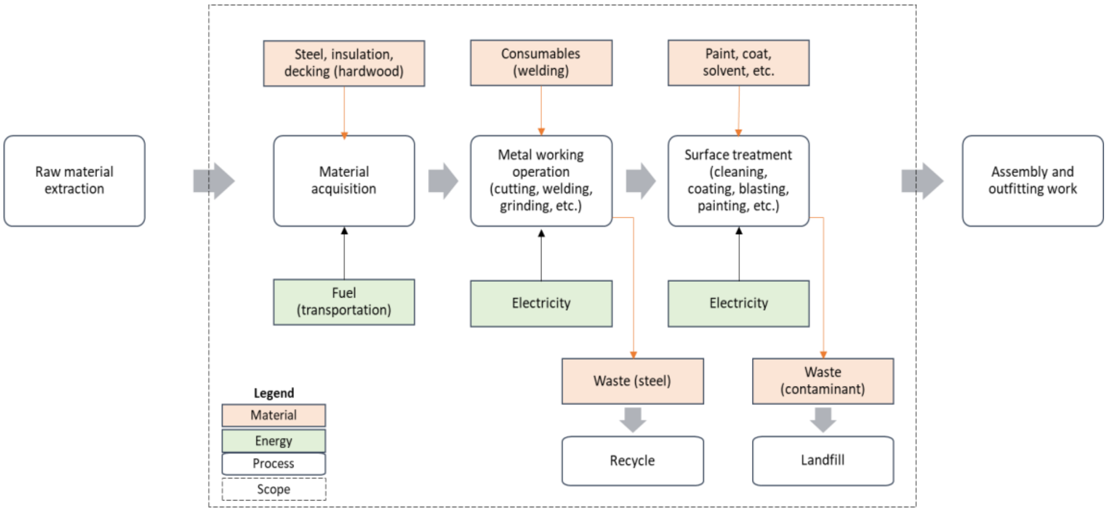

Figure 54: The simplified LCA scope and production process

Table 23: The production data used for LCA in the case study

Material/ Processes	Value	Data source and notes
Steel	800 tons	FIBRESHIP consortium, 2020; Umair, S., 2006
Glass wool for insulation	50 tons	FIBRESHIP consortium, 2020; Umair, S., 2006
Decking (hardwood)	100 tons	Ecoinvent process
Electric welding 5mm	1000m	Umair, S., 2006

Electric welding 2mm	600m	Umair, S., 2006
Energy used for production	37003.8GJ	Lingg, B., 2002, a resource input identified as unspecified energy
Coating (multiple layers)	9600 m^2	FIBRESHIP consortium, 2020, anticorrosive coating, zinc chromate based primers
Steel wastage	20% (100% recycle)	Category C
Surface treatment wastage	5% (100% landfill)	Category C
Deck paints (multiple layers)	2175m^2	FIBRESHIP consortium, 2020, zinc primers, epoxy polyamides, glass-fibre reinforced epoxy

The tolerance and target value of KPIs are listed in Table 24.

Table 24: The tolerance and target value of KPIs for environmental performance

KPIs	**Description**	**KPI value max.**	**KPI value target**	**Category**	**Data source or notes**
KPI_1^{env}	Global warming potential (GWP, kg-CO2 equivalent)	420	84	B	Umair, S., 2006
KPI_2^{env}	Photochemical oxidant creation potential (POCP), kg C2H4 eq	8750000	1750000	B	Umair, S., 2006
KPI_3^{env}	Resource depletion or Abiotic depletion (ADP), kg Sb eq	2250	1500	D	
KPI_4^{env}	Disability Adjusted Life Years (DALYs)	15	10	D	

4) Input for technical performance evaluation

This includes the PIs (Table 25) as well as tolerance and target value of KPIs (Table 26).

Table 25: List of PIs collected and used for evaluating technical performance

The list of PIs	**PI Values**	**Category**	**Data source or notes**
Total days of delay due to revised design because of equipment size	0	A	
Total days of delay due to revised design from owner and Classification	0	A	

Total days of delay due to new technology transfer problem	0	A	
Number of revised design because of equipment size	25	A	
Number of revised design from owner and Classification	20	A	
Number of new technology transfer problem	0	A	
Total days of delay due to customs clearance of material or equipment in port	7	A	
Total days of delay due to delay of material in shipbuilding	10	A	
Total days of delay due to delay of purchase order	5	A	
Number of delay of customs clearance of material or equipment in port	3	A	
Number of delay of material in shipbuilding	12	A	
Number of delay of purchase order	5	A	
Total days of delay due to worker performance	0	A	
Total days of delay due to sub-contractor performance	0	A	
Total days of delay due to mistakes of design	0	A	
Total days of delay due to instruction not responsibility	0	A	
Total days of delay due to revised production request from owner and classifications	0	A	
Number of delay due to worker performance	0	A	
Number of delay due to sub-contractor performance	0	A	
Number of mistakes of design	10	A	
Number of delay due to instruction not responsibility	12	A	
Number of delay revised production request from owner and classifications	15	A	

The data provided from shipyard include the number of technical issues occurred, which may not be required for the KPI calculation but will be useful when analysing the performance evaluation result which will be further discussed in the next section.

Table 26: The tolerance and target value of KPIs for technical performance

KPIs	**Description**	**KPI value max.**	**KPI value target**	**Category**	**Data source or notes**
KPI_1^{tech}	Delay (days) during design, model test, planning process	45	0	A	
KPI_2^{tech}	Delay (days) during procurement	40	0	A	
KPI_3^{tech}	Delay (days) during construction process	37	0	A	

5) Input for HR performance evaluation

This includes the PIs (Table 27) as well as tolerance and target value of KPIs (Table 28).

Table 27: List of PIs collected and used for evaluating HR performance

The list of PIs	**PI Values**	**Category**	**Data source or notes**
Number of disciplinary issues per year	1	A	
Number of employees under training	6	A	
Number of qualified employees providing training	15	A	
Number of employees	24	A	
Number of employees terminated for whatever reasons	4	A	
Number of unavoidable termination	2	A	
Number of beneficial termination	1	A	
Number of employees qualified with (specific qualification that shipyard requires)	6	A	
Number of employees before the assessment period	28	A	

For this PPI, not all PIs listed in Appendix A are provided by the shipyard, the recruitment information was not made available to this research.

Table 28: The tolerance and target value of KPIs for HR performance

KPIs	Description	KPI value max.	KPI value target	Category	Data source or notes
KPI_1^{HR}	Overall retention rate ($R_{retention}$)	0.15	0	C	FIBRESHIP consortium, 2020
KPI_2^{HR}	Involuntary turnover rate (R_{IT})	0.1	0	C	
KPI_5^{HR}	Employee quality (R_{EQ})	0.25	0.4	C	
KPI_8^{HR}	Disciplinary matters (DM)	5	0	C	

6) Input for security management performance evaluation

This includes the PIs (Table 29) as well as tolerance and target value of KPIs (

Table 30).

Table 29: List of PIs collected and used for evaluating security management performance

The list of PIs	PI Values	Category	Data source or notes
Number of incidents during assessment period	3	A	
Number of deficiency regarding security policies and procedures and its implementation	2	A	
Number of deficiency regarding security equipment	5	A	

Table 30: The tolerance and target value of KPIs for security management performance

KPIs	Description	KPI value max.	KPI value target	Category	Data source or notes
KPI_1^{sec}	Number of incidents during assessment period (including incidents regarding people, physical assets and Cyber security)	10	2	A	
KPI_2^{sec}	Number of deficiency regarding security policies and procedures and its implementation (for purpose of both prevention and remediation) identified during inspections/ audits	10	2	A	

KPI_3^{sec}	Number of deficiency regarding security equipment (for purpose of both prevention and remediation) identified during inspections/ audits	10	2	A	

7) Input for supply chain management performance evaluation

This includes the PIs (Table 31) as well as tolerance and target value of KPIs Table 32).

Table 31: List of PIs collected and used for evaluating supply chain management performance

The list of PIs	PI Values	Category	Data source or notes
Total days between actual release of drawing and the planned date of release	0	A	
Number of drawings delivered	150	A	
Number of drawings containing mistakes that requires supplier for modification	3	A	
Total days between actual delivery date from purchase order and the promised date of delivery	25	A	
Number of order lines	1750	A	
Number of order lines containing faults	25	A	
Number of order lines containing broken parts	10	A	
Number of order lines containing missing parts	10	A	
Total days between actual arrival date at yard and planned arrival date	25	A	
Days of delay due to fault from subcontractor	10	A	

Table 32: The tolerance and target value of KPIs for supply chain management performance

KPIs	Description	KPI value max.	KPI value target	Category	Data source or notes
KPI_1^{sup}	Reliability of drawing delivery	0.033333	0.006667	A	
KPI_2^{sup}	Quality of drawings	0.1	0.053333	A	

KPI_3^{sup}	Reliability of supplier delivery	0.017143	0	A+C
KPI_4^{sup}	Incorrectness of supplier	0.02	0.001143	A
KPI_5^{sup}	Quality of supplier	0.008571	0.000571	A
KPI_6^{sup}	Quality of the subcontractors	5	1	A
KPI_7^{sup}	Delivery reliability at yard	0.017143	0.000571	A+C

8) Input for calculating weighting factors

Figure 55 is the pair-wise comparison suggested by shipyards mentioned Section 4.2.2.1, which is categorised as A.

Technical Performance	9	7	5	3	**1**	3	5	7	9	Health and Safety Performance
Technical Performance	9	7	5	**3**	1	3	5	7	9	Environmental Performance
Technical Performance	9	7	5	3	1	3	**5**	7	9	Economic Performance
Technical Performance	9	7	5	3	**1**	3	5	7	9	HR Performance
Technical Performance	9	7	5	**3**	1	3	5	7	9	Security Performance
Technical Performance	9	7	5	3	1	**3**	5	7	9	Supply Chain Performance
Health and Safety Performance	9	7	5	**3**	1	3	5	7	9	Environmental Performance
Health and Safety Performance	9	7	5	3	**1**	3	5	7	9	Economic Performance
Health and Safety Performance	9	7	5	3	**1**	3	5	7	9	HR Performance
Health and Safety Performance	9	7	**5**	3	1	3	5	7	9	Security Performance
Health and Safety Performance	9	7	5	3	**1**	3	5	7	9	Supply Chain Performance
Environmental Performance	9	7	5	3	1	**3**	5	7	9	Economic Performance
Environmental Performance	9	7	5	3	1	**3**	5	7	9	HR Performance
Environmental Performance	9	7	5	3	**1**	3	5	7	9	Security Performance
Environmental Performance	9	7	5	3	1	**3**	5	7	9	Supply Chain Performance
Economic Performance	9	7	**5**	3	1	3	5	7	9	HR Performance
Economic Performance	9	**7**	5	3	1	3	5	7	9	Security Performance
Economic Performance	9	7	5	3	**1**	3	5	7	9	Supply Chain Performance
HR Performance	9	7	5	**3**	1	3	5	7	9	Security Performance
HR Performance	9	7	5	3	1	3	**5**	7	9	Supply Chain Performance
Security Performance	9	7	5	3	1	3	**5**	7	9	Supply Chain Performance

Figure 55: The pair-wise comparison information suggested by shipyard

9) Assumed cost estimation for improvement

The data used for this purpose are categorised as Category D. In Table 33 below, the proposed activities for improvement and the assumed associated cost is listed. The activities are selected from the activities discussed in Chapter 3 based on the results of KPI evaluation. Although the effectiveness of such activities has been discussed in Chapter 3 in detail, the cost associated with such activities cannot be accurately estimated without the involvement of relevant suppliers or access to shipyard's confidential data (such as employee salary). Fortunately, this will not be an issue in reality, because the shipyard can request the accurate quote from relevant suppliers. For this reason, the improvement cost to be used in the case study will be assumed values only for the purpose of demonstrating the assessment procedure.

Table 33: Proposed improvement activity and assumed cost

PPI	Proposed activities	Assumed cost (£)	References
$PPI_{H\&S}$	- OHS equipment and PPEs - OHS training	10000	
PPI_{eco}	- Robotics to assist the production, e.g., drone for painting or welding robot	N/A	
PPI_{env}	- Install capture and collection system - Use scraped steel as building material	10000	
PPI_{tech}	- Digital system for material management - Enhanced communication channel	10000	
PPI_{hr}	- New recruitment of qualified staff - Salary increment	12000	Ongori, H., 2007; ERI Institute, 2021
PPI_{sec}	- Security equipment - Security awareness training	2000	
PPI_{sup}	- Enhanced QA/QC with AI techniques - Advanced database management - Track and trace system	15000	GOV.UK, 2021

4.2.3. Results and discussion

4.2.3.1. User preference

Based on the expert opinion provided by shipyard in Figure 55, a pair-wise comparison has been carried out to rank the importance level of each PPI for the case shipyard. The comparison matrix converted from Figure 55 is shown in Figure 56 below based on the instruction given in Chapter 4 and the calculated weights for each PPI is listed in Table 34. The CI was calculated as 0.09, which satisfied the consistency check.

	PPI_{tech}	$PPI_{H\&S}$	PPI_{env}	PPI_{eco}	PPI_{hr}	PPI_{sec}	PPI_{sup}
PPI_{tech}	1.00	1.00	3.00	0.20	1.00	3.00	0.33
$PPI_{H\&S}$	1.00	1.00	3.00	1.00	1.00	5.00	1.00
PPI_{env}	0.33	0.33	1.00	0.33	0.33	1.00	0.11
PPI_{eco}	5.00	1.00	3.00	1.00	5.00	7.00	1.00
PPI_{hr}	1.00	1.00	3.00	0.20	1.00	3.00	0.20
PPI_{sec}	0.33	0.20	1.00	0.14	1.00	1.00	0.20
PPI_{sup}	3.00	1.00	1.00	1.00	5.00	5.00	1.00

Figure 56: The pair-wise comparison matrix for analysing the importance level of each PPI.

Table 34: The calculated weights for each PPI based on user preference

w_{PPI}	weights
$w_{H\&S}$	0.179
w_{eco}	0.279
w_{env}	0.048
w_{tech}	0.114
w_{hr}	0.109
w_{sec}	0.047
w_{sup}	0.224

As can be seen from the table above, the most important PPI for the case shipyard is economic performance followed by H&S, while the list important one is security management similar to environmental performance.

4.2.3.2. The performance evaluation

Following the instruction in Chapter 3, the rating of each PPI and its associated KPIs can be calculated. Figure 57 shows the overall comparison of PPI ratings and the detailed results are listed in Table 35 including all assessed KPIs.

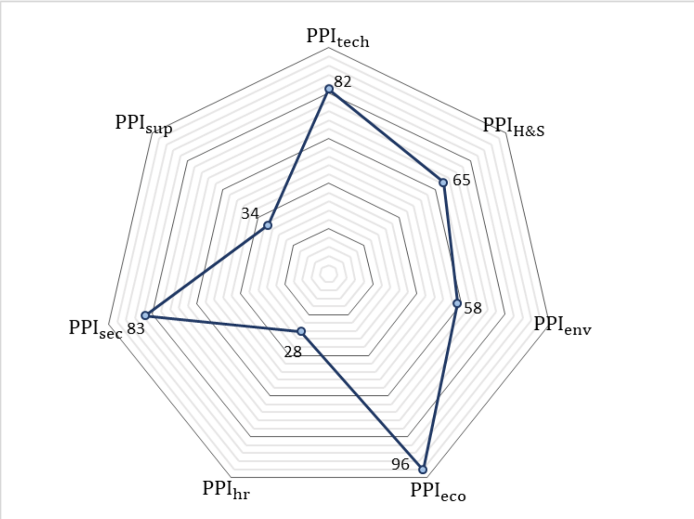

Figure 57: The overall comparison of PPI ratings

Table 35: The results of KPI rating evaluation

	Description	**Value**	**Rating**
$KPI_1^{H\&S}$	Risk assessment of incidents during production	19.5	50
$KPI_2^{H\&S}$	Average number of deficiency regarding implementation of safety measures identified during inspection annually	2.5	72
$KPI_3^{H\&S}$	Average number of deficiency regarding implementation of afterwards corrective actions identified during inspection annually	0.8	72
		$PPI_{H\&S}$	**65**
KPI_1^{ec}	Budget control	0.98	100
KPI_2^{ec}	Productivity	0.0045	92
		PPI_{eco}	**96**
KPI_1^{env}	Global warming potential (GWP, kg-CO2 equivalent)	101.7	95
KPI_2^{env}	Photochemical oxidant creation potential (POCP), kg C2H4 eq	7528824	17
KPI_3^{env}	Resource depletion or Abiotic depletion (ADP), kg Sb eq	1941	41
KPI_4^{env}	Disability Adjusted Life Years (DALYs)	11	80

		PPI_{eco}	**58**
KPI_1^{tech}	Delay (days) during design, model test, planning process	0	100
KPI_2^{tech}	Delay (days) during procurement	22	45
KPI_3^{tech}	Delay (days) during construction process	0	100
		PPI_{tech}	**82**
KPI_1^{HR}	Overall retention rate ($R_{retention}$)	0.15	5
KPI_2^{HR}	Involuntary turnover rate (R_{IT})	0.07	29
KPI_5^{HR}	Employee quality (R_{EQ})	0.25	0
KPI_8^{HR}	Disciplinary matters (DM)	1	80
		PPI_{hr}	**28**
KPI_1^{sec}	Number of incidents during assessment period (including incidents regarding people, physical assets and Cyber security)	3	88
KPI_2^{sec}	Number of deficiency regarding security policies and procedures and its implementation (for purpose of both prevention and remediation) identified during inspections/ audits	2	100
KPI_3^{sec}	Number of deficiency regarding security equipment (for purpose of both prevention and remediation) identified during inspections/ audits	5	63
		PPI_{sec}	**83**
KPI_1^{sup}	Reliability of drawing delivery	0	125
KPI_2^{sup}	Quality of drawings	0.02	171
KPI_3^{sup}	Reliability of supplier delivery	0.014	17
KPI_4^{sup}	Incorrectness of supplier	0.02	0
KPI_5^{sup}	Quality of supplier	0.006	36
KPI_6^{sup}	Quality of the subcontractors	10	-125
KPI_7^{sup}	Delivery reliability at yard	0.014	17
		PPI_{sup}	**34**

4.2.3.3. Priority for improvement

Overall, the case shipyard has best performed in economic aspect and the least performed PPI is human resource. More specifically,

- H&S performance: The PPI rating evaluated for H&S is just average. The KPI regarding incidents risk assessment is just 50, which means improvement activities is required. Considering the deficiencies identified during inspection, shipyard could consider to purchase more safety equipment and PPEs as well as conducting OHS awareness training to all staff on site including contractors.
- Economic performance: The result shows that the case shipyard has excellent performance in terms of budget control and productivity again labour hours. Therefore, the shipyard just need to make the arrangement to maintain their good performance. Further improvement such as using robotics or other digital tools to assist the production can be considered discretionarily, which can help to increase the efficiency and save the labour cost.
- Environmental performance: Not surprisingly, the KPI of GWP is very low mainly because of the use of steel, which may be able to improve by using steel from greener supply chain such as scrapped or recycled steel, though there could be concern about the strength of such material. In terms of POCP and human health, as the values of tolerance and target KPI was not from a reliable resource, the corresponding KPI rating can be just used for demonstrating the assessment procedure.
- Technical performance: The case shipyard has good technical performance in terms of quick response to manage adverse technical issues. Looking at each KPI, it can be noticed that the shipyard has experienced majority of the listed technical issues, the delay was only occurred during material acquisition phase. It is presumably due to various internal and external parties that are involved in this stage so that it cannot be fully controlled by the shipyard. In this case, a more efficient material management system and enhanced communication channel with its supply chain may be helpful.

The activities that proposed to enhance the reliability of the supply chain will also be useful for this PPI.

- HR performance: The calculated PPI rate in terms of HRM is the lowest among all PPIs. The overall turnover rate is very high, which will result in increased budget for recruitment next year. The shipyard may need to analyse why their employees are leaving and respond accordingly, such as salary increment. The score for employee quality is also low, which means more senior staff need to be recruited or specific professional training to upskill the employees is needed.
- Security performance: The case shipyard is good in terms of the security management. Future budget may be required for maintaining their security equipment or software and conducting the staff awareness training.
- Supply chain performance: The case shipyard has low performance in terms of supply chain management. The supplier of drawings is outstanding however, substantial improvement regarding other suppliers and subcontractors are required. Looking at the individual KPI, it is suggest the shipyard can consider to install the track and trace system to manage their order lines or implement the advanced QA/QC system using AI techniques or robotics to assist the production. These techniques can also help to improve productivity and technical performance.

To prioritise the PPIs for improvement, the performance evaluation results and user preference will be aggregated for comparison. Figure 58 is the SPPM matrix for ‘hotspots’ identification as introduced in Chapter 2.

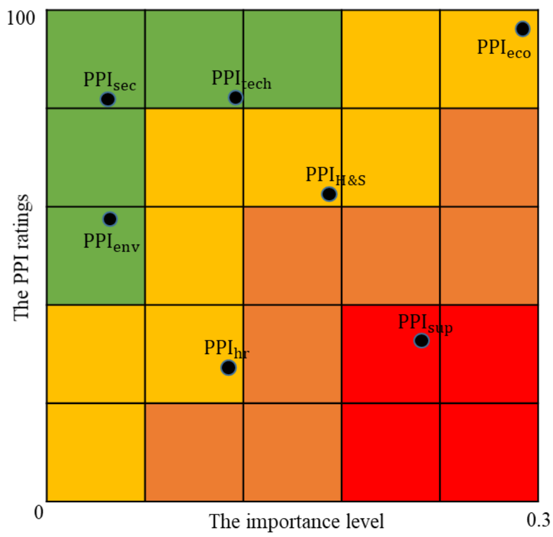

Figure 58: The SPPM matrix for the case shipyard

The SPPM matrix can be referred for identifying the hotspots among all PPIs. Based on the matrix, the supply chain management for the case shipyard has the highest priority for considering the improvement because of its high importance and low performance. This is then followed by HR and H&S management. In addition, although the rating for economic performance is excellent, considering its high importance, activities still required to maintain the performance (which may not require extra budget). Similarly, for environmental performance, its rating is low but it is not very important at the same time for the case shipyard so that its priority level is low.

After ranking the priority for improvement, the shipyard can start the PBB process and look into each PPI in detail. Based on the review of the case shipyard data, improvement activities have been proposed in Section 4.2.3.2.

4.2.3.4. Budget allocation analysis

As introduced in Chapter 4, the BAO function is aimed at optimising the restricted fund allocation by considering the effort required, the importance level and the cost effectiveness of each PPI. In this section, three BAO models introduced by this research will be demonstrated. It is worth emphasising that the cost data listed in Table 33 are assumed values and will be only used in the section for the purpose of demonstrating the BAO procedure.

The first BAO model is based on the concept of AHP. The first step is to conduct the pair-wise comparison against the effort required for each PPI. Effort is measured as difference (percentage) between target PPI rating (assumed to be 100) and the current measured values. A matrix similar to Figure 56 can be then constructed as shown in Figure 59, and the vectors can be calculated and listed in Table 36. CI is calculated as 0 in this case.

	PPI_{tech}	$PPI_{H\&S}$	PPI_{env}	PPI_{eco}	PPI_{hr}	PPI_{sec}	PPI_{sup}
PPI_{tech}	1.00	0.41	0.31	5.57	0.09	1.12	0.12
$PPI_{H\&S}$	2.42	1.00	0.76	13.46	0.21	2.71	0.29
PPI_{env}	3.18	1.32	1.00	17.70	0.28	3.57	0.38
PPI_{eco}	0.18	0.07	0.06	1.00	0.02	0.20	0.02
PPI_{hr}	11.27	4.66	3.54	62.71	1.00	12.65	1.33
PPI_{sec}	0.89	0.37	0.28	4.96	0.08	1.00	0.11
PPI_{sup}	8.48	3.51	2.67	47.20	0.75	9.52	1.00

Figure 59: Pair-wise comparison matrix against effort required for improvement

Table 36: Vectors calculated from Pair-wise comparison matrix against effort required for improvement

E_{PPI}	Value
$E_{H\&S}$	0,088
E_{eco}	0.007
E_{env}	0.116
E_{tech}	0.036
E_{hr}	0.411
E_{sec}	0.032
E_{sup}	0.309

Then combine these two matrix and obtain the final rank of the PPIs assuming both criteria are equally important:

Table 37: The aggregated priority vectors calculated for each PPI

P_{PPI}	Value
$P_{H\&S}$	0.134
P_{eco}	0.143
P_{env}	0.082
P_{tech}	0.075
P_{hr}	0.260
P_{sec}	0.040
P_{sup}	0.267

This means the PPI that requires more effort and more important will have more priority to receive improvement funding. The fund allocation (in percentage) can be then plotted in Figure 60 below. The highest the percentage of the fund has been allocated to supply chain management followed by HR and H&S, which is in line with the priority discussion in Section 4.2.3.3.

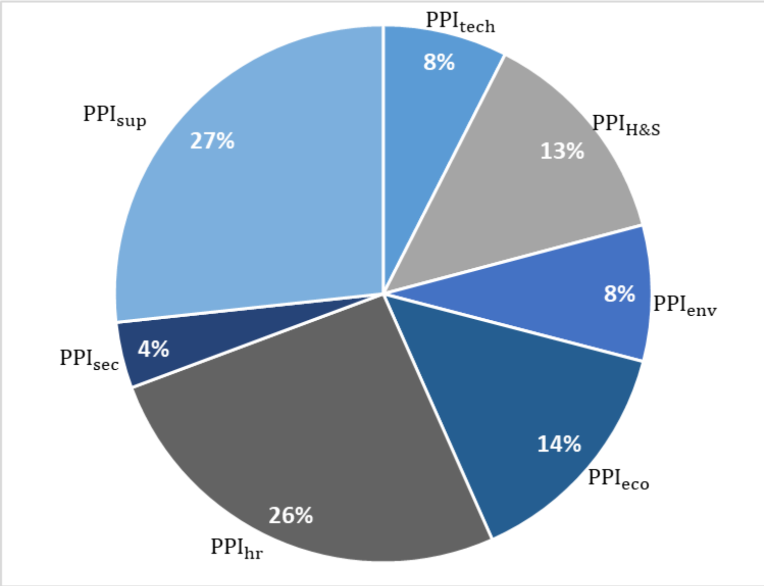

Figure 60: Result of MCDA based BAO estimation

As discussed in Section 3.4, in some cases, fine tuning of the PPI estimation result is required for the adjustment of the mathematical process or data availability. Such fine tuning is just expected to modify the exact numbers rather than the overall trend of the results. To demonstrate this description, a simple sensitivity analysis has been carried out using this case study data. In this analysis, 10 sets of random PPI ratings have been generated between 95% and 105% of the calculated PPI ratings as listed in Table 35, and then used as input to the assessment of MCDA based BAO. These datasets are listed in Table 38 below. The result is shown in Figure 61 below. It can be seen that there is no massive difference in the final results using all these data sets as input, i.e. no significant changes in the overall trend of fund allocation.

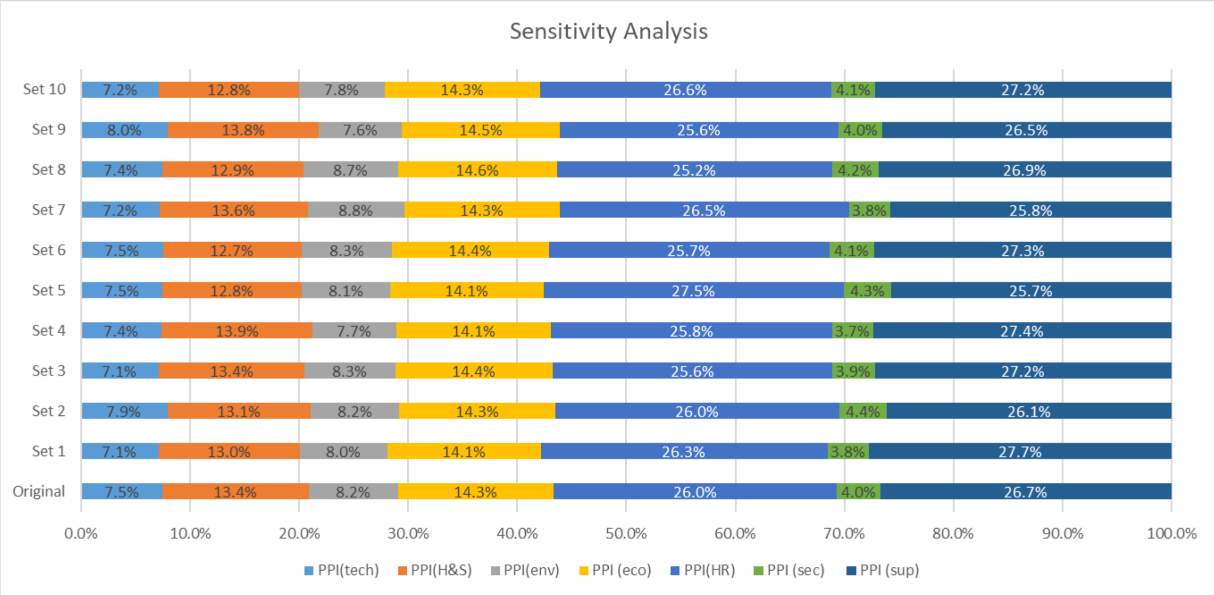

Figure 61: Result from sensitivity analysis to study the influence of fine tuning of the PPI rating

Table 38: The random PPI ratings (between 95% and 105% of the original PPI ratings) generated for sensitivity analysis

	Original	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10
PPI(tech)	82	85	78	85	83	82	81	84	82	78	84
PPI(H&S)	65	67	66	65	63	68	68	64	67	63	67
PPI(env)	58	59	58	58	61	59	57	56	56	61	59
PPI (eco)	96	99	96	95	98	98	95	96	93	94	96
PPI(HR)	28	28	28	29	29	27	28	28	29	29	27
PPI (sec)	83	85	80	84	86	81	82	85	81	83	82
PPI (sup)	34	33	35	34	34	36	33	36	34	35	33

The second method is through applying utility theory. The total available fund is assumed to be £59000 and the marginal cost for improvement is calculated from Table 33. The utility function is assume to be geometric mean of the value of improved PPI ratings. The calculation has been performed using commercial software MathCAD following the instruction given in Chapter 3. The BAO result can be plotted in Figure 62 below together with the comparison of PPI ratings before and after.

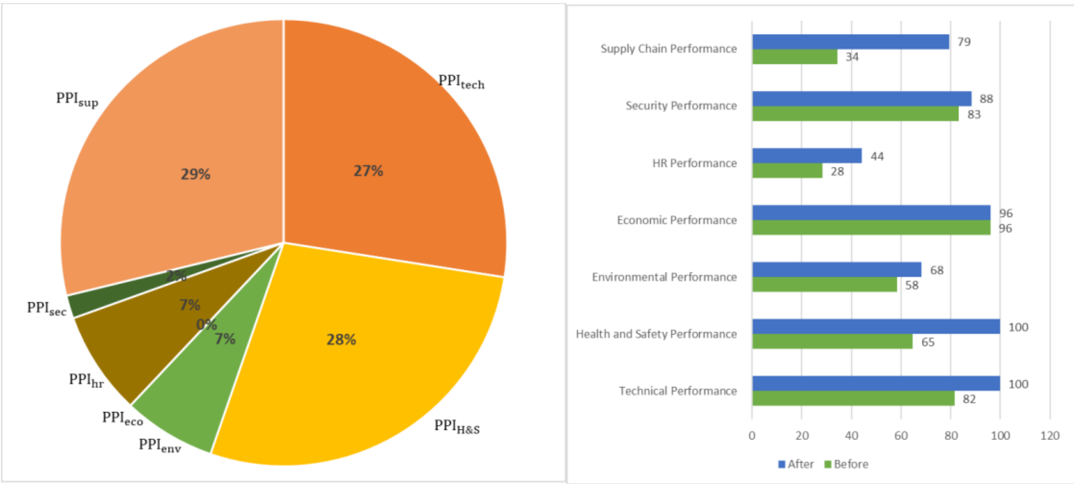

Figure 62: The BAO result using utility theory and the comparison of PPI ratings before and after

Comparing Figure 62 and Figure 60 (and the discussion in Section 4.2.3.3), the trend is slightly different. It is because in Figure 62, the cost effectiveness, i.e. the marginal cost for improvement has been taken into account instead of difference between current performance and the improvement target.

The last method is through mathematical programming, the similar assumption regarding marginal cost and total available fund has been used in this demonstration as well together with extra constraints on each variable to assist the computation process. The calculation has been performed using commercial software MathCAD following the instruction given in Chapter 3. The BAO result can be plotted in Figure 63 below together with the comparison of PPI ratings before and after.

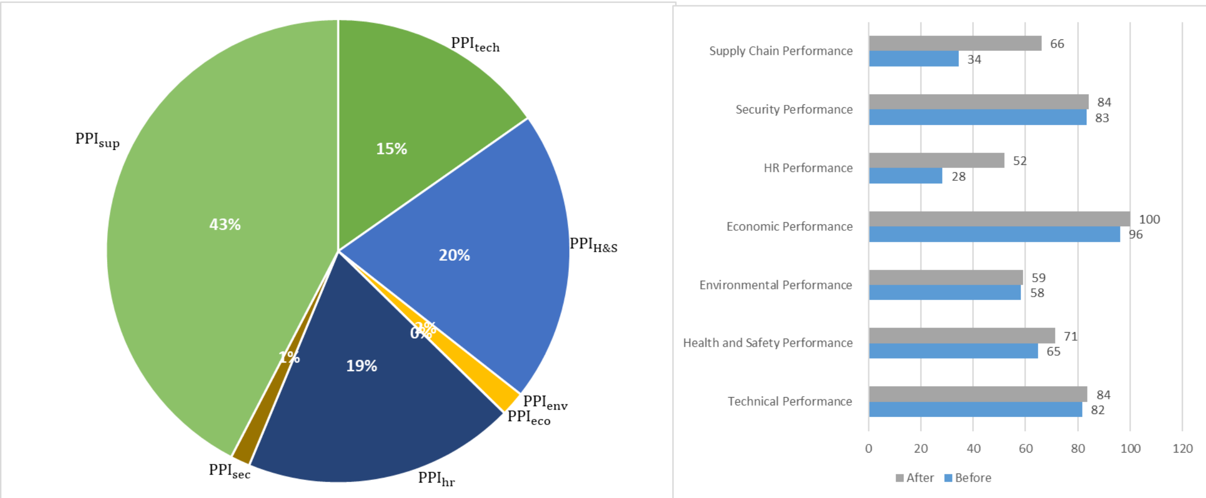

Figure 63: The BAO result using MP and the comparison of PPI ratings before and after

The trend shown in Figure 63 is also different from other figures, it is because in this method all three criteria, cost effectiveness, improvement target and importance level, have been incorporated.

It is difficult to decide which method is more accurate without considering all elements that have been involved in the assessment, because the utility theory and MP based methods are heavily dependent on how accurate the marginal cost is estimated and extra constraints or condition that user would like to add on. Nonetheless, when there is no reliable information regarding the marginal cost, which is the situation of this case study, the MCDA method is preferred since it does not require such information as input and the result is more straightforward to understand.

4.2.3.5. Discussion

As discussed in Section 4.2.1, the main purpose of this case study is to demonstrate the calculation procedure of SPPM, evaluate its capability and practicality as well as identify the requirement for future works. In this section, a brief discussion is provided to explain how this mission is accomplished. Firstly, as can be seen from the sections above, most of the assessments within SPPM framework have been conducted, except very few KPIs have to be excluded due to data availability. The data unavailability of these KPIs is mainly because it requires long-term in-depth collaboration to collect such data, which has been proposed as future work. More details about this can be found in Chapter 5. Fortunately, this can be also considered as an opportunity to demonstrate the flexibility of the developed framework. Secondly, with regard to the validity of the assessment, it can be described from two aspects. The first point is the applicability of the models. The assessment has been presented to the collaborative shipyards at the project meetings and included in a project deliverable (confidential report, only available to consortium members) peer reviewed by various SMEs in the consortium. Positive feedbacks have been received regarding the usefulness of the assessment and shipyards have confirmed their interest in such functions that can support the development of their performance management strategy. The other aspect regarding validity is the source of input data. As introduced in Section 4.2.2, the input parameters have been categorised as A, B, C, and D depending on their original source and uncertainty level. Over 95% of the data are within Category A, i.e. the data directly provided by shipyard, Category B, i.e. the data collected from literature review but reviewed by shipyard and Category C, i.e. shipyard assumed values due to confidentiality requirement. Uncertainty of data from these categories is fairly low leading to a confident result of the overall case study. Regarding Category D data, although its uncertainty level is high, shipyards have confirmed the availability of such data, which means it can still serve the original purpose of carrying out this case study. As per the request by shipyards, the data source has been made anonymous, a sample data collection questionnaire has been included in Appendix B as demonstration.

Besides, considering the original purpose of this case study, although the exact values of the performance evaluation results of this case study is not important for the present research, it has still provided discussion regarding the future performance improvement based on the results, which can be found in Section 4.2.3.3.

4.3. Remarks

In this chapter, the SPPM models have been verified and demonstrated. The verification has been done from the viewpoints of knowledge and information sources that provides the theoretical support for the model development, as well as the feedbacks obtained from potential users, researchers and SMEs in the field. Model demonstration is through a hypothetical case study aiming at demonstrating the complete process of using SPPM to support shipyard production performance management, from input data collection to result interpretation. Most of the input data were provided by shipyards, together with some data collected from secondary database and reviewed by shipyards. It is expected that this activity can also help to enhance the applicability, flexibility and feasibility of the developed algorithm.

Chapter 5: Conclusions and Future Work

"In literature and in life we ultimately pursue, not conclusions, but beginnings."

- Sam Tanenhaus

5.1. Conclusions

In response to fierce market competition, the shipyards have to do everything they can to maintain their high production performance. For this reason, successful development and execution of an effective performance management strategy become one of the critical tasks in their business operation. To develop the best-suited management plan, the first step for the shipyard is to conduct the benchmarking assessment to obtain a full understanding of their specific situation. Therefore, the shipyard should employ a performance evaluation algorithm to provide such service, which is sufficiently comprehensive, effective and most importantly, fit for their business nature.

Motivated by such industrial demand, this research aimed at developing such algorithm to support the shipyards in developing their performance management strategy. The developed decision support tool named SPPM, aiming at providing support for shipyards to enhance their production performance management focusing on shipbuilding related activities. There are two main functional modules in SPPM. The first one can be applied to conduct the production performance evaluation, while Module 2 will provide budget optimisation for performance improvement planning based on Module 1 results and user preferences. Besides, the tool also provides the function that allows centralised performance data management. The unified data model allows users to establish a single database where they can quickly access consistent information related to performance data from various departments, and drill to details.

As introduced in Chapter 1, the objectives of this research have been envisaged to achieve through several tasks. In the following paragraphs, the work carried out in each task and outcomes is briefly summarised.

Task 1. Literature review and consultation

This task aimed s to develop the repository to provide the information that supports the development of SPPM. There have been various secondary databases, relevant publications, industrial best practices, codes and standards reviewed. The information included in the repository covers shipyard organisational structure, shipbuilding procedures and activities, the information and data related to each PPI and associated KPIs, and the theoretical models for assessment such as KPI approach, budget optimisation, MCDA, utility theory, and mathematical programming, etc. The review also included the emerging technologies or modern management strategies that shipyards can implement to improve their production performance in various aspects. In addition to the literature review, this task has also included consultation to the SMEs to obtain the practical information beyond the textbook knowledge, which helped to guide the direction of the research, to identify the key area where this research should pay more attention to, and to help in verification of the innovative models developed in this project. The reviewed literature and the abstracted information as well as the practical information collected from consultations have been listed and referred to throughout this thesis.

Task 2. Development of the performance evaluation model with the tool

The work to develop SPPM Module 1 was carried out in this task. The input to this task is the knowledge repository developed in Task 1. As the result, there have been 30 KPIs identified to measure the production performance from seven aspects, i.e. the PPI categories defined by SPPM. Based on the research, these aspects have a great impact on production performance. The detailed description of each KPI and PPI are provided in Chapter 3. To summarise:

- **Health and safety performance:** There have been 3 KPIs identified in this PPI category based on the review of the incidents survey and industrial practice of the OHS management. As observed from literature review and interviews at the shipyards, a safe and healthy workplace was rated by the majority of the shipyards as the priority to assure their production performance and sustainability. The impact and cost associated with consequences due to OHS accidents are enormous, which may include delay of the project delivery, loss of reputation, employee retention, and even regulatory fines and legal action, etc. The KPIs selected for this PPI mainly measures the efficiency and effectiveness of the OHS prevention and protective policies and procedures that the shipyard has been implemented, including the afterwards corrective actions. It also includes the direct incident risk assessment, which can be done using the RPN method or any industrial standard figure such as lost days of injuries.

- **Environmental performance:** There have been 4 KPIs identified in this PPI category based on the review of the environmental impact caused by shipbuilding activities. Climate change is a topic of global concern, and all walks of life are constantly striving to improve it. Whether it is part of corporate social responsibility or enforcement by the government or authorities, shipyards must pay attention to maintaining their performance in terms of environmental impact. The KPIs selected for this PPI is a list of life cycle impact categories that the shipbuilding industry is mainly concerned about, including GWP, POCP, ADP and DALYs

- **Economic performance:** There have been 2 KPIs identified in this PPI category. The KPIs selected for this PPI aims at evaluating the shipyard's productivity and the shipbuilding cost focusing on budget control. The productivity can be viewed as a comprehensive indicator of the shipyard's effectiveness of the resource utilisation, capacity and capital. The other KPI is to measure the efficiency of the project financial management which would include the accuracy in cost estimation and the ability in budget control.

- **Technical performance:** There have been 3 KPIs identified in this PPI category. Production performance from the technical perspective is the comprehensive manifestation of multiple aspects, including the advancement of production technology and equipment, the yard capability, the rationality of the plan and its execution, the workers' skill and experience level, as well as the effectiveness of production management strategy, etc. The KPIs selected for this PPI evaluate the performance by counting the delay of the project due to technical issues throughout the production life cycle stages. Based on the consultation and the review of researches in the relevant field, an FMEA type of assessment has been carried out to identify the cause and effect of the technical issues. As a result, several common technical issues which can cause the project delay has been identified and listed as recommendations, which can be customised.

- **Human resource performance:** There have been 8 KPIs identified in this PPI category based on the review of HRM requirements in the context of the shipbuilding industry. As a labour-intensive industry, having an effective HRM strategy is very important for maintaining a high level of efficiency and sustainability of the business. The KPIs selected for this PPI reviews the performance from multiple dimensions, including employee retention, employee quality, recruitment efficiency and disciplinary matters. The user could select some of the KPIs to include in their evaluation based on the specific purpose of the evaluation.

- **Security performance:** There have been 3 KPIs identified in this PPI category. Security management in the shipbuilding industry is similar to other manufacturing industries, aiming at developing and implementing effective prevention and protection strategies for the shipyard's tangible and intangible assets. Consequences from poor security management can be destructive, which can cause the loss of assets, business reputation and potential regulatory fines and legal action as well as the costs of remediation. The KPIs selected for this PPI are the indicators to assess the efficiency and effectiveness of the shipyard's security policy and procedures as well as the implementation.

- **Supply chain performance:** There have been 7 KPIs identified in this PPI category. In a shipyard, the scope of SCM normally includes inventory control and distribution of drawing, material, assemblies, machinery, equipment and labour. It plays a vital role to ensure the production to go on smoothly. The KPIs selected for this PPI are mainly focusing on assessing the efficiency and effectiveness of the SCM from schedule and quality control perspectives.

The overall evaluation procedure adopted by SPPM is explained in Chapter 2. For each KPI the direct value from measurement will be compared to the user-defined tolerance limit and the improvement target to obtain the normalised KPI value, named KPI rating. Then in each PPI category, aggregate the rating of the assigned KPIs to calculate the PPI rating which can be used for the following assessment. The ratings of all PPIs can be plotted using a spider chart to obtain an overview of the production performance. It can be also combined with user-defined importance levels and using a matrix to identify the hotspots for improvement. The potential improvement activities reviewed and included in the repository can be considered, with a specific focus on the proposed KPIs.

Task 3. Development of the budget optimisation models with the tool

The work to develop SPPM Module 2 was carried out in this task. The inputs to this task are the knowledge repository developed in Task 1 and the evaluated PPI rating from Module 1. The motivation of this task is to support shipyards in optimising future improvement. The improvement planning is not only to select the suitable emerging technology but also to determine the capital investment required for such activities. As the observation from the literature review of the general practice, the budget optimisation needs to be designed for two scenarios. For the first scenario where no limit on the total available fund, the question to be answered is how much investment would be required for the improvement. For the other scenario where the total available fund is restricted, the algorithm will suggest how to allocate the limited fund among different PPIs to maximise the overall benefit. The detailed procedure is introduced in Chapter 4.

The budget optimisation model finalised for the first scenario is the adapted PBB approach. This model supports the principle of SPPM that builds the linkages between performance improvement and activities to be carried out. It is a model that combines planning and budgeting, which enables the user to not only optimise the budget but also identify the most efficient and cost-effective activity plan for performance improvement. Based on the performance evaluation from Module 1, the improvement activity can be planned with more attention on the KPIs (or PPIs) with a lower rating and more important for the user, i.e. the identified hotspots. When there are alternative routes of improvement, the MCDA model embedded in the algorithm can be applied to compare the effectiveness of each alternative.

In the scenario when the total available fund is restricted, the aim of the assessment becomes budget allocation optimisation, which can be viewed as the reverse of PBB. The budget allocated to each PPI is determined first in this assessment, then the shipyard can plan for the activities accordingly. Such optimisation can be done using several mathematical models and the finalised ones employed by SPPM are AHP, utility theory and LP. Each of them is based on a different principle:

- **AHP**: The objective in this decision context is to rank the seven PPIs in SPPM using their priority vectors and then convert this rank to the budget allocation.

- **Utility theory:** The target of utility-based BAO is to achieve utility maximisation via optimising the distribution of spending on improving the PPI ratings for each PPI category subject to a given budget constraint.
- **LP**: Considering the variables as the budget allocated to each PPI category, the optimisation target in this LP problem is to identify the variables that maximise the total increment of the PPI ratings.

The outputs from all three models are the same, i.e. the optimised allocation of the capital investment to each PPI category and the corresponded PPI increment. However, because of the difference in the optimisation objective, the exact value will be different. It would be the user's choice on what is their preferred optimisation target and the data availability. A more detailed discussion on this can be found in Chapter 2.

Task 4. Verification of the algorithm

The verification is mainly based on the review of two aspects – the quality and reliability of the data and theory used in this project; and the applicability and feasibility of the developed model in practice. Firstly, as mentioned above, there has been a repository of references, data and knowledge obtained in this research project and included in the thesis. This has supported the development of SPPM, which is the cornerstone of the model, and has ensured that the algorithm is well-founded. There has been a review performed regarding the quality of the references. For the credibility of this research, the specific effort has been made to ensure all critical steps and arguments are supported by references from trustable sources. In addition, during the model development, there have been numerous iterative discussions with various shipyards to ensure the feasibility of the model and to confirm the input data availability for using the model.

Task 5. Demonstrative case study

The research has also included a demonstrative case study. The primary purpose of this case study is to demonstrate the complete process of using SPPM to support shipyard production performance management, from input data collection to results interpretation. It was also expected through this demonstration, the applicability and feasibility of the developed algorithm can be enhanced. Most inputs to the case design were from discussion with the collaborative shipyards. This process can be viewed as a platform to directly work with shipyards to understand the availability of input data, where to find them and who is responsible for such information, etc. Besides, this has also provided opportunities to discuss with shipyards the difficulties or additional work required if they would like to incorporate SPPM into their performance management strategy. In short, this activity helps to improve the adaptability of theoretical models to industrial reality. As a result of this task, the complete assessment process of SPPM has been demonstrated via a case study that simulates the actual situation of the shipyard to the greatest extent possible.

It is believed that the objectives proposed in Chapter 1 have been achieved by accomplish of the above tasks. Firstly, a knowledge repository providing theoretical support to SPPM has been developed including secondary database, key factors influencing performance, activities that can potentially improve the performance, mathematical formulas, theoretical models, and information related to shipbuilding activities or shipyard organisation structures, etc. Most of these information has been applied or explained in this thesis. The rest have also been briefly mentioned and listed as references. Secondly, based on the detailed SPPM functionality description in Chapter 3, the SPPM is able to carry out assessment for shipyard production performance benchmarking and provide support in plan for the budget for future improvement. The demonstrative case study performed in Chapter 4 has successfully demonstrated the most calculation procedures implemented in SPPM, which has obtained the positive feedbacks from potential users and SMEs regarding the model applicability and capability.

As discussed in Chapter 3, the model has several limitations at this stage which requires further researches. To highlight, the limitations are mainly related to the assumptions applied in the algorithm such as the estimation of MC or some of the KPI evaluation models. Such assumptions may require engineering judgement which may introduce a degree of subjectivity. The accuracy of these assumptions can be improved if more data (in terms of both quantity and variety) can be made available when making such assumptions. More details about the future works are proposed in the next section.

In summary, the ultimate expectation for this research is the willingness of shipyards to implement SPPM or its concept into their performance management strategy. To achieve this target, future works, such as in-depth cooperation with more different shipyards, tracking and analysing long-term data, and more forward-looking researches, have been proposed.

5.2. Future works

Although this PhD project has been concluded at this stage, there are still several ideas which can be put forward as future works beyond the current scope, which can continue to enhance the research outcomes. The limitations about the developed models have been discussed in Chapter 3 and Chapter 4, according to which, the following potential future works are proposed.

Firstly, as mentioned in Section 4.2.1, due to the data availability, the developed model was only able to be partially validated. Therefore it is believed that the research and development will be benefited from a long-term in-depth cooperation to be continued with shipyards on this topic. On one hand, this can help to obtain more confidential data from shipyards to validate the applicability of the model and improve the model usefulness with more customised features. On the other hand, long-term collaboration can provide opportunities to conduct the study regarding the effectiveness of the algorithm through comparing the shipyard production performance before and after implementing the SPPM concept, which was not able to carry out in the current research. Access to the historical performance data from shipyard can also help to identify the suitable tolerance and target KPI values hence enhancing the accuracy of the assessment. As per the discussion in Section 3.3.3, defining the accurate marginal cost is a challenge to the practicality when using the MP and utility theory based BAO models. It is envisaged that with more practical case studies to be carried out to validate the model, it is also expected that this can help in formulating the function to calculate marginal cost especially for the interrelated KPIs. Incorporating an accurate cost database regarding the improvement activities can improve the efficiency and practicality for future planning, as well as its acceptability to the potential users.

Secondly, the current research has been mainly supported by the small and medium sized shipyards in the Europe, and some of the features in the model are more likely to be suitable for their daily operation. Therefore, it will help to enrich the model capability if there could be opportunities to work with more distinct types of the shipyards worldwide, so that the customised algorithm can be developed based on shipyard's unique characteristics. For example, large shipyards may have more variety of the shipbuilding projects and more complicated organisation chart, which may introduce more KPIs (or PPIs) or change the calculating methods of the current KPIs. They may also have more considerations with regard to company's CSR requirements and the management strategy may also differ from one shipyard to another.

In addition, the model has been developed based on the study of the current status of shipyard production activities. However, with development of emerging technologies to assist the production, the mode of production at the shipyard could evolve. This means their production performance could be managed and measured in different way. For example, the use of digital platform and robotics may improve the OHS and technical performance, but requires more concerns about the cyber security, results in more specific KPIs regarding to the security performance. In some cases, the some KPIs may need to be replaced entirely. For instance, change of production mode may also effect the HR management as the requirements of population and skill-set for the employees at the shipyard will be different. Although the framework of SPPM is still applicable, considering the future development of the shipbuilding industry, it would be beneficial to carry out some forward-looking studies.

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Appendix A

List of KPIs values and PI data collection template

$PPI_{H\&S}$: Health and safety performance evaluation			
KPI	**Description**	**Calculation**	**PIs required**
$KPI_1^{H\&S}$	Risk assessment of incidents	Equation 3-1	- Number of injury during performing each production activity - Loss of work days due to injury - Duration of the production activity
$KPI_2^{H\&S}$	Average number of deficiency regarding implementation of safety measures identified during inspection annually	Direct record	- Number of deficiency regarding implementation of safety measures identified by each inspection - Number of inspections annually
$KPI_3^{H\&S}$	Average number of deficiency regarding implementation of afterwards corrective actions identified during inspection annually	Direct record	- Number of deficiency regarding implementation of afterwards corrective actions identified by each inspection - Number of inspections annually
PPI_{ec}: Economic performance evaluation			
KPI_1^{ec}	Budget control	Equation 3-2	- Actual cost of the construction - The estimated cost of the construction
KPI_2^{ec}	Productivity	Input / CGT	- CGT - Input to the ship production
PPI_{env}: Environmental performance evaluation			
KPI_1^{env}	Global warming potential (GWP, kg-CO2 equivalent)	LCA	- Production material and energy consumption data
KPI_2^{env}	Photochemical oxidant creation potential (POCP)	LCA	- Production material and energy consumption data
KPI_3^{env}	Resource depletion or Abiotic depletion (ADP)	LCA	- Production material and energy consumption data
KPI_4^{env}	Disability Adjusted Life Years (DALYs)	LCA	- Production material and energy consumption data
PPI_{tech}: Technical performance evaluation			
KPI_1^{tech}	Delay (days) during design, model test, planning process	Direct record	Days of delay due to - Revised design because of equipment size - Revised design from owner and Classification

			- New technology transfer problem - Revised design due to issue of integration
KPI_2^{tech}	Delay (days) during procurement	Direct record	Days of delay due to - Customs clearance of material or equipment in port - Delay of material in shipbuilding - Delay of purchase order
KPI_3^{tech}	Delay (days) during construction process	Direct record	Days of delay due to - Worker performance - Inappropriate plan, such as dock busy with other business - Sub-contractor performance - Mistakes of production; re-work or additional work due to poor quality of delivery - Instruction not responsible - Revised production request from owner and classifications
PPI_{HR}: Human resource performance evaluation			
KPI_1^{HR}	Overall retention rate ($R_{retention}$)	Equation 3-6	- The total number of employees - The number who have left within assessment period
KPI_2^{HR}	Involuntary turnover rate (R_{IT})	Equation 3-7	- The total number of employees - Number of involuntary leavers
KPI_3^{HR}	Average length of employment (T_E)	Equation 3-8	- The total number of employees - Total number of years of employment for all employees
KPI_4^{HR}	Turnover rate considering star employees (R_{TS})	Equation 3-9	- The total number of employees - The number who have left within assessment period - The number of the top employees left within assessment period
KPI_5^{HR}	Employee quality (R_{EQ})	Equation 3-10	- The total number of employees - The number of qualified and experienced workers
KPI_6^{HR}	Time to hire (T_H)	Equation 3-11	- Date of Hire - Date Candidate Enters ATS
KPI_7^{HR}	Quality of hire (Q_H)	Equation 3-12	- The total number of new comers - The number of new hires who passed their appraisal after probation

KPI_8^{HR}	Disciplinary matters (DM)	Equation 3-13	- Total number of disciplinary violations - Predefined monitoring period
PPI_{sec}: Security management performance evaluation			
KPI_1^{sec}	Number of incidents during assessment period (including incidents regarding people, physical assets and Cyber security)	Direct record	- Number of incidents during assessment period (including incidents regarding people, physical assets and Cyber security)
KPI_2^{sec}	Number of deficiency regarding security policies and procedures and its implementation (for purpose of both prevention and remediation) identified during inspections/ audits	Direct record	- Number of deficiency regarding security policies and procedures and its implementation (for purpose of both prevention and remediation) identified during inspections/ audits
KPI_3^{sec}	Number of deficiency regarding security equipment (for purpose of both prevention and remediation) identified during inspections/ audits	Direct record	- Number of deficiency regarding security equipment (for purpose of both prevention and remediation) identified during inspections/ audits
PPI_{sup}: Supply chain management performance evaluation			
KPI_1^{sup}	Reliability of drawing delivery	Equation 3-14	- The total days between actual release of drawing and the planned date of release - The number of drawings delivered within the assessment period
KPI_2^{sup}	Quality of drawings	Equation 3-15	- Number of drawings containing mistakes that requires supplier for modification within the assessment period - The number of drawings delivered within the assessment period
KPI_3^{sup}	Reliability of supplier delivery	Equation 3-16	- Total days between actual delivery date from purchase order and the promised date of delivery - The number of order lines within assessment period
KPI_4^{sup}	Incorrectness of supplier	Equation 3-17	- The number of order lines which contains faults
KPI_5^{sup}	Quality of supplier	Equation 3-18	- The number of order lines containing broken parts

KPI_6^{sup}	Quality of the subcontractors	Equation 3-19	- The total days of delay due to fault from subcontractors within the assessment period
KPI_7^{sup}	Delivery reliability at yard	Equation 3-20	- The total days between actual arrival date at yard and planned arrival date. - The number of order lines within assessment period

Appendix B

Sample questionnaire for collecting **PI** data for case study from shipyard

Name	Anonymous	Position	N/A		
Shipyard	Anonymous Shipyard	Country	Denmark	Date	Mar 2021

Health and Safety			
Number of injury per month during grinding, converted to rank of P in RPN table	1	Loss of work days during mounting, converted to rank of S in RPN table	3
Loss of work days during grinding, converted to rank of S in RPN table	3	Duration of mounting, converted to rank of T in RPN table	5
Duration of grinding, converted to rank of T in RPN table	5	Number of injury per month during crane movement, converted to rank of P in RPN table	1
Number of injury per month during welding, converted to rank of P in RPN table	2	Loss of work days during crane movement, converted to rank of S in RPN table	2
Loss of work days during welding, converted to rank of S in RPN table	2	Duration of crane movement, converted to rank of T in RPN table	2
Duration of welding, converted to rank of T in RPN table	10	Number of injury per month during worker material handling , converted to rank of P in RPN table	2
Number of injury per month during cutting, converted to rank of P in RPN table	1	Loss of work days during worker material handling , converted to rank of S in RPN table	3
Loss of work days during cutting, converted to rank of S in RPN table	2	Duration of worker material handling , converted to rank of T in RPN table	3
Duration of cutting, converted to rank of T in RPN table	5	Number of deficiency regarding implementation of safety measures identified by each inspection	30
Number of injury per month during mounting, converted to rank of P in RPN table	2	Number of inspections annually	12
Number of deficiency regarding implementation of afterwards corrective actions identified by each inspection	10		

Economic			
Estimated cost of ship construction, £m	4.5	Number of employees involved in production activities	40
Actual spent, £m	4.4	CGT	8840

Environmental			
Steel	800t	Superstructure coating (anticorrosive coating (high solids epoxy coating (epoxy polyamides or a good surface-tolerant epoxy)	9600m2
Glass wool for insulation	50t	Superstructure paints (Superstructures Red lead or zinc chromate based primers)	9600m2
Deck (teak)	100t	Steel wastage	20% (90% recycle)
Electric welding 5mm	1000m	Surface treatment wastage	5% (100% landfill)
Electric welding 2mm	600m	Deck paints and Coats (Zinc primer, high solids epoxy coating, polyurethane topcoat or glass-fibre reinforced epoxy)	2175m2
Energy used for production	37003.8GJ		

Technical			
Total days of delay due to revised design because of equipment size	0	Total days of delay due to customs clearance of material or equipment in port	7
Total days of delay due to revised design from owner and Classification	0	Total days of delay due to delay of material in shipbuilding	10
Total days of delay due to new technology transfer problem	0	Total days of delay due to delay of purchase order	5

Number of revised design because of equipment size	25	Number of delay of customs clearance of material or equipment in port	3
Number of revised design from owner and Classification	20	Number of delay of material in shipbuilding	12
Number of new technology transfer problem	0	Number of delay of purchase order	5
Total days of delay due to worker performance	0	Number of delay due to worker performance	0
Total days of delay due to sub-contractor performance	0	Number of delay due to sub-contractor performance	0
Total days of delay due to mistakes of design	0	Number of mistakes of design	10
Total days of delay due to instruction not responsibility	0	Number of delay due to instruction not responsibility	12
Total days of delay due to revised production request from owner and classifications	0	Number of delay revised production request from owner and classifications	15

Human Resource			
Number of disciplinary issues per year	1	Number of unavoidable termination	2
Number of employees under training	6	Number of beneficial termination	1

Number of qualified employees providing training	15	Number of employees qualified with (specific qualification that shipyard requires)	6
Number of employees	24	Number of employees before the assessment period	28
Number of employees terminated for whatever reasons	4		

Security			
Number of incidents during assessment period	3	Number of deficiency regarding security equipment	5
Number of deficiency regarding security policies and procedures and its implementation	2		

Supply chain			
Total days between actual release of drawing and the planned date of release	0	Number of order lines containing faults	25
Number of drawings delivered	150	Number of order lines containing broken parts	10
Number of drawings containing mistakes that requires supplier for modification	3	Number of order lines containing missing parts	10
Total days between actual delivery date from purchase order and the promised date of delivery	25	Total days between actual arrival date at yard and planned arrival date	25
Number of order lines	1750	Days of delay due to fault from subcontractor	10