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A modelling approach for maintenance resource-provisioning policies

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A Modelling Approach for Maintenance Resource-Provisioning Policies

By

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THESIS CERTIFICATION

I, Winda Nur Cahyo, declare that this thesis, submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for any qualification at any other academic institution.

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Winda Nur Cahyo

August, 2015

THESIS DEDICATION

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This thesis is dedicated to my lovely wife: Hayin, our great son: Akhtar

and

also to our parents.

ABSTRACT

A study has been undertaken to understand the capability of system dynamics modelling in simulating interrelationships between maintenance and the resource provisioning policy. A review of the literature indicates that such an approach to resource provisioning policy selection considering the characteristics of maintenance and considering life cycle cost is both absent and would be of benefit.

The development of a system dynamics approach integrated with life cycle costing algorithms has been pursued. The results have been tested on 3 case studies to determine the suitability and accuracy of a new combined system dynamics simulation and the life cycle cost model.

It has been found that the integration of system dynamics simulation into a life cycle cost model provides a suitable modelling approach for maintenance resource-provisioning for complex engineered assets. Provisioning of resources that include human resources; spare parts and tools; and consumable materials can be adequately modelled. This modelling approach results in an estimate of the impact of a proposed provisioning policy on maintenance and asset performance. System dynamics simulation modelling can model the scenarios for all possible alternative resource provisioning policies. The development of sub model for: the maintenance program; purchasing and the inventory program; and human resource provisioning program, proved possible and useful.

A new life cycle cost analytical model has been developed and its compatibility and integration with system dynamics for modelling interrelationships between maintenance and its resource provisioning has been verified. The formula of the new life cycle cost model has been restructured from a currently available model. It utilises additional cost elements and accommodates financial factors: inflation and interest rates, for all cost elements. The case studies indicate that the newly developed models are valid and capable of studying alternative provisioning policies. The general form of the new combined models is made flexible for tailoring to different cases and was easily tailored in each of the three case studies.

It is concluded that the combination of system dynamic simulation with a life cycle cost model is capable of overcoming the modelling complexity associated with interrelated maintenance programs typically required for engineered assets in a

complex technical system. It is a suitable modelling approach for providing an integrated decision support model for maintenance resource-provisioning management.

Although the research explored the capability of a newly integrated model of system dynamics simulation and analytical life cycle cost modelling, there are some limitations that can be covered by further research. The limitations are related to the number of maintenance resources covered and the number and variety of case studies covered.

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DEFINITION OF TERMS

Term		Definition
Acquisition cost	:	Cost to acquire a certain number of units, and includes operating and redundancy units.
Asset Uptime	:	The accumulation time of the asset while operating without interruption.
Assets Failure	:	The number of asset failures which happen in the system.
Engineered Asset	:	An asset that may take the form of physical infrastructure, plant, machinery, property, building, [vehicles and] other (non-consumable) item[s] and related systems (both hardware and software) that have a distinct and quantifiable business function [or service].
Expected demand	:	The estimated number of resources (part or other resource) as calculated and forecast from past and future maintenance activities.
Inventory policy	:	This is a guideline for making decisions related with inventory level. In this research, inventory policy determines both the level of safety-stock, and desired inventory level.
Order quantity	:	The amount of part, consumable material and other resources which are ordered from suppliers.
Outsourcing	:	Total man-hours added as a result of outsourcing

policies.

Overtime	:	Total man-hours added as a result of overtime policies.
Policy	:	A course or principle of action endorse by an organisation or individual.
Purchasing policy	:	The consideration for selecting suppliers to supply a number/ amount of maintenance resources based on price, quality and lead-time. In this research, this policy includes the order quantity in every purchase.
Simulation days	:	A period of time in the simulation that represent one day in the real world.
Technical Systems	:	Man-made artefacts that are used to fulfil certain purposes or factions or operation.

1 INTRODUCTION

1.1 Statement of Purpose

This research is concerned with the management of the maintenance resource-provisioning process, and maintenance provisioning, associated with complex systems of engineered, or physical, assets that reside within an overall system. The objective of this process is to optimise the performance of these assets. The methods for modelling this problem are to be explored. Although methods of managing maintenance exist, it is thought that integrating system dynamic modelling into a life cycle cost model may provide improved results.

1.2 Engineered Assets and Complex Technical Systems

Maintenance is an important function in industry and has been a mainstream research focus in engineering asset management. In general, analysis and optimisation of the maintenance system can improve the system productivity (Khalili et al., 2015). Most of the research focus has been on optimisation, efficiency and effectiveness of maintenance (Iyoob et al., 2006). There has been a broad range of modelling to enhance maintenance and achieve optimisation.

Maintenance provisioning has an important role in realising successful maintenance programs for organisations. The range of policies in maintenance resource-provisioning is related to the maintenance programs directed at the engineered assets that are used by an organisation. Fundamental is the concept that the ownership and utilisation of those assets by an organisation involves a system of asset-related infrastructure and resources, where this system is defined as: "…a composite of people, products, and processes that provide a capability to satisfy stated needs. A complete system includes the facilities, equipment (hardware and software), material, services, data, skilled personnel, and techniques required to achieve, provide, and sustain system effectiveness" (U.S. Department of Defence (1991)).

According to British Standard Institution, engineered assets may take the form of physical infrastructure, plant, machinery, property, building, [vehicles and] other (non-consumable) item[s] and related items (both hardware and software) that have a distinct and quantifiable business function [or service]. Therefore, engineered assets

may be considered to exist within a hierarchy of the technical system where each can be further broken down into units or components.

The complexity of the technical system depends on the number and complexity of engineered assets that comprise that system, and the number and nature of technology of units within each asset. The more complex the technical system, then the more difficult it becomes to manage the associated maintenance resources.

To preserve the overall performance of the technical system, each unit within each engineered asset needs to be maintained effectively. This requires the use of maintenance programs that are specific to particular units.

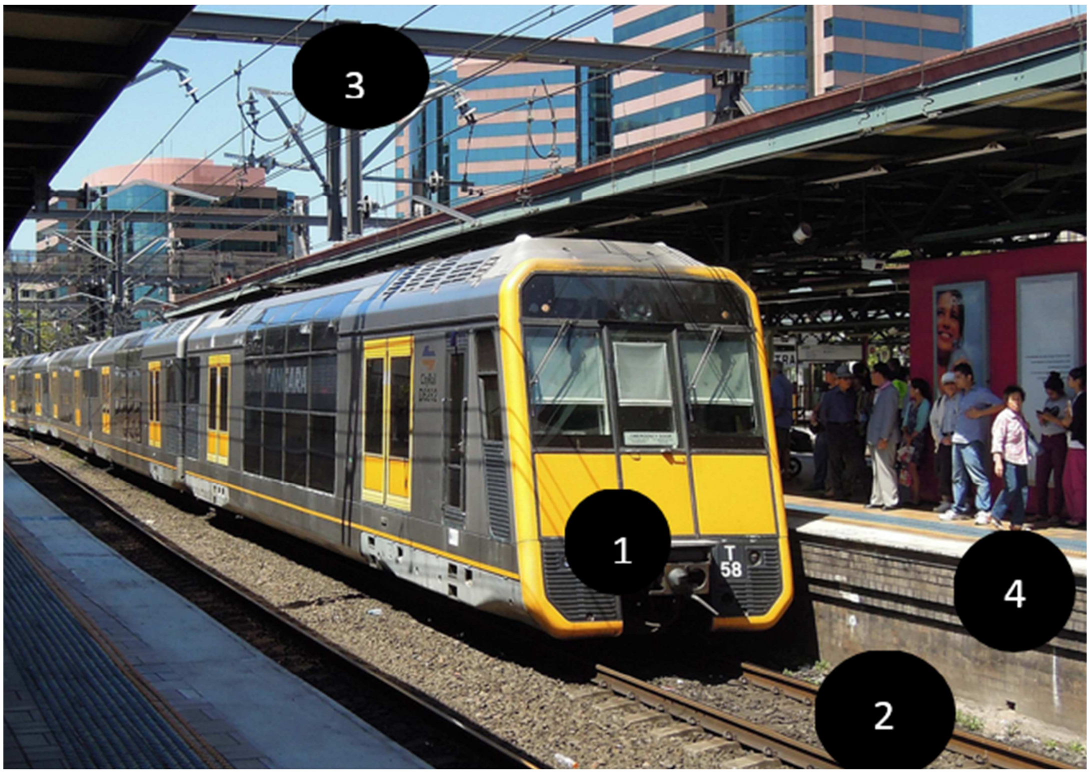


Figure 1-1: Example of a Complex Set of Engineered Assets
(https://www.flickr.com/photos/johncowper/8353215948)

Figure 1-1 shows as an example of a complex technical system: a train-based transportation system. It is composed of several types of complex engineered assets: train (1) the permanent way (2) the energy supply system (3), and the station (4). As stated in ISO 5500 (2014): Asset management – overview, principles and terminology, interactions of a set of assets generate a functioning system. Based on this railway system configuration, any faulty asset can interrupt the whole system.

For instance, any delay in providing maintenance resources for repairing a fault in the overhead wire causes delays in the train service. It is expected that a complex maintenance program is required to ensure that all units within assets are scheduled and repaired on time for the transportation system to achieve its purpose.

Another example of a complex technical system is a so-called wind farm. One wind farm may consist of hundreds of wind turbines. As shown in Figure 1-2, one wind turbine may itself be considered to be a complex engineered asset comprising several units including the: rotor blade, gearbox, generator, power cable, tower, and transformer: a set of identical convertors. Similar to the previous example, a faulty unit in a wind turbine will interrupt the wind turbine electrical power generation to the switchyard (grid). However this tends to reduce the output of the facility as opposed to halting the service as is the case for a train service.

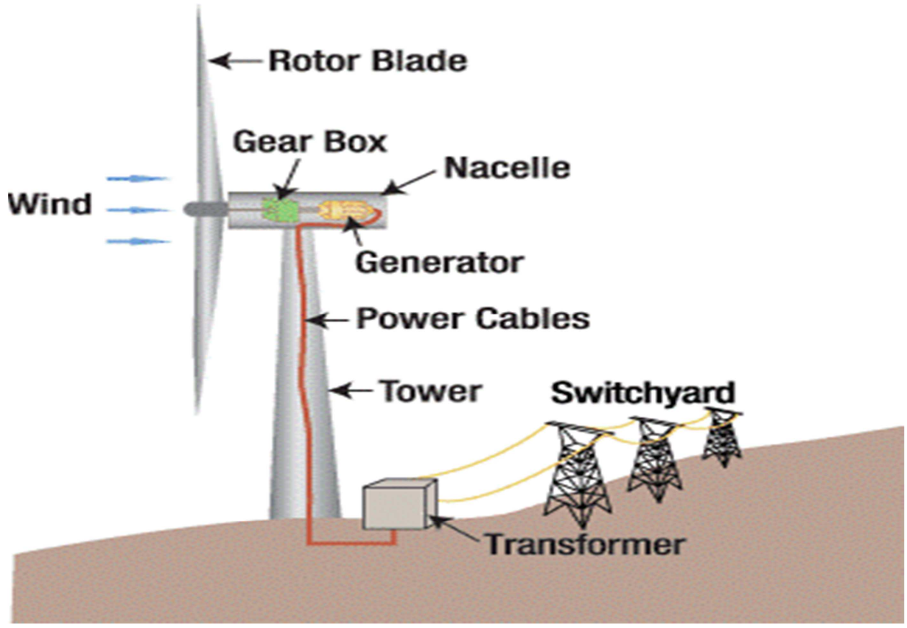


Figure 1-2: Wind Turbine as an Assets System
(http://www.michellehenry.fr/windfarm.htm)

To ensure the effectiveness of maintenance programs for engineered assets, one of the key issues is maintenance provisioning (Iyoob et al., 2006). The types of resources to be provisioned are numerous and include: personnel, materials, financial, spare parts, tools, data and time (Wang, 2011, Iyoob et al., 2006, Bruggeman and Van Dierdonck, 1985). Hence, maintenance resource-provisioning for complex technical systems is concerned with the process of providing maintenance resources to support an effective maintenance program. It deals with decisions to optimise the level of providing human resources, materials, spare parts,

tools and their allocation in a particular period of time, in order to achieve the targeted performance of the complex technical system.

A suitable model of this provisioning process would provide a basis for obtaining an optimum policy. Such a model would be most useful for complex systems. Such a modelling approach needs to be adaptable to different situations and asset types and configurations: e.g. a diverse set of engineered assets, as in the case of a rail system: or, a fleet of identical assets, as in the case of a wind farm.

1.3 Management of resource provisioning

The management of maintenance resources plays an important role in achieving asset performance and in supporting utilisation of physically engineered assets in an organisation. It is involved with matching available and required resources. It comprises management of all resources: human resources; spare parts and tools and consumable materials. An incorrect decision leading to a shortage of required maintenance resource to support maintenance tasks may result in an ineffective maintenance process (Wang, 2011). Similarly, an excess of maintenance resources constitutes an inefficient use of funds. Making policy or a decision in maintenance to attain the required asset performance is affected by the number of available resources. Conversely, uncertainty related to the need for resources driven by the uncertainty of failure events and their timing results in a complex process of requirement assessment.

From an integrated system perspective, there are some causal relationships between asset effectiveness and the associated maintenance policy and resource provisioning. This structure of causal impact in asset management constructs a complex environment for the decision maker to make an appropriate decision in order to maintain or improve the assets' performance (Tam and Price, 2008, Vanier, 2001, Dwight et al., 2011, El-Akruti and Dwight, 2013b). From a modelling perspective, the environment can impose complex factors on the decision making process in Asset management.

1.4 Asset Management, Maintenance Management and Life Cycle Cost Models

Asset management is concerned with how organisations manage their physical assets through their life cycle (El-Akruti, 2012). In this respect, the AM Council (Asset Management Council (2009)) defined asset management as: "The life cycle management of physical assets to achieve the stated outputs of the enterprise". This definition highlights that asset management is concerned with life cycle management which involves the life cycle activities at different stages. Those stages may be labelled: the development and acquisition stage; operation and maintenance stage; and the disposal stage. The AM system may subsequently be defined as: “The system that plans and controls asset-related activities and their relationships directed at ensuring the achievement of the asset performance that meets the requirement of the intended competitive strategy of the organisation.” (El-Akruti, 2012). This definition highlights the central role of asset management in controlling the maintenance activity as one of the life cycle activities.

Although choosing the right assets, monitoring their use, and balancing short-term performance against long-term sustainability during early stages is important, the operation and maintenance stage often deserves additional attention since it is the longest life stage and the most complex in terms planning and controlling (Quertani et al., 2008, El-Akruti, 2012). Therefore, these definitions highlight the link between and the impact of the planning and control of maintenance programs on the overall performance. The potential impact of maintenance on the accomplishment of the overall performance to meet the organisation objectives is usually hidden but recently has been explored in literature (Muchiri and Pintelon, 2007, Pinjala et al., 2006, El-Akruti, 2012).

Typically, every technical system is a set of engineered assets which have to be managed during their useful life to optimise their performance. Since maintenance resource-provisioning directly impacts maintenance management and maintenance is one of the life cycle activities, certainly both have a significant role in determining the overall performance. Optimising the overall performance throughout the life cycles of the various assets requires the use of life cycle cost (LCC) analysis and models for such performance optimisation (Blanchard and Fabrycky, 2011, Dwight, 1999, Dhillon, 2010, El-Akruti et al., 2013). There is no general LCC model that fits all but there are different modelling approaches and formulation models for the

purpose of LCC analysis which is usually influenced by different factors, such as the nature of the assets, the environment, the industry and the associated risk and safety issues. Generally, a LCC model will account for all cost elements occurring in all stages of the asset life. Ebeling (2010) , amongst others, has developed a LCC model that is a maintenance oriented model in the sense that it takes account of detailed formulation of most maintenance variables. In this sense, Ebeling's model provides the ability to involve all possible maintenance variables and allows for changing any of these variables to see the impact on the resulting LCC. For example, applying different maintenance policies will generate different maintenance costs and different asset performance. For instance, applying decentralised rather than centralised maintenance, or applying condition-based rather than periodic repair on certain assets may increase the maintenance cost but it may decrease the LCC due to extending the life of the asset, and may improve the performance by increasing asset availability. In this example, decentralised maintenance may be designated by increasing human resources and therefore using the LCC model can serve in determining the impact that maintenance resource-provisioning has on determining overall performance.

1.5 Current Approaches to Modelling Maintenance Provisioning

The development of a policy for maintenance provisioning is dependent on the use and available capacity of maintenance resources. If the status of the maintenance system at an instance is represented in terms of variables related to resources, capacities or facilities then those variables will construct a state of the maintenance system at that particular instance (Bank et al., 2005).

Maintenance policies provide lead control of the variables of a maintenance system and determine how the state of the maintenance system changes. To make a good decision in a complex maintenance system, it is important to observe the feedback of a policy of one unit to the others and the effects on the overall performance. Based on this consideration, it is necessary to have a good structure in terms of a model of the maintenance system that can be used to analyse the important relationships and their impacts among units and draw the system state over time. The model must also be able to explain the feed-back or consequences of a specific implemented maintenance policy on the whole technical system performance. Such a model should represent the dynamics associated with the complexity of the system

structure and the relationships among its units, and the feedback between them over time. Law and Kelton (2000) define a dynamic model as a model that embodies a system as it changes over time. The model sought for this research should be a model that adequately represents the change of the system state over time.

The model that represents such a system must be capable of representing dynamic behaviour and must be able to draw and explain the consequences of particular policies on the whole system. In order to have a complete understanding of the dynamic phenomenon associated with a complex technical system comprising multiple assets and multiple units within these assets. Each unit must be represented as an entity that interacts with the entities of the larger system. Reducing the model complexity, by dividing the total system into separate units, requires the understanding of the interrelationships between units and how the resources of the whole maintenance system are synthesised. Treating each unit as an interconnected entity can be done by evaluating the important relationship to the variable being observed and understanding the feedback structure among units or between any unit and parts of the system's environment (Jokinen et al., 2011). For analysing this type of system Jokinen, et al. (2011) utilised dynamic modelling.

Currently proposed models, typically analytical models, are usually theoretically sound but the complexity of systems required to be modelled makes them impractical in many cases. The failure of a mathematical model to capture the system complexity is evident even in systems with a limited number of units Iyoob et al. (2006). However, in the case of complex systems with multiple units mathematical modelling is difficult and requires a significant number of assumptions and it may not capture the aspect of interest in the system behaviour (Altiok and Melamed, 2007).

As an alternative, a system dynamics modelling approach may provide a solution. Xiaohu, et al. (2007) also point out that continuous approximation combined with dynamic modelling may be used to address some discrete events (e.g. sudden failure) or continuous events (e.g. system degradation) through observing changes in the system parameters of a maintenance system. This idea is also supported by Castanier, et al.(2005), who state that dynamic model is able to represent a system whose dynamic decisions may change over the period of planning.

The application of system dynamics to maintenance modelling is relatively rare compared to the use of other mathematical models. Bivona and Montemaggiore (2010) observe the relationships between maintenance and other departments: Financial; Human Resources; and, Asset Management, in a city bus company. This research focuses on supporting management in assessing different maintenance provisioning strategies in view of financial and customer satisfaction requirements. Unlike Bivona and Montemaggiore (2010), system dynamic modelling is extended to integrate with a life cycle model to handle the complex behaviour of engineered assets in technical systems.

Basically, in this research 2 models will be developed: a system dynamics model and a LCC analytical model. The system dynamics model is used to represent the particular characteristics and behaviour with different scenarios as alternative approaches to maintenance resource-provisioning, and the LCC model is developed to set decision criteria and parameters to optimize the overall system performance. It is argued that a combination of system dynamics and LCC models can enable a thorough investigation on the effect of different sets of maintenance programs and their resource provisioning policies on the overall system performance.

1.6 Problem Statement

A modelling method for maintenance resources provisioning management to optimise performance of engineered assets in complex technical systems is sought. It is proposed that the capability of system dynamic modelling for handling resource provisioning in asset management is not fully exploited and the integration of system dynamic modelling with a life cycle model is a suitable modelling approach to support decision making for maintenance resource-provisioning management.

The problem is concerned with handling the maintenance resource-provisioning for a set of interrelated maintenance programs for all units that make up the engineered assets in a complex technical system. In a complex technical asset, it is assumed that integrated maintenance programs are synthesized from the maintenance programs of each unit along with the required resource provisioning management. In this manner, all required resources are accumulated into total resources required for the whole technical system as a part of integrated maintenance planning. The required amount of resources as a result of maintenance resource planning has to be

compared with the available maintenance resource. This process is similar to the aggregate planning process in the manufacturing industry.

The problem involves defining ways to optimise maintenance resource-provisioning in order to achieve certain performance of the technical system that improves utilization to fulfil the business needs. In more detail, the problem involves identifying alternative resource provisioning methods in integration with maintenance programs and plans for improving the overall availability and reliability of the system.

The research question may be stated as: Is the combination of system dynamic modelling in integration with a life cycle model suitable as a modelling approach to support decision making for maintenance resource-provisioning management? In particular, how to develop this combination of system dynamic modelling with a LCC model as an approach to help establish a resource maintenance provision management policy for a complex system of engineered assets to optimize or improve the overall technical system performance?

In order to establish a suitable policy, appropriate modelling techniques are required. The time horizon of the policy must be considered in the modelling process. The modelling techniques must be able to capture the dynamic of the system to describe the effect or feedback of the maintenance policy for each unit to the overall technical system.

1.7 Research Objectives and Approach

The primary objective of this research is to provide modelling methods to help make decisions for optimising maintenance provisioning. This will be examined in the context of engineered assets within a complex technical system. For such systems, the objective is to provide a policy to improve the efficiency of maintenance resource-provisioning and achieve the target level of asset performance.

In order to achieve this objective, there is a need to define and develop the required models for optimising resource provisioning. Such models are required to help identify the optimum criteria for the suitable policy to improve the efficiency of maintenance resource-provisioning leading to achieve the target level of asset performance. System dynamics modelling provides the possibility to generate several alternative scenarios upon which compatible alternative resource provisioning

policies can be developed and explored. Each scenario represents a different provisioning policy that manipulates and balances resource requirements and availability, and integrates human resource, inventory and purchasing actions. The best scenario may then be selected based on criteria such as efficiency, effectiveness and cost.

In the early state of the system dynamics simulation process, several preliminary scenarios will be generated. Each scenario represents a distinct combination of several input variables. All generated scenarios will be applied to the system dynamics model to generate values for the simulation output variables. Then, all values are input into the life cycle model to determine the best scenario.

Furthermore, a statistical analysis is to be carried out to verify the generated results and find what input variables have significant impact to the optimisation of the maintenance resource-provisioning policy.

1.8 Method

A system dynamics model will be constructed with the aim of supporting management to determine the optimum policy for maintenance resource-provisioning for a multi-unit complex system. This will be tested using case studies by comparing several scenarios based on a developed LCC model. Each scenario represents a different maintenance resourcing policy. The best scenario is selected based on the optimum LCC. To serve this purpose, the suitable LCC model is then developed and adjusted as necessary with the simulation output. The LCC model developed will be utilised for the purpose of determining the optimum scenario. This leads to testing of the second hypothesis that the developed LCC model integrated with system dynamic simulation is capable of supporting the selection of the optimum scenario. The combination of both models provides a method to support decision making on maintenance resource-provisioning for a complex asset maintenance programs.

1.9 Thesis Structure

This thesis comprises 7 chapters:

Chapter 1 provides a basic introduction to this thesis. Following this introduction, chapter 2 provides a review of the literature covering literature-related discussion about maintenance resource management, and present methods in

maintenance resource-provisioning policy, which is the motivation for proposing a new approach in maintenance resource-provisioning policy. It also critically reviews literatures for life cycle costing and system dynamics modelling.

Chapter 3 establishes the approach and proposed method for maintenance resource-provisioning modelling. It also presents policies for different types of maintenance resources and the new LCC and system dynamics approach for analysing maintenance and maintenance resource-provisioning policies.

Chapter 4 presents the development of the new LCC model. The new LCC model also incorporates inflation and time value of money factors, so it can be more accurate. After the development of the LCC model, the development of the system dynamics simulation model is presented in chapter 5, along with a summary about current available models in maintenance resource-provisioning, and reasons for system dynamics application. The steps to develop the model will be discussed in more detail in this chapter.

Chapter 6 considers a number of case studies. These are mainly related to maintenance and maintenance resource-provisioning policies for a wind farm. The case studies cover maintenance and maintenance resource-provisioning policies for the converter module, generator, and gearbox separately. The implementation of this approach in each separate case study comprises of the description of the case, model development, scenario management, output analysis, LCC analysis, and discussion of the result.

Chapter 7 extends the discussion about the implication of the new approach, as well as providing the research finding and organisational implementation. In the final chapter, conclusions and recommendations are provided. The implication of the research findings in theory and practise are also discussed, along with research limitations.

2 A REVIEW OF AVAILABLE MODELS FOR A MAINTENANCE RESOURCE-PROVISIONING POLICY

2.1 Maintenance resource-provisioning as Part of Maintenance Management

Maintenance management has been functionally evolved. Pintelon and Parodi-Herz (2008) argue that there are four important stages in the maintenance evolution timeline. The stages show that maintenance is evolving from “inconsiderable” activities to corporate strategic partnership. The first stage is maintenance as a necessary evil. In 1940, the first generation of maintenance when it was only considered as an unnecessary process in the production, most companies practiced only reactive maintenance or a repair-and-replace policy. The second stage was during the 1960s and 1970s when organisations started to pay attention to maintenance, and consider its optimisation as a technical matter. During this period, optimising maintenance resources began to received attention, as indicated by Lifsey (1965), who suggested dynamic programming techniques as a modelling approach to determine the proper number of maintenance resources.

The next stage of maintenance evolution was the profit contribution stage, during the 1980s and 1990s. Considering maintenance as a profit contribution, it was required to optimise the process, and its modelling required the use of data base management and maintenance software such as in Silcox (1980); Burch and Grupe (1993); Jones (1994); Jones and Collis (1995); Keith and Stephen (1996); Hipkin (1996). During this stage, maintenance resources management was addressed by Bruggeman and van Dierdonck (1985) and John (1995). The last stage in Pintelon and Parodi-Herz (2008) is a stage named cooperative partnership. This period started in the 2000s, and it argues that maintenance as a corporate strategic partnership applies till today. Nowadays, management recognises that maintenance has a significant part to play in the cooperative partnership of organisations. Organisations consisting of technical systems that are composed of complex engineered assets require complex maintenance and resource management programs. The significance of maintenance programs and associated maintenance resource-provisioning programs can be realised from financial saving through optimising these programs.

As part of the overall performance, reliability and availability of assets are affected by good maintenance programs, while in turn depend on the right allocation

of maintenance resources (Pintelon and Parodi-Herz, 2008). According to Wang (2011), an insufficient number of maintenance resources results in ineffective maintenance programs, and may lead to asset failure. A low level of maintenance resources may reduce maintenance costs, but may lead to a condition where the required resources are not available when needed. Unavailability of maintenance resources causes more frequent or longer breakdown of assets that generate delays and losses. Conversely, an excessive amount of maintenance resources will cause high maintenance cost (Ben-Daya and Rahim, 2001, Cahyo et al., 2014).

Classifying maintenance and its resource provision management as profit making activities in organisations involves considering maintenance policies and programs, and all related maintenance resource policies and programs through purchasing, inventory, and human resources. The cause-effect relation between maintenance policy and resource provisioning policy and complexity of the maintenance programs make the analysis for optimisation modelling more complex than usual.

2.2 Maintenance Resource Management as Part of Asset Management

Maintenance is one of the critical issues in an organisation operating complex engineered assets (Tam and Price, 2008). Appropriate maintenance management assures that set assets are performing well enough to support the organisation's objective. The role of asset management is significant, and covers controlling all asset related activities from asset planning and acquisition to asset disposal, in order to assure the delivery of asset targeted performance (El-Akruti, 2012). To achieve the desired performance of the assets, effective maintenance management is required. In this respect, maintenance resource-provisioning management is very important as part of an integrated asset management. Mismanagement of maintenance resource leads to inefficient maintenance provisioning and an ineffective maintenance program. In the long term, an ineffective maintenance program reduces the organisation's performance and profit.

The role of maintenance resource-provisioning in asset management is related to the coordination and integration of the management of maintenance activities with the management of the related supporting activities such as inventory and purchasing. The asset management system has been defined as: "The system that plans and controls the asset-related activities and their relationships to ensure that the

asset performance meets the intended competitive strategy of the organisation" (El-Akruti, 2012). According to this definition, maintenance resource-provisioning is considered as one of the asset management system activities.

The Asset Management Council has adopted a new concept of an overall asset management that defines asset management as "the balance between asset performance, cost and risk" (Brown et al., 2014). Also, a new standard for asset management systems, named as ISO 55000, has been established (Beedles, 2014, Krauss, 2014, Smith, 2014). The benefit of applying this standard in organisations is to attain its objectives by an effective and efficient management of its assets (Iso, 2014a). One of the ISO 55000 fundamentals is aligning asset management to the organisation's objectives by translating the objectives into technical and financial decision, plans and activities. Thus, asset management should integrate the process with other organisational functions such as finance, quality, and human resources (Iso, 2014c). To achieve the objectives of an asset management system, a plan should be developed in order to determine strategy, method, risk, cost and benefit, activities, required resources, and time frame (Iso, 2014b).

The ISO 55000 standard provides an overview of asset management, its principles and terminology, and expected benefits from adopting asset management in an organisation (Iso, 2014a). The benefit of this standard for organisations is to attain their objectives by an effective and efficient management of their assets (Iso, 2014a). There are four fundamentals of asset management based on ISO 55000:

1. Value: is about how assets provide value to the organisation.
2. Alignment: asset management translates the objective of the organisation into technical and financial decisions, plans and activities, while integrating with other functional management processes, such as finance, human resources, information, logistics and operation.
3. Leadership: is concerned with the role of leadership in the implementation of activities for value contribution by asset management.
4. Assurance: asset management commits to maintain assets in order to perform as required.

From the aforementioned, it can be extracted that maintenance resource-provisioning plays a role in asset management by determining the maintenance policy and

required resources that lead to an appropriate decision based on efficiency, effectiveness and optimum cost.

2.3 The Role Resource Provisioning in Maintenance Policies and Programs

Manufacturing or service companies assign technical systems in their organization in many forms (Cople and Brick, 2010). In such organisations, the performance of technical systems influences other systems and the overall performance of the organisation. One of the requirements to maintain technical systems to a desired performance is by applying an appropriate maintenance policy. Sarkar et al. (2011) refers to the type of maintenance policies that can be divided into policies for one-unit system maintenance and policies for multi-unit maintenance. Sarkar et al. (2011) also elaborate on the types of maintenance policies but concentrate on a policy that is selected to serve only one unit of an asset. Examples of maintenance policies for a single unit are:

1. Age-dependent preventive maintenance;
2. Periodic preventive maintenance;
3. Failure limit;
4. Sequential preventive policy
5. Repair limit policy;
6. Repair number counting and reference time policy.

A complex engineered asset can be composed of several different or identical units of assets. For complex assets, a maintenance policy can be considered as a multi-unit maintenance policy. In a complex asset, each unit may require a different maintenance policy, and there exist alternatives for a maintenance policy e.g.: (1) group maintenance policy; and (2) opportunistic maintenance policy that are not considered when dealing with a single unit

Most maintenance policies focus on time –based, reliability-based, and condition-based maintenance. There is an extensive number of articles on maintenance policy, with different approaches suggested to achieve optimisation, including Zhang and Gockenbach (2011), Castro, et al. (2011), Tsai, et al. (2011), Ahmadi and Newby (2011), Huynh, et al. (2011). The area of reliability maintenance and its derivatives, are presented by Zhou, et al. (2007), Cheng, et al. (2008), Selvik and Aven (2011), Jagannath (2011). Zhao, et al. (2010), Bouvard, et al. (2011) Neves, et al. (2011), and

also some work that studies condition based maintenance. Other maintenance programs and/or policies are presented by Allaoui, et al. (2008), Zhou, et al. (2009), Park, et al. (2009), Simeu-Abazi and Ahmad (2011).

In General, maintenance programs applied on a single-unit technical system are able to be applied independently at each unit in a complex asset system, as presented by Castanier, et al. (2005) and Tian and Liao (2011). However, the management of the maintenance resource of single-unit and complex asset systems is completely different. In a single-unit maintenance program, the maintenance resource-provisioning only serves a particular unit. In complex asset maintenance, there exists a cause-effect relationship between resource provisioning and maintenance polices that impact optimisation at the enterprise level. From reviewing the literature, the maintenance programs and/or policies found to be used when dealing with complex engineered assets are those that focus on improving the performance of the overall technical system; e.g. Reliability-Centered Maintenance, Condition-Based Maintenance as presented by Barros et al. (2002); Castanier, et al. (2005); (Ling et al. (2009) and Tian and Liao (2011).

In the above mentioned approaches, it can be concluded that there is limited consideration in research of the role of maintenance resource-provisioning in maintenance programs or policies for optimising asset performance. There is literature on maintenance resources but the nature of each industrial system makes its maintenance resource management different or unique in terms of type, capacity and requirement. Iyoob et al. (2006) emphasize that most of the literature on maintenance programs optimisation does not consider the process of maintenance resource provisioning to fulfil the requirement of maintenance action. This highlights the need for undertaking research for the compatibility of combining maintenance resource-provisioning with the required maintenance programs and/or policy to achieve the performance of the industrial technical system.

Integrated maintenance and maintenance resource provisioning systems can be classified into: (1) integrated maintenance and purchasing & inventory system, and (2) integrated maintenance and human resource provisioning system (Martorell et al., 2010). The relations can be elaborated as follow:

1. Integrated maintenance system with purchasing & inventory system

From a business perspective, a purchasing and inventory system is a supporting system for the maintenance system. To achieve a particular stage of asset performance, management needs to determine a maintenance policy. To apply the maintenance policy, maintenance resources such as spare parts, materials, and tools, need to be provided at the right amount and right time. The provision of this kind of maintenance resource is managed by the purchasing and inventory system. To ensure that the integrated maintenance with purchasing & inventory system works as expected, a good communication between related departments is required. The maintenance department needs to provide a forecast or estimations of required resources, as well as when it should be provided to the purchasing & inventory department. It should give the required time to the purchasing & inventory department to provide this request. Then, the purchasing & inventory department is responsible to provide this request following purchasing & inventory procedures. Purchasing & inventory policies are created to maintain the request that can be fulfilled with minimum cost. These policies may include supplier selection, and order quantity.

Wang et al. (2009) propose a combination of condition-based replacement and spare provisioning policy. The combined proposed approaches are used for a deteriorating system with a number of identical and independent units. The approaches consider inspection interval (T), maximum stock level (S), reorder level (s), and preventive replacement level (Lp). The combined approaches mostly use analytical solutions involving mathematical equations. Then, A Monte Carlo simulation model is developed to evaluate the proposed order-replacement policy. Wang et al. (2009) argue that the proposed approach can optimise integrated spare part inventory management, condition-based replacement and inspection schedule at the same time. The evaluation is based on Average Cost per unit per unit time over an infinite time span. The proposed approach is feasible only for a technical system with condition-based policy. They highlight that in the situation where the maintenance policy is changed by the engineer, it is difficult to adjust the model. Also, the aspect of value of money for a multi-year asset lifetime becomes unimportant and is neglected in the proposed approach. Building on their results, it can be said that there are two

opportunities for improvement: (1) propose a more flexible model, and (2) associate time value of money in the cost equation.

A Similar approach was proposed by Huang et al. (2008). Conversely, they only proposed an analytical approach for joint optimisation of block replacement and periodic review of spare inventory with random lead time without simulation. They claim that their model developed is applicable in many fields with some necessary modifications. However they highlight the difficulty and uncertainty that may be associated with feasibility in term of time, effort and cost to modify the proposed approach for a complex asset system with a different number of assets and maintenance resources.

Hmida et al. (2013) explores a method to optimise inventory policy for offshore vessel maintenance. The purpose of their method is to reduce inventory and keep the level sufficient to ensure uninterrupted service to clients. They propose a classification method with a preventive maintenance program. The method is also known as the ABC method. It aims to classify items based on their cost or their frequency of usage. The inventory policy discussed in this paper is only concerned with reducing the inventory level without considering total inventory cost. A low inventory level may not ensure low inventory cost and may cause delays that lead to high overall cost. This research only recommends the level of inventory for preventive maintenance and does not explicitly recommend the number of parts for corrective maintenance. It is only stated that an extra part bought and placed in the inventory to avoid the chance of downtime.

Horenbeek et al. (2013), discussed the effect of fleet size on a joint policy of maintenance and inventory of spare parts with different quality. Their proposed approach combined Monte Carlo simulation for system representation and a genetic algorithm for optimisation. Their proposed approach only discussed two systems (two units of asset) with one type of maintenance resource (spare part). Based on their approach, it can be realized that for more complex systems, duplicating the approach to be able to accommodate a greater number of assets and different type of maintenance resource (e.g. human resources) is a very big challenge. It may not be possible to simple duplicate the model, but it may require developing a new model due to the various additional considerations.

2. <u>Integrated maintenance with human resource provisioning system.</u>

Essentially, the relation between maintenance system and human resource provisioning system is similar to the integrated maintenance with purchasing & inventory system. Based on the maintenance policy, the number of technician for a particular period of time can be estimated. The human resource department is responsible for providing the number of human resources as requested. It can be done by considering several human resource policies such as: recruiting, overtime, sub-contract, and annual leave policies.

Martorell et al. (2008) investigate a modelling approach for maintenance planning for integrating maintenance strategies and human resources. The main approaches used in their paper are genetic algorithms and reliability centred maintenance (RCM). RCM is used as an approach for the maintenance strategy, and the genetic algorithm is used for maintenance resource optimisation. They associate their modelling approach with a cost model. In a particular situation this combined approach is useful and applicable. However, the combined approach will not be feasible for a complex technical system with a multi-year life time because the frequency of maintenance could be significantly different, and could lead to a new calculation for maintenance resource optimisation. Also, their cost model doesn't accommodate different values of money during the assets' lifetime. Martorell et al. (2010), added material resources as a new considered aspect which makes the modelling more complicated for a complex engineered system.

Khalili et al. (2015) propose the use of a fuzzy queueing system to optimise the number of workforce to handle emergency breakdowns. The basis of this approach is to consider the maintenance process as a queue system and the workforce as the service facility to serve the queue. By assigning a different size of workforce to the maintenance department, a fuzzy total cost function can be obtained. Then, the optimum number of workforce can be determined using a fuzzy ranking method. The study presented 13 units of asset which are sufficient to be considered for a case of a complex asset. To duplicate the unit number of assets or maintenance resources using this approach is quite simple; however the application of this approach can be impractical considering the asset with longer or multi-year lifetime and due to changes in the failure rate of the asset from

time to time. This is also the reason that Khalili et al. (2015) excluded values of money in the cost function.

In conclusion, there are several approaches that are used to optimise maintenance and its associated resource provisioning system; however the application of combined system dynamics and life cycle cost model to support decision making for maintenance resource-provisioning management has not been investigated. The approaches found in the literature: analytical approach, Monte Carlo simulation, and meta-heuristic (e.g. Fuzzy approach, genetic algorithm) mostly handle single systems while considering few resources. However, for a complex asset with a multi-year asset lifetime, those approaches or combination of approaches may be impractical. This research focuses on investigating the appropriateness of using a combination of system dynamics with a life cycle cost model as a modelling approach for maintenance resource-provisioning policy development.

2.4 Reviewing Modelling Approaches for Maintenance resource-provisioning policies

As stated in the Chapter 1, there is a need to explore the potential modelling approach that in particular suits the purpose of achieving a combined resource provisioning and maintenance policy for a complex set of assets in a system. However, there is lack of research on modelling maintenance resource-provisioning in integration with maintenance optimization programs of complex engineered assets. Publications in this area mainly focus on optimising the preventive maintenance interval and opportunistic maintenance for a single unit, for instance Park et al. (2009); Xi and Zhou (2009); Hou and Jiang (2011); Zhijun et al. (2011). The types of model proposed in these publications are analytical models. Although analytical models are common for modelling the maintenance system, they lack the ability to represent a complex system as mentioned in Endrenyi, et al. (2001), Tam et al. (2006), Altiok and Melamed (2007) and Okogbaa et al. (2008), who dealt with the intervention analysis method for a system under transient state.

Other types of models have also been suggested to optimise maintenance programs. Yan et al. (2010) proposed to optimise the predictive maintenance schedule for complex asset maintenance using genetic algorithms that results in a feasible and effective method to minimise the maintenance cost. Sung and Schrage (2009) and Zhouhang (2014) suggest simulation models to optimise the maintenance

program. The simulation model in Sung and Schrage (2009) is based on the Monte Carlo method, and seeks an optimal maintenance policy considering operation cost and safety. A Petri nets model is proposed by Zhouhang (2014) to predict the effectiveness of maintenance strategies.

Each of the aforementioned proposed models is developed for a particular situation, but for the purpose of achieving a combined resource provisioning and maintenance policy that optimises utilisation of a complex asset system, a more flexible model is required to deal with the cause-effect relationship between resource provisioning and maintenance of all units in these assets. Hence, an optimisation model that considers integrating the relationship between maintenance programs and maintenance resource-provisioning to develop an optimum maintenance policy is required.

Research on modelling maintenance resource-provisioning is relatively limited compared with the other issues (e.g. maintenance policies, maintenance performance and measurement) where extensive research has been done and models developed. Maintenance resource management is usually modelled using mathematical modelling techniques. Some models for maintenance resource management have been proposed: Sittithumwat, et al. (2004); Johnson (2006); De Castro and Cavalca (2006); Ilyas Mohammed, et al. (2006); Yeddanapudi, et al. (2008). According to Law and Kelton (2000), ways to study a system by mathematical model can be classified into analytical solution and simulation. The presented models can be categorized as analytical solution with a sublevel of mathematical model.

In a maintenance program for complex engineered assets, the use of a particular maintenance resource for one asset may generate unavailability for others. It may lead the other maintenance programs running ineffectively and may cause the unit to fail or not work properly (Wang, 2011). From this perspective, a maintenance program for complex engineered assets involves links as variables of maintenance resources that always change as a function of time, and the nature of maintenance task on the different types of units. This type of situation requires a detailed analysis of requirement, provision, and allocation of maintenance resources in a systematic and dynamic maintenance resource policy model.

In general there are two types of models: iconic model and mathematical model. An iconic model is usually called a physical model. A mathematical model is a

system representation in the form of rational and quantitative relationships. Law and Kelton (2000) classify mathematical models into two different sub-models, namely analytical solution and simulation. In a particular situation or complexity, this sort of model is effective and efficient to solve the problem being observed. However, in the case of complex asset systems with complex cause-effect relationship between unit requirements, analytical models become inefficient and the use of other types of model and in particular simulation, is recommended. The use of simulation rather than mathematical model for analysing a complex system is because mathematical modelling becomes difficult if not infeasible for handling complex relationships (Altiok and Melamed, 2007).

From a modelling perspective, the complexity of maintenance resource-provisioning is affected by the number of maintained units and the types of maintenance resources being observed. In this regard, a number of related articles with different purpose models is presented: Tsai et al. (2004) offer a model for preventive maintenance of multi-component systems based on the availability of the system. In this model, the interval of preventive maintenance was derived based on the maximisation of availability following the decision of maintenance time. The decision to perform preventive maintenance is determined by checking the asset availability; and the action is decided by analysing the benefit of doing the preventive maintenance in that particular time. Then, the schedule of preventive maintenance is developed step-by-step to gain maximum system effectiveness of the system.

Another mathematical model was also presented by Cui and Li (2006) in order to introduce a shock model for multi-component systems. Okogbaa et al. (2008) suggest a methodology for analysing intervention of complex assets in a system with continuous characteristics under transient response. Park, et al. (2009) propose a block preventive maintenance model using the assumption of periodic inspection and periodic imperfect maintenance with age reduction. Laggoune et al. also proposed two preventive maintenance models for multi-component systems, namely model for a multi-component series system subjected to random failures, where the cost rate is minimized under a general life-time distribution (Laggoune et al., 2009), and a model for coordinating the component replacement based on the partial periodic renewal policy in a multi-component system (Laggoune et al., 2010). Tian and Liao (2011)

report a proportional hazard model for multi-component units where economic dependencies exist among different components.

Endrenyi et al. (2001) state that the complexity of mathematical models makes them were rarely used because it involves a large number of input information that is sometimes unavailable or difficult to attain. This implies that whenever the required inputs for the mathematical model are unavailable, the model cannot be used. The complexity of the mathematical model can be indicated from the number of variables or data required (Tam et al., 2006). Tam et al. (2006) also argue that difficulties in obtaining the required data for complex mathematical modelling are the main reason for a decision maker to avoid using this kind of model.

Law and Kelton (1991) and Altiok and Melamed (2007) suggest that decision-makers utilise simulation models in place of complex analytical models based on the flexibility of the simulation model and the difficulties of building an analytical model for a complex system. In other words, simulation is able to cover the disadvantage of the mathematical model, especially in complexity and flexibility. In this respect, only a small number of articles employ simulation as a tool for complex assets in a technical system. Barata et al. (2002); Aparna and Chaipal (2006); Xiaohu et al. (2007); and Bivona and Montemaggiore (2010) utilise simulation to optimize the maintenance of complex assets. Barata et al. (2002) utilise Monte Carlo simulation to optimize the maintenance of complex assets in a technical system subject to deterioration. As can be extracted from the aforementioned research, Monte Carlo simulation is only used to model the deteriorating system and not the whole resource provisioning system. Barata et al. (2002) shows possibilities to model the failure process of a technical system using simulation, but the maintenance resource-provisioning system is too complex to be modelled using Monte Carlo techniques. In Aparna and Chaipal (2006), deterioration of the complex assets is represented by a continues-time jump diffusion model and then simulation is used to obtain the optimum policy of maintenance action. In Barata et al. (2002), simulation is used to model the deterioration of technical systems. Aparna and Chaipal (2006) use simulation to select optimum maintenance action. Regardless of the type of simulation used, there is a possibility to use simulation both to model the deterioration of the technical system and to select the optimum maintenance action.

In modelling of multi-component or complex asset maintenance systems, Xiaohu et al. (2007); Bivona and Montemaggiore (2010) employ system dynamics simulation. Xiaohu et al. (2007) develop a model for the maintenance program of complex physical assets in a system. The model is used to analyse the basic structure and elements of the system. Bivona and Montemaggiore (2010) suggest system dynamics simulation for maintenance programs of buses. The relationships and interactions of maintenance and maintenance resource-provisioning cannot be represented in a Monte Carlo simulation. With system dynamics simulation, the maintenance program variables such as degradation and repair of the units; change of maintenance requirements; and supply of maintenance resources can be modelled Xiaohu et al. (2007). In Bivona and Montemaggiore (2010), the model also shows how maintenance and maintenance resource provision interact. However, both models do not explicitly represent the units as sub models. In a maintenance and resource provision program of complex assets, the main focus is the units and the requirements for maintenance, and how the maintenance resource-provisioning fulfils the requirements.

In summary, it can be stated that:

1. There is a lack of research on suitable models for integrated maintenance policies and maintenance resource-provisioning policies.
2. The complexity of complex asset maintenance systems and their resource provisioning makes it difficult to be observed with an analytical model. In complex asset maintenance system, each organisation may apply different maintenance policies and different resource provisioning policies to achieve optimum performance. Hence, the flexibility of the model becomes the main issue in the modelling method.
3. A more flexible modelling approach for an integrated maintenance and maintenance resource-provisioning optimum policy need to be developed for complex asset systems for improving the overall performance of the organisation.
4. To cope with the limitation of the analytical solution, a system dynamics model is suggested.

5. System dynamics simulation may be able to model the maintenance and maintenance resource-provisioning, and integration with an LCC model for optimising maintenance resources-provisioning policy in a complex engineered asset is not yet explored.

2.5 System dynamics modelling

System dynamics has been known as an effective tool to support policy making process in handling problems in a dynamic and complex environment (Bivona and Montemaggiore, 2010). Recent reports on utilisation of system dynamics to support policy making in maintenance can be found in Böhm et al. (2008), Yang et al. (2009), Shahanaghi and Yazdian (2009), Bivona and Montemaggiore (2010), and Jokinen et al. (2011). However, the use of system dynamics modelling in the policy making of maintenance resource-provisioning is relatively rare and its application in the policy making of maintenance resource-provisioning in maintenance programs of complex assets has not been observed. Although there is indication that system dynamics may be the most appropriate tool to solve maintenance related problems in a dynamic and complex environment but its capability has not been examined in the field.

The important role of maintenance in enterprises running complex assets has been explored, for instance by Tam et al. (2006) and El-Akruti and Dwight (2013a). As discussed by El-Akruti and Dwight (2013a), maintenance is one of the asset life cycle activities that needs to be considered along with other supporting activities including human resource management and purchasing. Most studies in maintenance and optimisation e.g., Xiaohu et al. (2007) and Kothari (2004) seem not to extensively cover the maintenance resources that in fact need to be considered in actual practice in organisations (Iyoob et al., 2006). Most of the modelling approaches in this area are analytical solutions that have limitations in modelling complex assets in a system (Altiok and Melamed, 2007, Endrenyi et al., 2001). The limitations of an analytical model are mentioned in Endrenyi et al. (2001) and Tam et al. (2006), however; system dynamics has the potential to manage and make decisions in a maintenance program and in the resource provisioning of complex assets.

The application of system dynamics in maintenance ranges from the area of maintenance supply chain, value added estimation to analysis of new maintenance strategy implementation, but publications on its application in maintenance programs for complex assets are limited. In maintenance supply chains, Fan, et al. (2010) used system dynamics to analyse policy to improve military supply chain efficiency and reduce the bullwhip effect. Thun (2006); and Shahanaghi and Yazdian (2009) provided an example of how system dynamics can be used to analyse the effect of such a policy in relation to Total Productive Maintenance in a company. They considered the dynamic behaviour of the systems to show the effectiveness and usefulness of the implementation of TPM. In a smaller scope, Böhm, et al. (2008) utilized system dynamics to optimize maintenance systems through comparing the efficiency of different maintenance activities or a combination of activities. Kothari (2004) and Xiaohu, et al (2007) developed a model for preventive maintenance using system dynamics. Kothari (2004) developed a generic model that allows many adjustments, especially for the model parameters before adopted to a certain technology. Xiaohu, et al (2007) have proposed a dynamic model for the implementation of Condition Based Maintenance. The model is relatively complex and contains some sub models which are the sub system of CBM.

Although the aforementioned researches mostly focus on application to a single-unit of the technical system, the research done by Kothari (2004), Xiaohu, et al (2007), and Böhm, et al. (2008), highlights the potential of using system dynamic modelling for resource provisioning in maintenance programs. For example, Fan, et al. (2010), shows that system dynamics is capable of modelling the supply chain and inventory system and, Thun (2006), Shahanaghi and Yazdian (2009) and Handani and Uchida (2013) shows its capability for modelling maintenance management.

The research on the application of system dynamics simulation for maintenance and asset management is relatively limited comparing with the use of an analytical solution or mathematical model. Some examples of system dynamics model development for investigating the dynamic behaviour of maintenance on an asset management system can be found in Thun (2006), Xiaohu, et al (2007), Böhm et al. (2008), Shahanaghi and Yazdian (2009), Bivona and Montemaggiore (2010), and Cahyo et al. (2013). In a literature review on system dynamics simulation for maintenance and asset management, most studies focus on one unit and do not

consider the interrelations between maintenance resources of other units and other subsystems. The most relevant paper to this research is the one by Bivona and Montemaggiore (2010), where a system dynamics model is used to discover the effect of one particular decision on the entire system. The model includes five major functions in the observed company: Production, Human Resources, Maintenance, Asset Management, and Finance. At an enterprise level, this model is considered sufficient to represent a general function, yet only one type of maintenance resource is included, i.e., human resource. So, in an environment where other resources (e.g., parts, tools, and equipment) have significant contributions to the total cost, a more complicated model should be considered in decision making. To comply with the requirement for a model that integrates maintenance resources policy in a complex system involving asset performance management, further investigation is required. It is argued that system dynamics has the ability to model the integrated relationships between maintenance program management and maintenance resource-provisioning management.

According to Sterman (2000), a system dynamics model has four characteristics which, are: (1) feedback representation; (2) non-linearity; (3) time delay; and (4) stock and flow representation. Based on these four characteristics of system dynamics, it can be argued that system dynamics has the ability to account for the interrelationships and interdependence or cause-effect relation between maintenance and maintenance resource-provisioning policies. These characteristics are directly related to maintenance resource management in maintenance programs in terms of the capability of handling the cause-effect relationship introduced in managing more than one unit in a system. The relevance of these characteristics can be explained as:

1. <u>Feedback representation</u>

Briefly, feedback representation shows relationships of variables in the system, how they influence one another and how that affects the total system. Consider for example, the relationship between scheduled maintenance and equipment defects; scheduled maintenance plays a role in reducing equipment defects. In other words, more frequent maintenance scheduling may tend to reduce cost but may also increase the opportunity of equipment defects. In maintenance resource provision, feedback representation can be found in the relation between the number of resource available

and the purchasing process. For example, the more frequently the number of resources runs out, the more frequent purchasing orders are issued. In the feedback representation, all those variables (scheduled maintenance, equipment defects, purchasing orders, and maintenance resource requirement or/and availability can be modelled in a simple integrated model as shown on Figure 2-2.

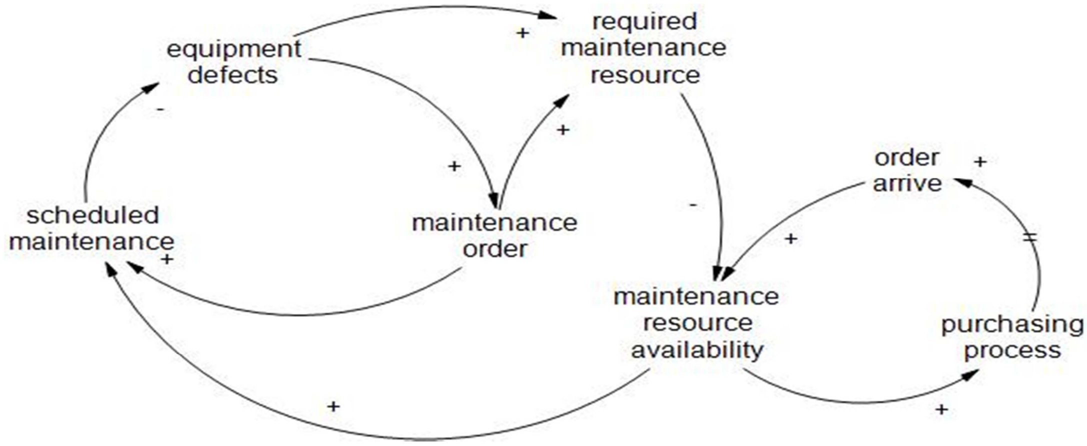


Figure 2-1 : Example of feedback representation for maintenance and its resource management (adapted from Cahyo et al. (2015))

2. <u>Non-linearity</u>

As shown in Figure 2-1, the representation of the non-linearity of maintenance system is found in the relation between scheduled maintenance and equipment defects. The delay of schedule maintenance may double the effect of the number of equipment defects. This circumstance may affect the required maintenance resources to be doubled.

3. <u>Time delay</u>

Time delay shows how a relationship between two variables causes a time delay in delivering or completing activities. In Figure 2-1, time delay can be seen from the relationship between purchasing process and order arrivals. The delay is caused by the lead time of the order. Time delay may be found also in the relationship between maintenance order and scheduled maintenance because of maintenance resource unavailability.

4. Stock and Flow

Some variables in the maintenance system can be presented as having such a level or amount of quantity. The level can be increased by inflow variables and reduced by outflow variables. The example of stock and flow representation in maintenance and maintenance resource management can be found in the level of maintenance resource and equipment's time-to-failure variable. Maintenance resources stock level is influenced by order arrivals as inflow variables and scheduled maintenance as outflow variable. More order arrivals can increase the level of available resources; conversely more scheduled maintenance can reduce it.

From the elaboration of the characteristics of system dynamics, it is concluded that system dynamics has the potential to develop an appropriate model to represent the integrated relationship between maintenance and maintenance resource-provisioning. Based on the aforementioned conclusion, a system dynamics model is then proposed for the purpose of modelling the relationship between maintenance resource-provisioning and maintenance programs.

The proposed system dynamic model is assumed to be able to generate scenarios of representing the expected situations resulting from the cause-effect relationship the applied maintenance resource-provisioning and maintenance program policies. The future generated scenarios by the system dynamic model require analysis and comparison to choose the suitable one for optimizing the system overall performance. This leads to integrate system dynamic modelling with the LCC model to choose the suitable scenario for optimizing the overall system performance. To serve this purpose, LCC models need to be reviewed and a life cycle model that has the potential flexibility to be modified for integration with the system dynamic modelling is to be adopted. The LCC model to be adopted has to be modified to accommodate input from system dynamics simulation and/or combined actual system data to analyse, compare scenarios as options for the combined maintenance resource and maintenance program policies, and to select the optimum option.

2.6 Life cycle costing

As this research focuses on providing an integrated maintenance and resource provisioning model by combining system dynamics simulation with an asset LCC

model, the concept and the available LCC models should be reviewed to adopt a suitable model. Typically, every technical system is a physical asset which goes through stages during its useful life (Fabrycky and Blanchard, 1991).

Those stages are development, acquisition, operation, support, and disposal. Optimising the overall performance through the life cycle of the asset requires using life cycle cost analysis (LCCA) for such performance optimisation. All types of costs occur in all stages of the assets is known as life cycle cost (Ebeling (2010), Farr (2011)).

There are various fields of the LCC model, from manufacturing (Gram and Schroeder, 2012, Sheikhalishahi and Torabi, 2014); public facility (Almeida et al., 2015) to power generation (Sinisuka and Nugraha, 2013, Lesmerises and Crowley, 2013). The main issue of the LCC model is how to consider uncertainty. Ammar et al. (2013) indicates that most life cycle modelling approaches assume deterministic behaviour. To deal with this issue of uncertainty, some approaches have been presented and combined with the LCC model, such as Monte Carlo simulation in Sinisuka and Nugraha (2013) and Almeida et al. (2015); or Fuzzy logics in Ammar et al. (2013) and Sheikhalishahi and Torabi (2014). It can be indicated that there is lack of research which explores system dynamics simulation to deal with uncertainty in the LCC model. Also, research on the LCC model development that focuses particularly on the area of maintenance and its resource provisioning program is relatively limited. The LCC model presented by Ebeling (2010) is the most practical model in this area.

In relation to policies applied in maintenance and maintenance resource management, it can be stated that different policies may generate different costs. For instance, applying reactive, preventive, or predictive maintenance may produce different total maintenance cost. Implementation of preventive maintenance policy may generate shorter total breakdown time compared to reactive maintenance, but has more preventive maintenance time. Since different maintenance programs generate different cost elements, time spans for scheduling, the number of tasks to be undertaken, and the number of resources to be used, the resulting total LCC will depend on the cause-effect relationship between cost drivers and its contributors.

In the maintenance resources side, different provisioning policies may result in a different number of technicians available to serve the maintenance process, or

different purchasing and inventory policies may result in different components becoming available for replacement. All these circumstances generate different total LCC. Suppose that a combination of different policies applied to the assets as scenarios, different scenarios may generate different cost elements. To determine the optimum scenario, LCC analysis needs to be applied.

In addition to all these influential factors mentioned, external factors such as inflation need to be considered in the life cycle analysis. Theoretically, inflation may increase costs and prices, and makes organisations have less purchasing power (Farr, 2011). Inflation needs to be considered in the LCCA specially to determine the increase or decrease of prices and costs affected by inflation or deflation respectively. Also, time value of money is another important factor that needs to be considered in the LCC. The value of money should be carefully taken into account when making decisions involving flow of money during the decision period (Fabrycky and Blanchard, 1991).

The change of value of money over time is estimated in terms of interest rate equations. The term ‘interest rate’ can be defined as the price that should be paid to use the money borrowed from the bank. In engineering economics, the present value of money is denoted by P and the future value by F. Shortly, future value of money is the value of money in the next n years affected by interest (denoted by *i*). Eq. 2-1 shows equation used to calculate F with P is given, during n years and interest *i* (*F/P*,*i*,*n*).

$$F= P(1+i)^{n} \quad \text{Eq. 2-1}$$

$$P= F(1+i)^{-n} \quad \text{Eq. 2-2}$$

Conversely, the present value of money can be calculated also based on its future value. To calculate P where F is given, with interest i and during n years is shown in Eq. 2-2. The method of developing a life cycle cost model will require all the consideration mentioned.

3 RESEARCH APPROACH AND METHODOLOGY

3.1 Research Approach

The approach to this research involves modelling to set the resource provisioning policies and integrate with the maintenance policy for optimisation of the overall performance of a technical system. The models are required to provide a decision support framework that generates alternative policies of maintenance and its resource provisioning, and to identify the optimum criteria a the suitable policy to improve efficiency and effectiveness leading to achieve the target level of asset performance. As a general approach, the research provides a framework that considers all possible resources and the relationships between maintenance activities and related supporting activities. It also identifies the required modelling techniques and their integration with the organisation decision making to support the research objective. In order to validate the application of the proposed models in the decision making framework for achieving the research objective, three case studies are conducted. Although the general approach framework tends to consider all resources and relationships, the selected case studies focused only on three main resources that involve relationships of maintenance with purchasing, inventory and human resource management systems.

The research modelling approach is focused on developing an integrated model that relates the resource provisioning variables involved in the relationships between maintenance policies and the policies of purchasing, inventory and human resource systems. The modelling approach adopted by this research is based on integration of system dynamics simulation with a life cycle model. The purpose of system dynamics simulation is to support the decision maker in investigating the effect of different combined maintenance and resource-provisioning alternatives on the performance of the complex asset. By involving a feedback structure, non-linearity, time delay, and stock and flow representation in the system dynamics simulation model, the model will be able to generate scenarios for all possible alternative resource provisioning policies. The purpose of the integration of the simulation with a life cycle model is to determine decision criteria for the integrated policy that achieve optimum overall performance of the technical system. The application of this approach is verified and validated by the application of the developed integrated

model in three case studies. In this research, some alternatives that represent different policies are to be generated utilizing system dynamics simulation for each case study. Then, the combination of different purchasing and inventory policies are to be combined with human resource policies and maintenance policies. The combined policies are then assessed to find the optimum policy at the enterprise level instead of optimisation at each functional level. The detail framework about how to develop the combined policies will be presented in the following section.

3.1.1 Modelling Approach to Relationship of Maintenance policies with Human Resource policies

Human Resource Policies can be defined as a set of decisions established by organisation to manage human resources related to personnel function, performance, compensation and benefit, relations, and planning (Barbeito, 2004). The relationship of concern in this research is between a policy or combination of policies of human resource provisioning and policies for maintenance activities. The number of the required and available human resources is the main variable in this relationship and is measured in man-hours. A fully skilled and trained person, who works full time, is considered as one full time equivalent (FTE). The man-hours available is calculated based on the full time equivalent.

Policies in human resource provisioning are applied in order to maintain the number of man-hours at a rational level to support maintenance so that optimum performance at the enterprise level can be achieved. The human resource provisioning policies that may be used to vary scenarios in system dynamics modelling may include: (1) New hiring, (2) Overtime, (3) Outsourcing, (4) Lay off, and (5) Combination of policies.

The term ‘new hiring’ or recruitment refers to fulfilling the required personnel for more permanents purposes. The process begins with need identification, attracting candidates, applicant assessment, hiring, and training. The candidates do not gain a FTE until the training process is finalised. The candidates may be considered as 0.5 FTE at the beginning of the training for man-hour calculation purposes because they are not fully trained. In this circumstance, even though the candidates work for 8 hours per day, in term of human resource availability, they are

only considered as 4 man-hours per person based on their FTE. The FTE of the trainee may not be relevant to the salary.

Overtime is the additional hours beyond the normal working hours. Usually, it is a temporary solution for the shortage of man-hours at a particular period of time caused by high demand or low availability of man-hours. For companies, overtime may increase cost because they must pay more than salary in the normal hours. For the personnel, overtime can cause burnout. Therefore, for the longer term, overtime is not recommended for either the company or personnel. Frequent overtime indicates that there is an inaccuracy in planning of the human resource provisioning.

The third policy for human resource provisioning in this thesis is outsourcing. Outsourcing is allocating some functions or business processes to external service providers. The business processes or functions considered for outsourcing are usually the supporting ones. By applying an outsourcing policy, the company may have a better quality of work from a qualified work force without a long term obligation or other responsibility to this work force (e.g. health, insurance, and pension). In the field of asset management, outsourcing is considered for providing improvement, lowering cost and ensuring better quality of work due to human resource expertise.

The logic of human resource provisioning policies is measured and controlled by the number of man-hours which has to be kept at a rational level. This logic may be maintained through recruiting or downsizing or lay off.

Combined policies: two or more policies are usually used to keep the man-hours at the rational level as required. For instance, some of the maintenance may be done in-house and may involve overtime, while other maintenance work is outsourced. These aforementioned policies are possible alternatives for providing the man-hours to fulfil the requirements of scheduled and unscheduled maintenance. This research is aiming at setting the approach to determine how the best resource provisioning policy based on the optimum LCC should be selected.

3.1.2 Modelling Approach to Relationship of Maintenance policies with Procurement policies

Procurement policies are concerned with purchasing activities and inventory activities. In general all resources that need to be procured should be considered in modelling the procurement policy as part of the resource provisioning policy but for

the purpose of this research only the procurement of components/parts or spare parts is considered. The objectives of modelling the relationship between procurement and maintenance are related to (1) ensuring that the required components/parts can be obtained with best value and quality, (2) properly controlled and valued, also (3) delivered to the clients at the correct time, in the correct amount and quality. The purchasing policy is concerned with selecting suppliers based on their performance in terms of quality, price, delivery time, or other parameters that may impact the maintenance performance. The inventory policy is concerned order quantity, number of orders, lead time, safety stock and other parameters that impact the maintenance performance. Both purchasing and inventory policies are to be enacted in collaboration with financial policies. Changes in any one of these policies influence other policies and impact on the value contribution and the overall performance of technical systems. For instance, the number of orders and the amount of order quantity may be different between fixed order interval policies and fixed amount policies.

3.2 A Framework for an Integrated Maintenance resource-provisioning

A framework for an integrated maintenance resource-provisioning is developed as presented in Figure 3-1. This framework is developed based on ISO 55001: 2014 clause 5.2, the setting of asset management objective.

The framework in Figure 3-1 is built based on system perspective where the asset management system is considered as interactions between its elements such as maintenance policy, man power, purchasing and inventory, and finance and budgeting to achieve the objective of the asset management system. The objective of this asset management system is to achieve optimum asset performance. To serve this objective, the framework is set for determining an integrated resource provisioning policy to achieve performance optimisation at the enterprise level. The framework provides the arrangement to serve the objective by developing system dynamics simulation to generate values for the output variables of a set of future scenarios, and considers the generated output of these scenarios as a set of policies for maintenance resources provisioning. Then the framework provides for comparison of these output alternatives from the simulation through a life cycle model to select the optimum one based on the minimum LCC.

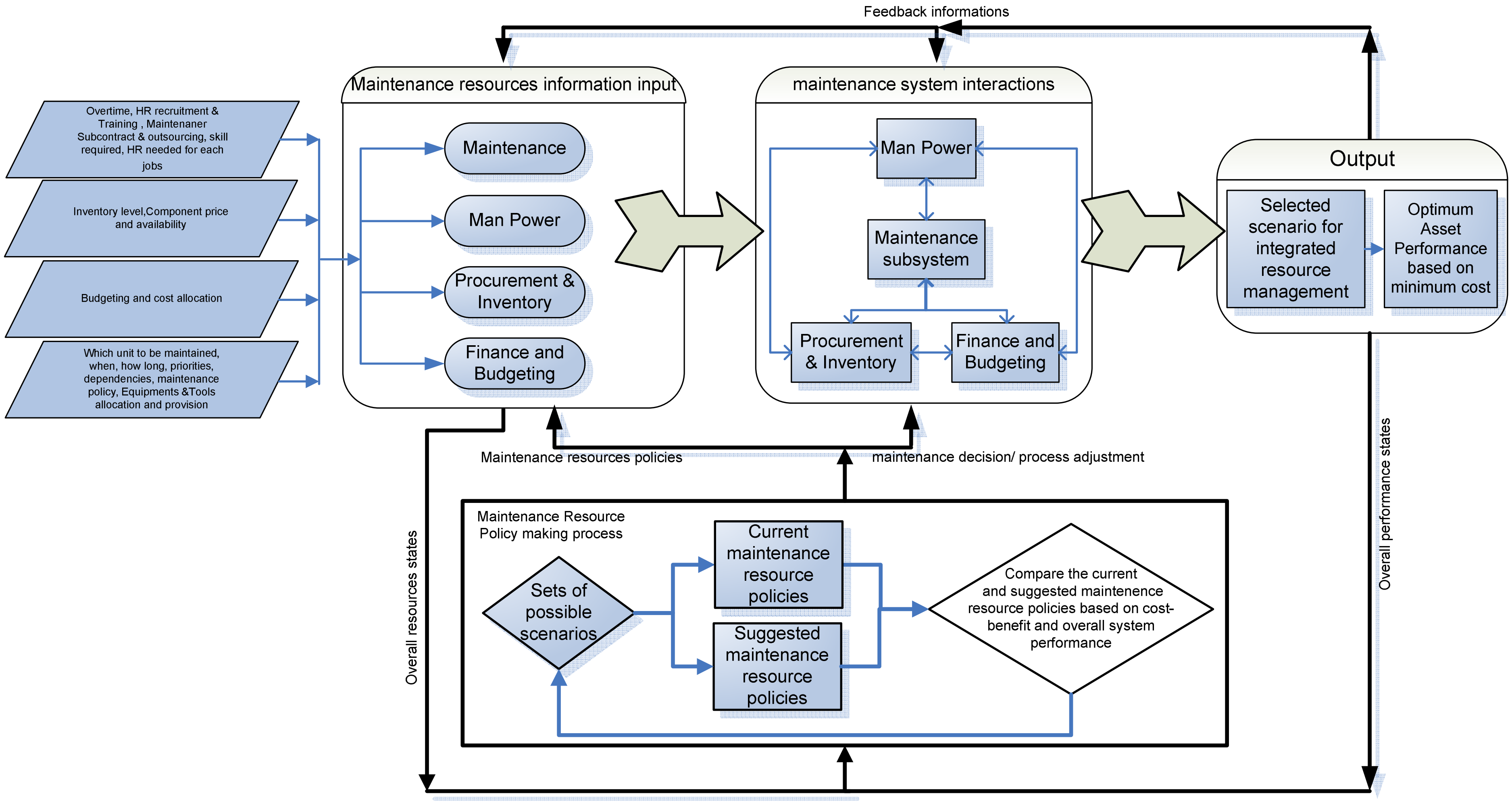


Figure 3-1 Framework for integrated maintenance resource-provisioning

As shown in Figure 3-1, the selected scenario is influenced by interactions in the maintenance program where elements affect each other. As part of the asset management system, this framework integrates maintenance policies with provisioning policies of all the required resources. This integration is considered for executing any maintenance program for which a particular number of resources are required. All the decisions in selecting maintenance policies and maintenance resource-provisioning are confined by LCCA. The decision made in the interaction box of maintenance is based on the input information provided as shown by the flow of information in Figure 3-1. In the box of maintenance resources information input, the input consists of the data or information from maintenance, man power, purchasing and inventory, and finance or budgeting.

The process of determining the maintenance resource-provisioning policy is an iterative process that requires information about the overall performance state and all resources states. The overall performance state can be defined in terms of a set of parameters reflecting the state of performance of the assets. The resource states can be defined in terms of a set of parameters reflecting input maintenance resource information. From those two types of parameters, a set of possible scenarios for maintenance resource-provisioning can be generated. Each scenario then becomes a suggested maintenance resource-provisioning policy, and is compared with the current policy to find the best policy for overall system performance based on the cost -benefit analysis.

This iterative process of maintenance resource-provisioning policy making can be adopted to check whether optimum performance has been achieved at any particular point of time during the asset lifetime.

3.3 Research Methodology

3.3.1 Modelling as a Research Method

Modelling is the method adopted in this research. The modelling sought for this research is based on combining system dynamics and LCC models to support the development of an integrated policy of maintenance resource-provisioning and maintenance programs for optimising the overall performance. The output of the developed integrated model is to be verified through several case studies and then

recommendations are proposed based on the result of this analysis. The purpose of the developed models is to support the decision making process in terms of establishing a maintenance resource-provisioning policy to enhance system performance. The system dynamics modelling focuses on the dynamics of the maintenance resource level to generate alternative policies for maintenance resource provisioning. The LCC modelling focuses on analysis and comparison to select a suitable scenario for optimising performance. The developed combination of modelling has to consider data and information of different maintenance programs, policies, requirements, availability of resources. It also has to consider other relevant parameters, such as cost elements related to provisioning of resources or maintenance programs, unit failures and required performance.

3.3.2 Modelling Methodology

The modelling process in this research is established based on adopting the methodology established by Maani and Cavana (2007). Briefly, the proposed methodology consists of five phases, which are:

1. Phase 1 : Problem structuring
2. Phase 2 : Preliminary model development
3. Phase 3 : Data Acquisition and model refinement
4. Phase 4 : Simulation modelling and policy formulation
5. Phase 5 : Policy evaluation, analysis and implementation.

In this research, these phases of system dynamics modelling established by Maani and Cavana (2007) are constructed into relevant steps and presented into a flowchart as shown in Figure 3-2.

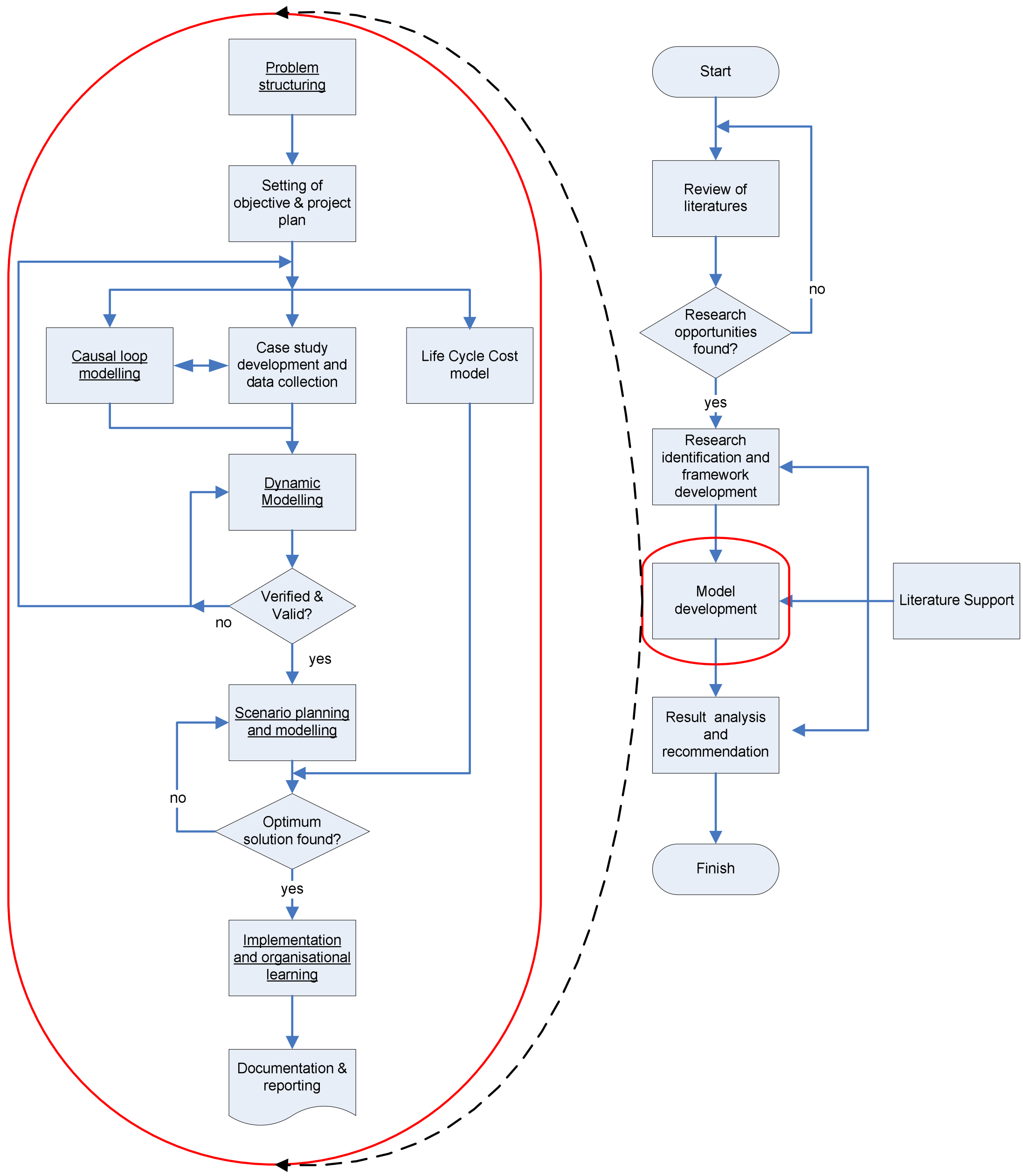


Figure 3-2 Research Flowchart

The flowchart exposes the model development process. As shown in Figure 3-2, the representation of the system dynamics modelling is elaborated into more detailed steps on the left hand-side. The procedure is adapted from the steps of simulation in (Bank et al., 2005), and combined with the phases of system dynamics modelling in Maani and Cavana (2007). The detailed elaboration and key activities of each phase are as follows:

a. Phase 1 : Problem structuring

In this research, the problem statement is developed based on the framework for integrated maintenance resource-provisioning as shown in Figure 3-1. The main challenge in this phase is the difficulty distinguishing between the problem and the symptoms. For instance, the problem of maintenance resource availability can be a problem of planning and scheduling instead of insufficient resources. In this case, adding more resources will lead to inefficiency while an effective resource planning can be a better solution.

After the problem statement is clearly defined, the objective of the modelling should be stated along with the overall project plan. The objective refers to a goal that should be achieved by using the system dynamics simulation. The objective may also designate a question that should be answered using system dynamics modelling. The project plan is composed of resources required to develop the model, and evaluation of the effectiveness and efficiency of the proposed alternative systems.

b. Phase 2 : Preliminary model development

Briefly**,** phase 2 represents preliminary model development. After the problems are well articulated in phase 1, the following step is to develop a preliminary model, or in general it's defined as a conceptual model. In system dynamics modelling, a conceptual model is usually developed in a form of a diagram that represents causal links among related variables. The diagram is called a causal loop diagram (CLD).

CLD represents the feedback structure in the system. Feedback is one of the characteristics of system dynamics modelling. CLD consists of variables and arrows. Arrows denote the causal influence among the variables. The arrows are assigned with positive (+) or negative (-) sign to indicate how the change of the "cause" variable influences the change of the "effect" variable.

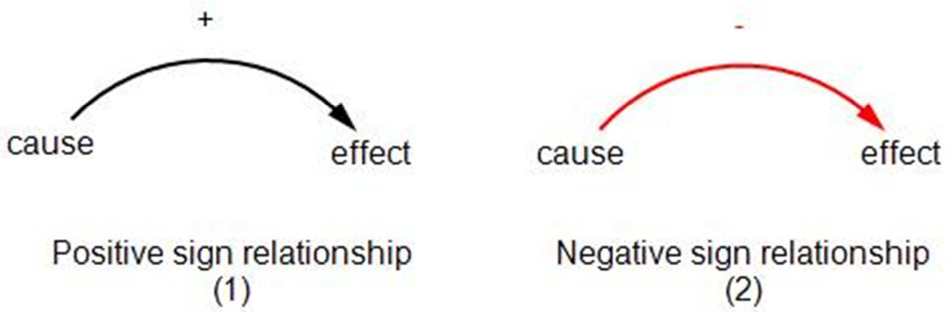


Figure 3-3 Basic CLD relationships

It can be explained from Figure 3-3 that in a positive sign relationship, an increased or decreased value of the "cause" variable leads to an increased or decreased value of the "effect" variable, respectively. In the negative sign relationship, an increased amount of the "cause" variable leads to a decreased amount of "effect" variable, and vice versa. During the modelling process, one or more loops may be formed based on the basic CLD relationships. Two basics loops that may exist are Exponential Growth or Reinforcing Feedback (R) and Goal Seeking or Balancing Feedback (B). Examples of Exponential Growth and Goal seeking loop are shown in Figure 3-4.

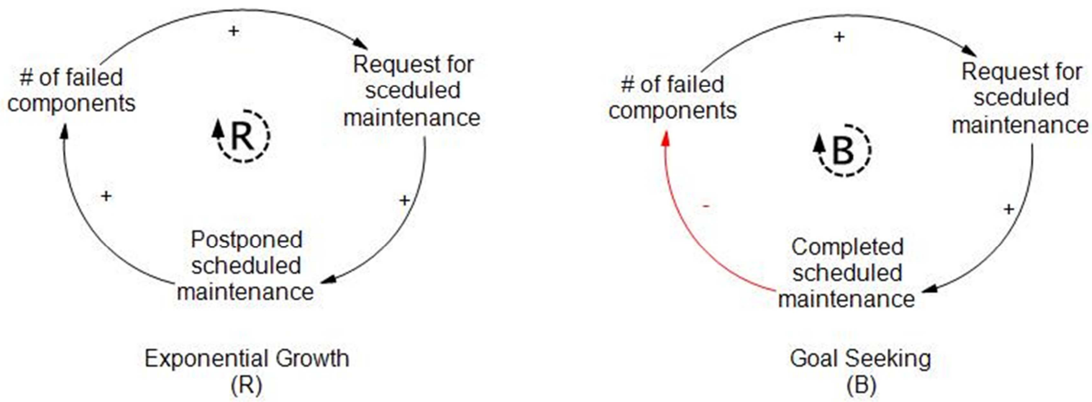


Figure 3-4 Example for Exponential Growth and Goal Seeking

1. Exponential Growth or Reinforcing Feedback (R)

This loop produces exponential growth, and arises from a self-reinforcing feedback. It represents either a growing or declining system state. Reinforcing feedback is a positive feedback, which means that in the loop, the accumulation of the signs of all relationships is positive. An example of this type of feedback is a

bank account and its relationship with interest. An account with a larger balance produces additional amounts obtained from interest. Then, this amount will be added into the original balance, which produces an even larger amount of balance.

The Reinforcing loop in Figure 3-4 shows that all the signs are positive; this means that this is a positive feedback. The reinforce figure shows that the value of the failed component may increase exponentially, caused by the delay of scheduled maintenance. When the number of failed components increases, it will generate more requirements for scheduled maintenance. More requested scheduled maintenance tends to generate higher numbers of scheduled maintenance and higher delays of scheduled maintenance. The delay of scheduled maintenance may generate more components or asset failure.

2. Goal Seeking or Balancing Feedback (B)

Goal seeking or balancing feedback is a feedback loop that seeks equilibrium. Balancing feedback is a negative feedback which has a negative value in the accumulation of the signs in the loop. In general, balancing feedback accommodates a process to compare desired and actual conditions, also takes an action to correct the gap. How air conditioners work is an example of this type of feedback. To operate an air conditioner, a certain level of temperature should be determined as an objective. Then, the air conditioner works to keep the temperature as desired.

The goal seeking loop in Figure 3-4 is an example of a balancing feedback. The accumulation of the signs is negative. The loop tends to seek stability of the number of failed components to a desired number. When required, a scheduled maintenance is requested and when it has been done, it will reduce the number of failed components to a desired level.

c. Phase 3 : Data acquisition and model refinement

In this phase, an iterative process in the model development is started. After the CLD is developed, the related data and information should be gathered. Gathering data and information from the selected organisation will be central in this phase. To collect information about the maintenance program, semi structure interviews are appropriate. A semi structured interview is an interview where the

interviewer has a set of pre-defined questions. This method was proven to be effective in model development and refinement. However this method has weaknesses, the interviewee may have only partial comprehension or knowledge about the system. In this circumstance, a focus group discussion will be conducted.

The objective of a semi structured interview is to find out the detailed process and information of the maintenance program in a certain level. The result of the interview is sometimes rich in information, but supporting quantitative data from other sources is also needed. Supporting quantitative data that is acquired from the organisation includes:

1. Organisational structure for maintenance, as well as job descriptions and specifications.
2. The number of personnel in each position of the organisational structure and the maintenance human resource recruitment system.
3. Maintenance scheduling for each unit covered.
4. Unit maintenance and breakdown records, for determining breakdown rate, time to failure, time needed for maintenance activities, and personnel needed.
5. Job scheduling system and work shift.

The result of the interview, focus group discussion, and other quantitative data acquisition are used to refine the preliminary model developed in phase 2. After the interview, the model is refined and then discussed in the next meeting. The meeting may result in requiring additional model refinement. The detailed questions for the semi structured interview will be included.

This phase is the most challenging phase in the research. The biggest challenge in the interview process is finding the appropriate person who has an integrated understanding of the maintenance program and maintenance resource management. The process to acquire the knowledge will be crucial in the model development. It is important to distinguish between actual processes that happen in the system, and perceived conditions that sometimes reside only in the mind of the interviewee. Although data generation is permitted in simulation as the result of expert statements, the availability of quantitative data as the input of the simulation is a challenge. Another major challenge in this phase is justification to the relationship among variable. It can be found that there are six basic methods for this purpose:

1. Conservation considerations: this method adapts the concept of conservation of electrical current flow. This method accounts for the total quantity of variables which has entered the system and that which has left for the system.
2. Direct observation: this method models an actual decision process instead of the process that should exist.
3. Instruction to that effect: this method is used to assess the effect of a particular link on the model behaviour.
4. Accepted theory: this method uses theory from related disciplines as a basis to build the model.
5. Hypothesis or assumption: this method can be used in circumstances when evidence related to the existence of a link could not be found.
6. Statistical evidence: this method employs statistical analysis to infer the relationship among variables.

Each has its own benefits and weakness. Choosing the most appropriate method or combination among them is another difficulty.

d. Phase 4 : Simulation model development and Policy formulation

The main objective of this phase is converting the conceptual model refined from interviews and focus group discussion in phase 3 combined with the quantitative data into a simulation model. The result of this phase is a dynamics simulation model for maintenance resource-provisioning policy using a selected simulation program. In this research, Powersim Studio is chosen. The model will represent the maintenance program being covered in this research with its dynamics behaviour. The next step is validating the model. The validation process will consist of testing the model structure, model behaviour and policy implications. The process also engages interviewees in phase 3 in order to keep the model run as expected.

In this phase, converting the conceptual model into a computerized simulation model is complicated; however the validation process can be even more complex. These processes are also iterative, when the result of validation shows that the model is not valid, the process can return either to phase 2, 3 or from the computer based model development.

The scenario development is also another big challenge. Insightful knowledge about the current system is crucial for this process. To develop a good set of

scenarios, the modeller must cooperate with the key person of the maintenance program. In this research, one criteria for choosing the best scenario is optimum overall cost. Thus, a LCC model will be developed to involve the system dynamics simulation output. The following chapter presents the development of lifecycle cost.

e. Phase 5: Policy evaluation, analysis and implementation.

After developing scenarios of improvements, these will be tested in this phase. The model may need to be refined and adjusted to meet the requirements of the scenarios.

This process also includes the key person in decision making in the observed system, because the result of the simulation in some cases only shows the best possible scenario based on quantitative data in the simulation output. The decision maker may have an insightful view about the system. There are some aspects that are difficult to be approached by quantitative data.

4 LIFECYCLE COST MODEL FOR SCENARIO OUTPUT COMPARISON

4.1 Basic Cost Model Development

Generally, the major cost categories of Life Cycle Cost (LCC) are defined in terms of the major life cycle activities. In a cost breakdown structure these categories are defined as cost elements. The major cost elements in a LCC structure may include capital cost, lifetime operating cost, lifetime maintenance cost, disposal cost, and residual value. The review in chapter 2 has shown that various LCC models exist and are used for decision making in many applications: manufacturing, public facility, and power generation.

The LCC model presented by Ebeling (2010) is adopted initially for further development to establish the LCC model that can be integrated with a system dynamics simulation model. The complete LCC equation is formulated in terms of cost elements in Eq. 4-1 and the details of the cost elements in the Ebeling (2010) LCC model is shown in Table 4.1. Each cost element is formulated in terms of variables that reflect the relationships between maintenance and related resource provisioning activities, as shown in Eq. 4-2.

LCC = acquisition cost + fixed cost of operating + unit annual operating cost + failure cost + initial acquisition cost for repair channel + annual support cost for repair channel + replacement cost – salvage cost ……………………………………………………..…..Eq. 4-1

$$LCC(m,s,k,MTBF,MTTR,s_i,k_i)=C_u(MTBF,MTTR)(m+s)+F_o+A_{sys}P_A(r,t_d)C_o m+P_A(r,t_d)\frac{t_o}{MTBF}A_{sys}m(C_f+L.MTTR)+F_{rep}k+P_A(r,t_d)C_{rep}k+\sum\left[C_iS_i+P_A(r,t_d)C_{rep,i}m_i\right]-P_F(r,t_d)S_a(m+s)$$

…………………………………Eq. 4-2

Table 4-1: Cost elements of the Ebeling (2010) LCC

No	Cost Element	Brief Description	Equation
1	Acquisition cost	Cost to acquire a certain number of units, including operating and redundancy units.	$C_u(\mathrm{MTBF}, \mathrm{MTTR})(m + s)$
2	Fixed cost of operating	Required fixed cost to maintain the unit operated.	F_o
3	unit annual operating cost	Annual cost required to run the operating unit	$A_{sys}P_A(r, t_d)C_o m$
4	failure cost	Cost occurred by unit failures.	$P_A(r, t_d)\frac{t_0}{\mathrm{MTBF}}A_{sys}m(C_f + L.\mathrm{MTTR})$
5	initial acquisition cost for repair channel	Cost required to provide a certain number of repair channels	$F_{rep}k$
6	annual support cost for repair channel	Cost required to provide support for a repair channel	$P_A(r, t_d)C_{rep}k$
7	replacement cost	Cost required to conduct replacement, also includes spare parts cost	$\sum[C_i S_i + P_A(r, t_d)C_{rep,i}m_i]$
8	salvage cost	The value of units at the end of its operating period	$P_F(r, t_d)S_a(m + s)$

where C_u(MTBF,MTTR) = unit acquisition cost

MTBF = the MTBF of the system failure distribution in operating hours

MTTR = repair or replacement time in hours

m = number of operating units

s = number of spare units (standby redundancy)

k	=	number of repair channels
s_i	=	number of spares of component *i*
k_i	=	number of repair channels for component *i*
A_{sys}	=	effective system availability (average percentage of the *m* units operating)
F_o	=	fixed operating cost
C_o	=	annual operating cost per unit
F_{rep}	=	initial acquisition cost per repair channel
C_{rep}	=	annual (support) cost per repair channel
C_f	=	fixed cost per failure
C_i	=	unit cost of component *i*
$C_{rep,i}$	=	annual cost per repair channel for component *i*
L	=	labour rate ($ per hour)
t_0	=	number of operating hours per year per unit
t_d	=	design life (in years)
S_a	=	unit salvage value (a negative value is a disposal cost)
r	=	discount rate
$P_F(r,td)$	=	$1/(1+r)^{td}$ is a present value factor of a future amount at time t_d years at a discount rate of *r*
$P_A(r,td)$	=	$[1/(1+r)^{td}-1]/ [r/(1+r)^{td}]$ is the present value factor of an annuity over t_d years at a discount rate of *r*

In Eq. 4.2, the term discount rate (r) is used to represent bank interest (i). The discount rate is the interest rate to earn, or a given amount of money today, to end up with a given amount of money in the future. So basically the value of the discount rate equals bank interest.

In order to use the LCC model proposed by Ebeling (2010) in this research, further development is needed to fit it with the proposed integrated system dynamics

simulation. Ebeling (2010) has proposed assumptions in association with the application of his LCC model. These assumptions are:

1. The component replaced is as good as new
2. All operating units are identical and obtained at the same time
3. Constant annual operating requirement
4. The system is in steady state
5. No preventive maintenance is undertaken during the operational period of unit
6. No failures occur in standby, perfect switching with insignificant down time.

From these assumptions it is clear that this LCC model does not consider preventive maintenance activities, and therefore it is only applicable where a corrective maintenance policy applies.

In order to establish a new LCC model that suits a general purpose LCCA in maintenance and its resource provisioning program, further modification and considerations for the new LCC model are required. The main inclusions that are considered in the new LCC model are:

1. introduction of related maintenance resource-provisioning variables;
2. inclusion of preventive maintenance and/or scheduled maintenance in the LCC model;
3. inclusion of the time value of money and inflation in all associated cost elements;
4. accommodating uncertainty

Therefore, the new integrated LCC model should account for the cost of human resources, purchasing cost and inventory cost. The cost elements and the proposed new LCC model are presented as Eq. 4-3 and Eq. 4-4, respectively.

The adjustment done on the LCC model in Eq. 4-1 to arrive at the LCC model in Eq. 4-3 is by adding new cost categories and restructuring some of the old cost elements as sub-elements under the new cost categories as follows:

1. maintenance cost, which is composed of scheduled maintenance and unscheduled maintenance;
2. human resources provisioning cost;
3. purchasing and inventory cost;

4. stoppage cost: and
5. restructuring the terms failure cost, initial cost for repair channel, annual support cost for the repair channel, and replacement cost as part of the maintenance cost.

The adjustments in terms of restructuring those elements can be explained as:

1. The term failure cost in Eq. 4-1 only refers to the cost of breakdown maintenance that occurs when a failure happens. Therefore this cost only includes the repair cost of corrective maintenance. To cover the requirement for calculating scheduled and unscheduled maintenance, the term failure cost is transformed into formulas as part of the maintenance cost, as shown in Eq. 4-4.
2. The terms initial cost for repair channel and annual support cost for repair channel in Eq. 4-1 are related to maintenance resources for maintenance activities. Assuming that the repair channel is related to the provisioning of human resources, the two cost elements are changed into the human resources provisioning cost.
3. In Eq. 4-1, there is also the replacement cost which consists of annual support cost for the repair channel, and the cost for the replaced components/parts in the operating unit. Mainly, the replacement process requires two types of maintenance resource: human resources and spare parts. Hence in Eq. 4-3 and Eq. 4-4, the annual support cost for the repair channel is included in the human provision cost, and the purchasing and inventory cost.

The detailed new equations are Eq. 4-3 and Eq. 4-4:

LCC = acquisition cost + fixed cost of operating + unit annual operating cost + maintenance cost + stoppage loss + human resource provisioning cost + purchasing and inventory cost – salvage cost ………………………...……………………………..…..Eq. 4-3

$$LCC = C_u(MTBF, MTTR)(m+s) + F_o + A_{sys}P_A(r,t_d)C_o m + \sum_{r=1}^{n_{SM}}(F_{SM} + C_{SM,r}) + \sum_{s=1}^{n_{UM}}(F_{UM} + C_{UM,s}) + n_d.F_{SL} + T_d.C_S + (n_{HR}.L) + \sum_{l=1}^{n_p}(\frac{t_{p,l}}{365}.L) + [(n_R.F_R) + \sum_{p=1}^{n_R}(n_{NHR,p}.\frac{t_{NHR,p}}{365}.L)] +$$

$$[(n_{RO}.F_{RO}) + \sum_{q=1}^{n_{RO}}(n_{o,q}.C_{o,q})] + F_i + (n_p.C_p) + (n_c.C_i) + (\frac{n_i+n_c}{365}.C_{inv}) - P_F(r,t_d)S_a(m+s) \quad \text{Eq. 4-4}$$

Eq. 4-4 is established by formulating each cost element in Eq. 4-2 by Ebeling (2010) in terms of the variables that reflect the relationships between maintenance and the resource provisioning functions. Eq. 4-5 is established by excluding the time value of money from the annual operating cost and salvage cost in Eq. 4-4. This adjustment is done to allow for the possibility of including the time value change and inflation in the system dynamics simulation.

$$LCC = C_u(MTBF, MTTR)(m+s) + F_o + A_{sys}C_o m + \sum_{r=1}^{n_{SM}}(F_{SM,r} + C_{SM,r}) + \sum_{s=1}^{n_{UM}}(F_{UM,s} + C_{UM,s}) + n_d.F_{SL} + T_d.C_S + (n_{HR}.L) + \sum_{l=1}^{n_p}(\frac{t_{p,l}}{365}.L) + [(n_R.F_R) + \sum_{p=1}^{n_R}(n_{NHR,p}.\frac{t_{NHR,p}}{365}.L)] + [(n_{RO}.F_{RO}) + \sum_{q=1}^{n_{RO}}(n_{o,q}.C_{o,q})] + F_i + (n_p.C_p) + (n_c.C_i) + (\frac{n_i+n_c}{365}.C_{inv}) - S_a(m+s) \quad \text{Eq. 4-5}$$

The new introduced cost elements in the new LCC model equation are presented in Table 4-2.

Table 4-2: Introduced cost elements in the new LCC

No	New cost elements	Equation
1	Maintenance cost	$\sum_{r=1}^{n_{SM}}(F_{SM,r} + C_{SM,r}) + \sum_{s=1}^{n_{UM}}(F_{UM,s} + C_{UM,s})$
2	Stoppage loss	$n_d.F_{SL} + T_d.C_S$
3	Human resource provisioning cost	$(n_{HR}.L) + \sum_{l=1}^{n_p}\left(\frac{t_{p,l}}{365}.L\right) + [(n_R.F_R) + \sum_{p=1}^{n_R}\left(n_{NHR,p}.\frac{t_{NHR,p}}{365}.L\right)] + [(n_{RO}.F_{RO}) + \sum_{q=1}^{n_{RO}}(n_{o,q}.C_{o,q})]$
4	Purchasing and inventory cost	$F_i + (n_p.C_p) + (n_c.C_i) + (\frac{n_i+n_c}{365}.C_{inv})$

Further explanations of deriving the terms of these new cost element inclusions are:

4.1.1 Maintenance Cost (C_M)

In the LCC model in Ebeling (2010), the maintenance cost is only reflected in the failure cost as $P_A(r, t_d)\frac{t_0}{MTBF}A_{sys}m(C_f + L.MTTR)$. The failure cost is calculated from the number of failure that occur ($\frac{t_0}{MTBF}A_{sys}$) multiplied by the number of operating units (m) and the cost per failure ($C_f + L.MTTR$). The MTBF and MTTR in the failure cost are assumed to be constant. In real systems, this assumption is impractical and very difficult to fulfill, but a random event approach of MTBF and MTTR can be practically achieved.

From this idea, the new maintenance cost is introduced in the new LCC and includes costs for scheduled and unscheduled maintenance in Eq. 4-6. The cost also accommodates fixed and variable cost of both types of maintenance. Variable cost of maintenance is denoted by C_{SM} and C_{UM} for scheduled and unscheduled maintenance respectively, and can be determined by multiplying the daily expenses by the number of days required to perform that maintenance activity.

$$C_M = \sum_{r=1}^{n_{SM}}(F_{SM,r} + C_{SM,r}) + \sum_{s=1}^{n_{UM}}(F_{UM,s} + C_{UM,s}) \quad \text{……………..….. Eq. 4-6}$$

where F_{SM} : fixed cost of scheduled maintenance

C_{SM} : total variable cost for every scheduled maintenance performed

F_{UM} : fixed cost of unscheduled maintenance

C_{UM} : total variable cost for every unscheduled maintenance performed

The values MTBF and MTTR are generated by the simulation model and inputted into the maintenance cost element. The proposed maintenance cost element is calculated based on the number of scheduled and unscheduled maintenance from the simulation output multiplied by its associated fixed and variable cost. The fixed and variable maintenance cost may include labour cost, equipment cost and transport cost. This maintenance cost does not include the cost of spare parts used because this is included as part of the purchasing and inventory cost.

4.1.2 Stoppage loss (CSL)

Units may produce profit when they are operating. When units stop operating because of any failures, they stop generating profit. Stoppage loss is calculated by the number of unit stoppage multiplied by the loss of opportunity caused by the stoppage, as shown in Eq. 4-7.

$$C_{SL} = n_d . F_{SL} + T_d . C_S \quad \text{...... Eq. 4-7}$$

where n_d : number of stoppage occurrences

F_{SL} : Fixed cost of a unit's stoppage

T_d : amount of time the units fail

C_S : opportunity loss per measured time

4.1.3 Human Resource Cost (CHR)

In the Ebeling (2010) LCC, the term repair channel is used to describe maintenance resources. This research is particularly concerned with two categories: human resource, and a unit's components/parts as the maintenance resources. The cost element for human resources is dealt with in this section, while the unit's components/parts category will be dealt with in the following section.

The human resource provisioning cost includes salaries for maintenance personnel, recruitment and outsourcing costs, as shown in Eq. 4-8.

$$C_{HR} = (n_{HR} . L) + \sum_{l=1}^{n_p} (\frac{t_{p,l}}{365} . L) + [(n_R . F_R) + \sum_{p=1}^{n_R} (n_{NHR,p} . \frac{t_{NHR,p}}{365} . L)] + [(n_{RO} . F_{RO}) + \sum_{q=1}^{n_{RO}} (n_{o,q} . C_{o,q})] \quad \text{...... Eq. 4-8}$$

where n_{HR} : number of maintenance personnel

L : labour rate

n_p : number of partial labour (labour that not work for a whole year for any reason)

t_p : partial labour's number of days in a year.

n_R : number of recruitment undertaken

F_R : fixed cost for recruitment

n_{NHR} : number of new maintenance personnel

t_{NHR} : new personnel's number of days in one year

n_{RO} : number of outsourcing committed

F_{RO} : fixed cost of outsourcing

n_o : number of personnel from outsourcing

C_o : outsourcing personnel's salary

4.1.4 Purchasing and Inventory Cost (CPI)

Purchasing and Inventory Cost includes fixed operating cost for purchasing and inventory activities, purchasing cost, and variable inventory cost as shown in Eq. 4-9.

$$C_{PI} = F_i + (n_p . C_p) + (n_c . C_i) + (\frac{n_i + n_c}{365} . C_{inv}) \text{ ………….....……….. Eq. 4-9}$$

Where F_i : Fixed purchasing and inventory cost

n_p : number of purchases

C_p : purchasing cost

n_i : number of initial inventories

n_c : number of components purchased

C_i : cost of a component

C_{inv} : inventory cost

4.2 Further Development of the New Life Cycle Cost Model

As indicated by Fabrycky and Blanchard (1991) and Dhillon (2010), to develop a LCC model, some aspects that affect the cost elements of the LCC are :

1. Time value of money
2. Inflation
3. Uncertain factors in the cost elements

In addition to considering the time value of money and inflation, some uncertain variables in the LCC also needs further attention. The new integrated LCC model in Eq. 4-5 does not include inflation and the time value of money. With respect to the inclusion of time value of money and inflation, two alternatives are possible:

1. inclusion of the value of money and inflation change through the system dynamics simulation, in which case Eq. 4-5 can be used, or
2. inclusion of the value of money and inflation factors through the LCC model, in which case Eq. 4-5 needs to be further developed to include the value of money and inflation factors in all related cost elements.

To consider the value of money and inflation in all the elements of the LCC, discount rate and inflation factor should be used. Therefore, the inflation factor (π) and discount rate (r) are to be accommodated in the new model. The further development of the model to accommodate the inflation factor (π) and discount rate (r) can be as follows:

Denoting the total yearly cost as TC_t which is the total cost emerges in year t, then TC_t can be formulated as:

$$TC_t = C_{A,t} + F_{o,t} + C_{o,t} + C_{M,t} + C_{SL,t} + C_{HR,t} + C_{PI,t} + C_{S,t} \quad \text{Eq. 4-10}$$

where $C_{A,t}$: acquisition cost at time t

$F_{o,t}$: fixed cost of operating at time t

$C_{o,t}$: annual operating cost at time t

$C_{M,t}$: maintenance cost at time t

$C_{SL,t}$: stoppage loss at time t

$C_{HR,t}$: human resource provisioning cost at time t

$C_{PI,t}$: purchasing and inventory cost at time t

$C_{S,t}$: salvage value at time t

If t_d denotes the final year in the lifetime of a unit then the LCC can be expressed as shown in Eq. 4-11. If the cost elements increase each year based on the inflation value π, the LCC can be expressed as shown in Eq. 4-12.

$$LCC = \sum_{t=1}^{t_d} TC_t \quad \text{Eq. 4-11}$$

$$LCC = \sum_{t=1}^{t_d} TC_t(1+\pi)^{t-1} \quad \text{Eq. 4-12}$$

To consider the value of money in the LCC calculation, the present worth formula is applied into Eq. 4-12. The new LCC equation considering inflation and present worth of money with discounted rate r is presented in Eq. 4-13.

$$LCC = \sum_{t=1}^{t_d} TC_t(1+\pi)^{t-1}(1+r)^{-t} \quad \text{Eq. 4-13}$$

Combining Eq. 4-5 and Eq. 4-13 produces a new LCC equation which considers inflation and time value of money as shown in Eq. 4-14.

$$\begin{aligned} LCC = \sum_{t=1}^{td} [& C_{u,t}(MTBF, MTTR)(m, t+s, t) + F_{o,t} + A_{sys}C_{o,t}m + \\ & \sum_{r=1}^{n_{SM,t}}(F_{SM,r,t} + C_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t} + C_{UM,s,t}) + n_{d,t}.F_{SL,t} + \\ & T_{d,t}.C_{S,t} + \left(n_{HR,t}.L_t\right) + \sum_{l=1}^{n_{p,t}}\left(\frac{t_{p,l,t}}{365}.L_t\right) + \left[\left(n_{R,t}.F_{R,t}\right) + \right. \\ & \sum_{p=1}^{n_{R},t}(n_{NHR,p,t}.\frac{t_{NHR,p,t}}{365}.L_t)] + [(n_{RO,t}.F_{RO,t}) + \\ & \sum_{q=1}^{n_{RO,t}}\left(n_{o,q,t}.C_{o,q,t}\right)] + F_{i,t} + \left(n_{p,t}.C_{p,t}\right) + \left(n_{c,t}.C_{i,t}\right) + \\ & \left(\frac{n_{i,t}+n_{c,t}}{365}.C_{inv,t}\right) - S_{a,t}(m, t+s, t)] (1+\pi)^{t-1}(1+r)^{-t} \end{aligned} \quad \text{Eq. 4-14}$$

Eq. 4-14 provides a general equation for calculating LCC while accounting for time value of money and inflation changes. The equation is compatible with the system dynamics simulation by attaining its input directly from the simulation output. Further modification or simplification of Eq. 4-14 may be required to tailor its application to specific cases.

5 SYSTEM DYNAMICS MODEL DEVELOPMENT

5.1 System Dynamics Simulation

As stated in the research objective, the simulation involves developing an integrated system dynamics and LCC model for establishing maintenance resource-provisioning policies and maintenance policies to optimise the overall performance of the system. In this chapter, system dynamics simulation is developed. It covers the development of a causal loop diagram and a generic system dynamics model for maintenance programs and maintenance resource-provisioning.

5.1.1 Causal Loop Modelling

The process of constructing the CLD starts by determining the related elements or activities and its relationship. The preliminary CLD of the maintenance resource-provisioning is shown in Figure 5-1. Figure 5-1 represents relationships between each element or activity in the maintenance program, and between elements or activities in maintenance resource-provisioning. In figure 5-1, the relationship between maintenance activities (scheduled and unscheduled maintenance) with asset performance is presented. Both maintenance activities have arrows pointing to the asset performance with positive sign, which indicates that the more maintenance activities done the higher the asset performance. Conversely, the arrows from asset performance to both maintenance activities are expressed with negative signs, which show that better asset performance leads to less maintenance requirement. The relationship from each maintenance activity with asset performance produces a balance (B) loop or balancing feedback. Balancing feedback produces equilibrium (Sterman, 2000). The relationships of asset performance and maintenance activities produce equilibrium between the desired asset performance and the number of scheduled and unscheduled maintenance. In the relationship between maintenance activities and maintenance resource-provisioning, both scheduled and unscheduled maintenance has a positive sign to the human resource and purchasing and inventory. Therefore, more maintenance activities require more resources, including human resources and purchasing and inventory department.

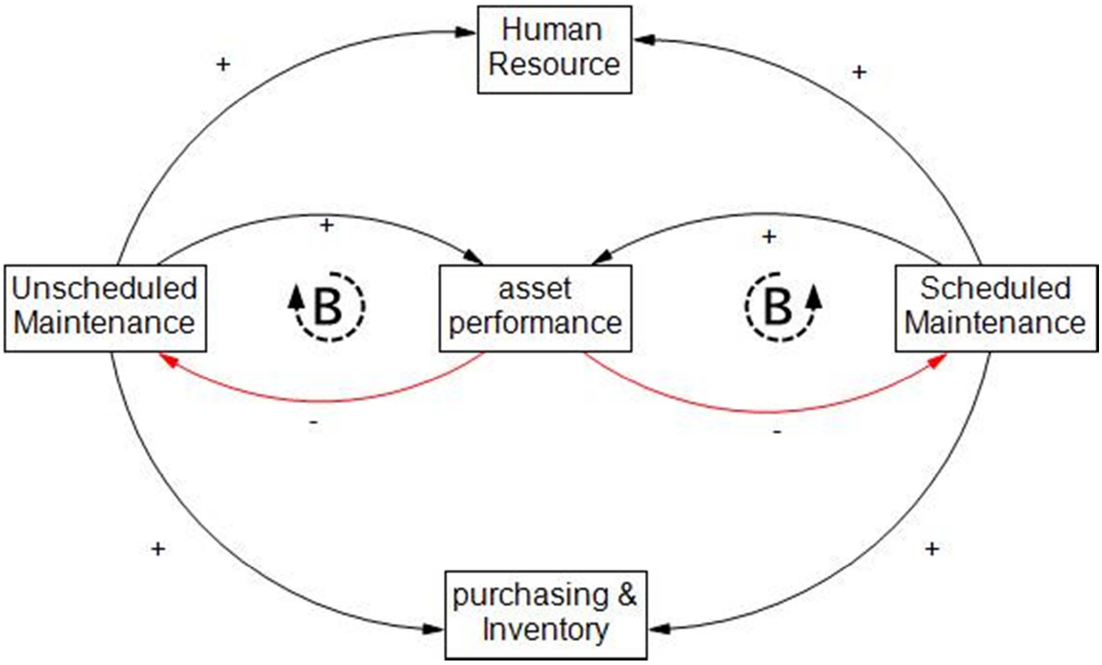


Figure 5-1 Preliminary CLD of the maintenance resource-provisioning

Figure 5-1 shows the associated variables for modelling purposes in each loop and the relationships among them. These associated variables and the relationships provide the basis for a more detailed CLD to be constructed. The selected associate variables in relation to the maintenance program are:

1. Failure rate : Frequency of asset failure per unit time.

2. SM schedule : Schedule for SM is generated from maintenance policy. It can be based on periodic maintenance or condition based maintenance. A value for this variable is only generated when the scheduled maintenance is performed.

3. Required/ Delayed Scheduled Maintenance (SM) : After the time for scheduled maintenance is arranged, it generates a value for required scheduled maintenance. Scheduled maintenance can be delayed because of insufficient resource to complete the task. This variable

			represents the total number of scheduled maintenance that is required or postponed in a particular time to restore the unit to an expected condition.
4.	Completed Scheduled Maintenance (SM)	:	Once the required/delayed scheduled maintenance is finished, the status of the scheduled maintenance is completed. The number of completed scheduled maintenance is represented in this variable.
5.	Assets Failure	:	The number of asset failures that happened in the system
6.	Required Unscheduled Maintenance (UM)	:	When asset failure occurs, UM is required. This variable is the number of total UM required to restore the asset to an operable condition.
7.	Completed UM	:	The number of UM that has been completed.
8.	Delayed UM	:	The number of UM that are deferred for some conditions or because of insufficient resource to complete the operation.
9.	Asset Uptime	:	The accumulation time of the asset while operating without interruption.
10.	Repair time	:	The total time required for Unscheduled and Scheduled maintenance

11. Required Man-hours : The total man-hours required in a certain time horizon for scheduled or unscheduled maintenance

In the maintenance resources provision system, the selected variables and their definition are as follow:

1. Assigned Man-hours : Assigned man-hours is the total number of man-hours assigned to carry out scheduled and/or unscheduled maintenance.
2. Available Man-hours : The total number of man-hours available to carry out maintenance tasks in a certain time horizon. The value can change over time due to the requirement of man-hours and other human recourse policies.

3. Absence/Leave : The total man-hours reduced in a certain period of time caused by the absence of, or leave taken by maintainers.

4. Overtime : The total man-hours added as the result of overtime policies.

5. Outsourcing : The total man-hours added as the result of outsourcing policies.

6. New hiring : The total man-hours added as the result of recruiting new maintainers.

7. Replaced parts/components : The amount of parts or other

	or consumables		maintenance resources that can be provided in a certain UM session.
8.	UM required parts/components or consumables	:	The amount of parts or other maintenance resources needed to complete UM.
9.	SM required part/ components or consumables	:	The amount of parts or other maintenance resources needed to complete SM.
10.	Installed parts/components or consumables	:	The amount of parts or other maintenance resources that can be provided in a certain SM session.
11.	Available parts/components or consumables	:	The amount of parts and other maintenance resources available for SM and UM activities
12.	Expected demand	:	The estimated number of resources (parts or other resources) as calculated and forecast from the past and future maintenance activities.
13.	Order quantity	:	The amount of parts, consumable materials and other resources which are ordered from suppliers.
14.	Purchasing policy	:	The consideration for selecting suppliers to supply a number/ amount of maintenance resources based on price, quality and lead-time. In this research, this policy includes the number of order quantity in every purchase.

15. Inventory policy : This is a guideline for making decisions related to the inventory level. In this research, the inventory policy determines the level of safety stock, and the desired inventory level.

The established CLD that includes all promoted variables for maintenance and the maintenance resource-provisioning system are presented in Figure 5-2. The CLD consists of three parts: human resource subsystem; maintenance subsystem; and purchasing and inventory subsystem. In the human resource subsystem, the key variable used for human resource provisioning is available man-hours (MH). Human resource provisioning can contribute to overall optimum performance for asset management by providing the optimum number of available MH. From the CLD, the policy for providing the optimum number of MH can be done by considering some variables related to the available MH. The available MH can be increased by applying overtime, outsourcing, and new hiring. Overtime is better to solve the short term shortage problems. If the shortage is predicted for a longer term, outsourcing or new hiring is a better option. In the new hiring policy, there is a “delay” symbol (ǂ) on the arrow to available MH, as shown in Figure 5-2. This symbol shows that there is a time delay from the implementation of the recruitment policy to be accomplished to fulfil the shortage of available MH. To keep the rationale number of available MH, downsizing or lay off can be applied in situations when the workload of the people is predicted to be low for a longer time. On a daily basis, the available MH is affected by the number of absences/leave, the number of MH assigned for maintenance activities, and the number of MH which return after completing the maintenance activities.

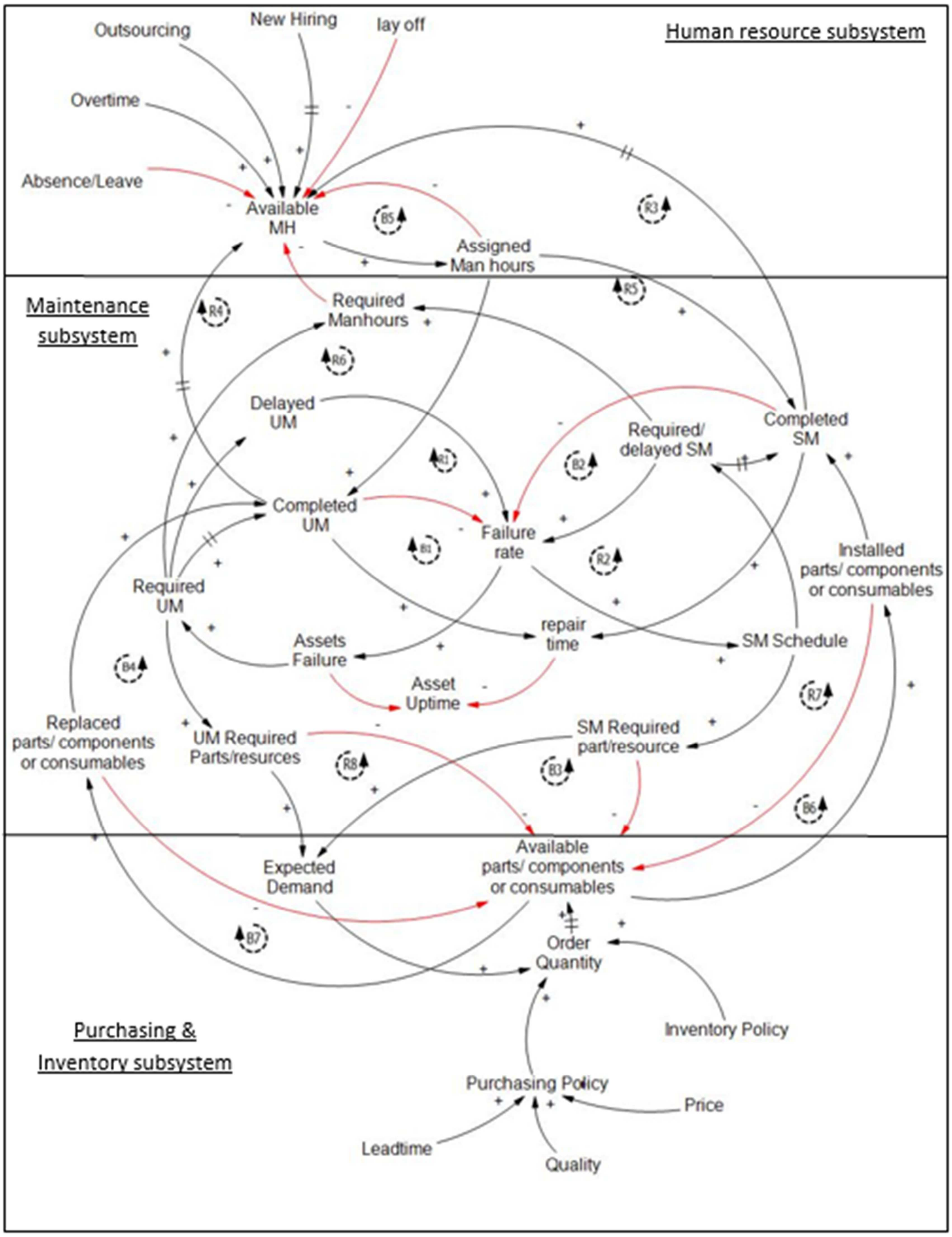


Figure 5-2 : Causal loop diagram of the maintenance resource-provisioning

The second part of the CLD is the maintenance program. The main objective of the maintenance program in this CLD is to optimise the asset uptime by minimising asset failure and repair time. Asset failure can be reduced by completing scheduled and unscheduled maintenance that will decrease the failure rate.

Nevertheless, more scheduled and unscheduled maintenance activities will increase the total repair time that leads to lower asset uptime. In other words, the number of maintenance performed in a period of time should be balanced by minimising asset failure time and repair time.

The third part of the CLD is the purchasing and inventory program. The main objective of this program is to provide parts/components or consumables at an optimum level to support the maintenance activities. The number of available parts/components or consumables is subtracted by the usage for maintenance purposes and increased by the arrival order. The number of orders which arrive is determined by order quantity. To find the optimum number of parts/components or consumables ordered, there are four aspects that should be considered: Inventory control policy, desired inventory level, ordering policy, and financial pressure.

5.1.2 Feedback analysis

It is necessary to perform feedback analysis to verify the relationship between variables. The analysis is focused on the loops formed in the CLD. There are fifteen loops generated in the CLD, seven balancing feedbacks and eight reinforcing feedback. Each loop is explained as follow:

a. Loop B1: Completed unscheduled maintenance sub system

Complete unscheduled maintenance➔ *Failure rate* ➔ *Assets Failure*➔ *Required unscheduled maintenance* ➔ *Completed unscheduled maintenance.*

When the failure rate of an asset is increasing, this can lead to a failure of the asset, and therefore the asset returns to its operational state, and unscheduled maintenance action is required along with all required resources (parts, human resource, and other resources). The completion of unscheduled maintenance reduces the asset's failure rate in general. The purpose of this loop is to achieve the desired level of failure rate by repairing asset failure.

b. Loop B2: Completed scheduled maintenance sub system

Completed scheduled maintenance ➔ Failure rate ➔ Scheduled maintenance schedule ➔ Required/delayed scheduled maintenance ➔ Completed scheduled maintenance

Completed scheduled maintenance reduces the failure rate. To maintain the failure rate at the desired level, scheduled maintenance is arranged at reasonable intervals or states of condition. When the time for scheduled maintenance occurs, it generates a requirement for scheduled maintenance. Similar to Loop B1, this loop is also a balancing loop to attain the desired failure rate, but in this loop attaining the desired failure rate is by completing the scheduled maintenance.

c. Loop B3: Order Quantity (from SM requirement perspective)

Order quantity ➔ Available parts/ components or consumables ➔ Installed parts/ components or consumables ➔ Completed SM ➔ Failure rate ➔ Scheduled of SM ➔ SM required parts/ components or consumables ➔ Expected demand ➔ Order Quantity

The objective of this loop is to keep a reasonable inventory level by balancing installed parts/components or consumables as inventory output with the order quantity as its input. The level of available parts/components or consumables is accrued by a number of order derived from order quantity. The availability of parts/ components or consumables supports scheduled maintenance actions to reduce the failure rate. Then to keep the failure rate at the necessary level, scheduled maintenance should be arranged. This arrangement enables the requirement of parts/components or consumables to be forecast. The result of the forecast can be an input to determine the expected demand for the following period of time which is essential to determine the number of parts/components or consumables that should be ordered.

d. Loop B4: Order Quantity (from UM requirement perspective)

Order quantity ➔ *Available parts/ components or consumables* ➔ *Replaced parts/ components or consumables* ➔ *Completed UM* ➔ *Failure rate* ➔ *Assets failure* ➔ *Required UM* ➔ *UM required parts/ components or consumables* ➔ *Expected demand* ➔ *Order Quantity*

This loop is also proposed to determine the number of order quantity, but from an unscheduled requirement perspective. To complete the unscheduled maintenance, required parts/components or consumables are obtained from available parts/components or consumables for replacement purposes. The completion of unscheduled maintenance affects the failure rate by reducing it. When the asset is in a failed condition, unscheduled maintenance action is required, along with required parts/components or consumables. Forecast requirement of parts/ components or consumables for unscheduled maintenance constructs the number of expected demand collectively with forecasted parts/components or consumables for scheduled maintenance. This number of expected demand determines the number of order quantity after considering other related aspects (e.g. desired inventory level, financial pressure)

e. Loop B5 : Available Man-hours

Available man-hours ➔ *Assigned man-hours* ➔ *Available man-hours*

This is a small loop between available man-hours and assigned man-hours. A higher number of available man-hours may allow a higher number for assigned man-hours to perform the maintenance activities. Conversely, a higher number of assigned man-hours reduces the number of available man-hours. In the whole CLD there are several reinforcing loops that include this loop. The inclusion of available man-hours and assigned man-hours in all reinforcing loops is done through including Loop B5 in them. In theory, a loop that consists of a combination of reinforcing and balancing loops will have a different behaviour from the original reinforcing or balancing loop behaviour.

f. Loop B6 : Available parts/components or consumables for scheduled maintenance

Available parts/components or consumables ➔ *Installed parts/ components or consumables* ➔ *Available parts/ components or consumables*

This loop simulates relationship between available parts/components or consumables and installed parts/components or consumables for scheduled maintenance. A higher number of available parts/components or consumables covers requests for installed parts/components or consumables for scheduled maintenance. Increasing the number of parts/components or consumables installed leads to a lower availability of number of parts/components or consumables. Loop B6 has the same function as Loop B5, which is a-counter-weighting between variables to maintain the rational level of values for these variables, e.g. available and required parts/ components or consumables. The other loops that include this type of loop is Loop B3 and R7.

g. Loop B7 : Available parts/ components or consumables for unscheduled maintenance

Available parts/ components or consumables ➔ *Replaced parts/ components or consumables* ➔ *Available parts/ components or consumables*

This loop maintains relationships between available parts/components or consumables with replacement parts/components or consumables for unscheduled maintenance purposes. More parts/components or consumables used for replacement will generate a lower availability of the number of parts/components or consumables. On the other hand, a higher number of available parts/components or consumables provides more parts/components or consumables that can be used for replacement in unscheduled maintenance. This loop also helps to keep the available parts/ components or consumables at a realistic level. The loops that include this type of loop in it are Loop B4 and R8.

h. Loop R1: Delayed unscheduled maintenance

Delayed unscheduled maintenance ➔ *Failure rate* ➔ *Assets failure* ➔ *Required unscheduled maintenance* ➔ *Delayed unscheduled maintenance*

This is loop explains the effect of postponing scheduled maintenance on other variables. In a situation when the maintenance resources are insufficient or delayed for some reason, the unscheduled maintenance will be delayed. More delayed unscheduled maintenance can generate a higher asset failure rate, so that the asset become more fragile and requires more unscheduled maintenance action.

i. Loop R2: Required/delayed scheduled maintenance sub system

Required/delayed scheduled maintenance ➔ *Failure rate* ➔ *SM schedule* ➔ *Required/delayed scheduled maintenance*

Required/delayed scheduled maintenance is the total number of scheduled maintenance that should be completed to restore the unit to an expected condition. Every asset has arrangements for scheduled maintenance. Scheduled maintenance must be performed at the right time. If for any reason the scheduled maintenance cannot be completed, it becomes delayed scheduled maintenance, which leads to increased failure rate. In turn, increase of failure rate triggers a new scheduled maintenance to be arranged.

j. Loop R3 : Assigned man-hours for scheduled maintenance

Available man-hours ➔ *Assigned man-hours* ➔ *Completed scheduled maintenance* ➔ *Available man-hours*

This loop represents the cycle of man-hours and considers scheduled maintenance activities as a black box. It only focuses on monitoring man-hours from its requirement, assigned until returning to the available man-hours variable. Based on analysis of the signs, this loop is a reinforcing loop because all signs are positive. It is also important to look at the role of Loop B5 which controls the number of available man-hours. A higher number of available man-hours allows for a higher number of man-hours to be assigned for maintenance activities. After a number of man-hours are assigned, the assigned man-hours variable reduces the man-hours availability (see the negative sign from the assigned man-hours to available MH). The assigned number of man-hours for scheduled maintenance returns and increases

the number of available MH variable after completing the scheduled maintenance actions.

k. Loop R4: Assigned man-hours for unscheduled maintenance

Available man-hours ➔ Assigned man-hours➔ Completed unscheduled maintenance➔ Available man-hours

The behaviour of this loop is similar to Loop R3: the assigned man-hours for scheduled maintenance. This loop cannot be analysed as an independent loop without considering Loop B5. Therefore, when a number of man-hours are assigned for unscheduled maintenance, they will be deducted from the number of available man-hours at the same time. The assigned number of man-hours for scheduled maintenance returns and increases the number of available MH after completing the unscheduled maintenance actions.

l. Loop R5: Required Man-hours for scheduled maintenance

Required man-hours➔ Available man-hours ➔Assigned man-hours➔ Completed scheduled maintenance➔ Failure rate ➔ SM schedule➔ Required/delayed scheduled maintenance➔ Required man-hours

The loop represents how man hour is assigned in the completion of scheduled maintenance. At the time for scheduled maintenance, a number of man-hours are required and assigned from available man-hours to complete the scheduled maintenance. The completion of scheduled maintenance retrieves the failure rate to the desired level. At such a level of failure rate, another scheduled maintenance is arranged and a number of required man-hours will be assigned. This loop also includes Loop B5 to balance the available man-hours.

m. Loop R6: Required Man-hours for unscheduled maintenance sub system

Required unscheduled maintenance➔ Required man-hours➔ Available man-hours ➔ Assigned man-hours➔ Complete unscheduled maintenance➔ Failure rate ➔ Assets failure➔ Required unscheduled maintenance

This loop also includes Loop B5 to maintain the number of available man-hours to a rational level. The number of man-hours required for the completion of unscheduled maintenance to fix a failure in an asset is determined from the required unscheduled maintenance. The required man-hours is then compared with the available man-hours. Depending on the availability of man-hours and the priority of the unscheduled maintenance completion, a certain number of required man-hours is assigned to complete the required unscheduled maintenance. The assigned number of man-hours can be partial or the whole number of required man-hours, depending on the availability of the man-hours. More man-hours assigned will decrease the number of man-hours available (based on Loop B5). The policy to assign a certain number of man-hours can affect the result and completion time of unscheduled maintenance. After the unscheduled maintenance is completed (loop B1), the number of assigned man-hours returns to the available man-hours, and respectively increases its value.

n. Loop R7: Required part for scheduled maintenance

Schedule of SM ➔ SM required parts/ components or consumables ➔ Available parts/ components or consumables ➔ Installed parts/ components or consumables ➔ Completed SM ➔ Failure rate ➔ Scheduled of SM

To complete a schedule maintenance order based on the arranged scheduled, a number of parts/ components or consumables is required. This number of required resources is to be provided from the available parts/components or consumables. After the required parts/components or consumables are obtained, they will be installed in order to complete the scheduled maintenance. At a predetermined situation or level of failure rate another scheduled maintenance is to be organized. This loop includes Loop B7 as an equaliser to maintain the variable of available parts/ components or consumables at the correct level.

o. Loop R8: Required part for unscheduled maintenance

Required UM ➔ UM Required parts/ components or consumables ➔ Available parts/resource ➔ Replaced parts/ components or consumables ➔ Completed UM ➔ Failure rate ➔ Assets failure ➔ Required UM

This loop expresses how the process of generating required parts/components or consumables, until it is used to complete an unscheduled maintenance action. When an unscheduled maintenance is required, a requirement of parts/components or consumables is generated to complete it. This requirement is to be supplied from available parts/components or consumables. Then, the supplied parts/ components or consumables are installed as part of an unscheduled maintenance completion. The completion of unscheduled maintenance will reduce the failure rate and lead to a smaller chance of asset failure. This loop also employs Loop B7.

The CLD in Figure 5-2 represents only one unit in an asset. If a set of assets consists of n number of units to be observed independently, the CLD can be extended as shown in Figure 5-3. On the maintenance program in Figure 5-3, n units of assets are presented in boxes from unit 01, unit 02 to unit n. Each box represents a maintenance element/activity of the CLD in Figure 5-2. To conduct scheduled and unscheduled maintenance in each unit, a request for maintenance resources is conveyed to available man hours and available parts/components or consumables. From the available man-hours, a number of man-hours will be assigned and distributed to requesting units. After all requested resources are distributed, the maintenance actions are performed.

In this research, the main focus of the maintenance and its resources-provisioning system is to maintain the desired performance of the asset. Hence from Figure 5-2, asset uptime is selected as the main variable leading the behaviour of the maintenance and its resources-provisioning system. All decisions in the maintenance system, the purchasing & inventory system, and the human resources system should be made in order to achieve optimum performance of the asset. Since the model covers the integration of three different entities, decision makers related to those entities (maintenance manager, purchasing & inventory manager, human resource manager, and the CEO) can use the model to support the decision making process. Further, the result of the integrated LCC model with the system dynamics simulation can serve as information to support the decision making process in other entities such as the department of finance.

In the maintenance system, the decision maker investigation finds the optimum maintenance policy (e.g. breakdown maintenance, preventive maintenance,

and predictive maintenance), along with the optimum interval of preventive maintenance as necessary. To ensure that the maintenance policy is successfully applied, maintenance resources should be provisioned in the right amount and at the right time. This condition is the basis for a decision maker in the purchasing & inventory system and human resource system to develop policies. In the purchasing & inventory system, a particular inventory level should be maintained to fulfil requirements for maintenance activities. This can be done by determining the purchasing policy (e.g. order quantity) and inventory policy (e.g. safety stock) based on the component's lead time and price. Similarly, in the human resources system, a particular number of man-hours should be provided. This can be done by applying one or combined policies, as discussed in section 3.1.1.

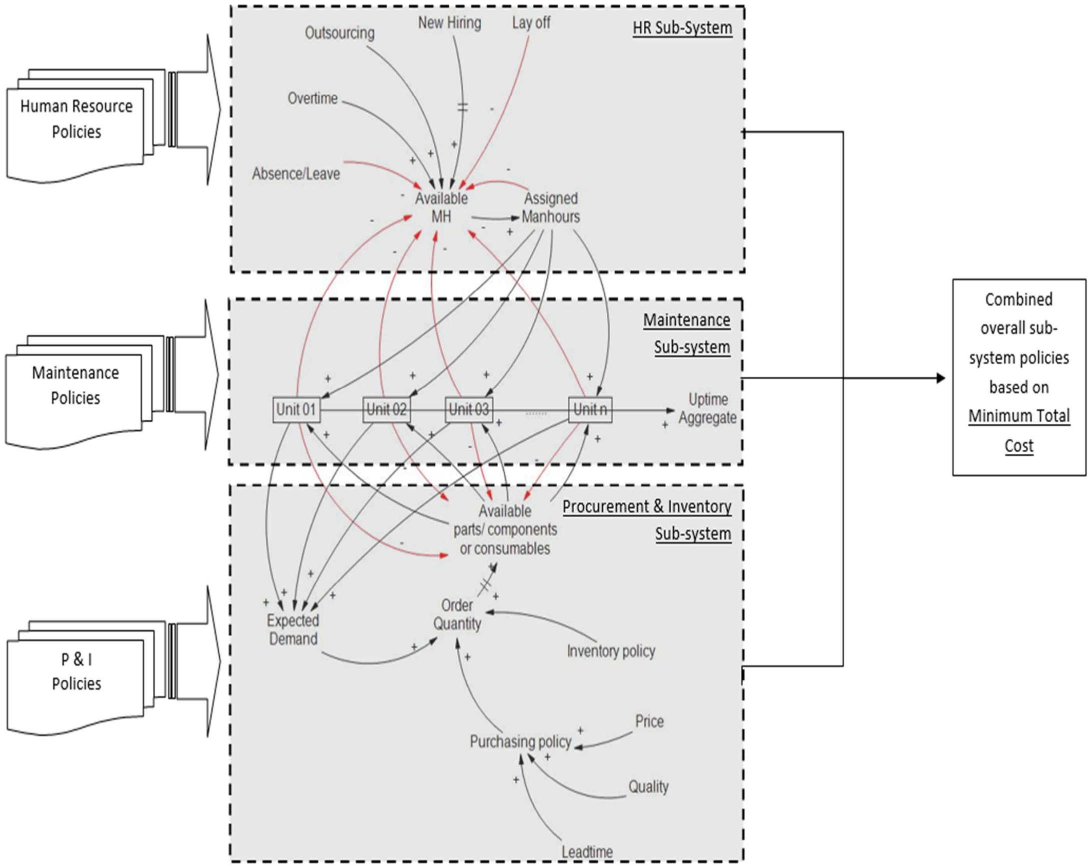


Figure 5-3 The CLD for n units in an asset

Figure 5-3 also illustrates how policies in human resources, maintenance, and purchasing and inventory subsystems are applied. It shows that each subsystem has a set of possible policies. It is assumed that each department in an organisation aims at minimising their expenses by applying appropriate policies. For instance, the department of purchasing and inventory will tend to minimise the inventory of parts to save cost, but the maintenance department will argue to have as many inventories as possible to keep the maintenance activity run without any interruption due to waiting for parts/components or consumables to arrive for example. These two different interests should be accommodated at the enterprise level by finding the best solution that integrates maintenance policies, human resource policies, and purchasing and inventory policies, based on optimum cost.

Reviewing Figure 3-1 (Framework for integrated maintenance resource-provisioning), the CLD for n units in an asset in Figure 5-3 representing the maintenance program interaction. The maintenance program interaction in Figure 3-1 is composed of manpower, maintenance activities, purchasing and inventory, and also finance and budgeting activities. These established CLDs illustrate for the interrelationships between maintenance programs and its resource provisioning, and provides the logic for system dynamics modelling.

5.2 System Dynamics Simulation Model for Maintenance resource-provisioning

A causal loop diagram is essential to model the character, relationships and its direction in the observed system. For a modeller, CLD can help the modelling process by providing better knowledge of the system dynamics, and also communication within the organisation. To handle the different structures and relationships of maintenance programs, together with resources provision and policies applied in each case, a computer based system dynamics simulation model is required. This section discusses the process of converting the Causal loop diagram into a computer based system dynamics model. In the system dynamics model, three sub models are developed: a sub model for the maintenance program, a sub model for purchasing and the inventory program, and a sub model for the human resources provisioning program.

5.2.1 Introduction to the types of variables in system dynamics simulation

In system dynamics simulation modelling, there are four categories of variables: level, rate, auxiliary, and constant. Each category of variables has a particular function in system dynamics modelling. The challenge of converting a causal loop diagram into a computer-based system dynamics simulation is related to determining how to fit each variable in the CLD into the categories of variable in the system dynamics simulation.

Figure 5-4 Symbol for categories of variables

a. Level

Level, also known as stock, is a variable that represents quantity that accumulates over time in the system. Examples of this variable in the real system are inventory, available man-hours, population, and level of knowledge. In system dynamics modelling, level is usually symbolised as a rectangle, as shown in part (1) of Figure 5-4.

b. Rate

Rate (alternatively called a Flow) is a variable that contributes to a change per unit of time within a level. There are two types of rate, in-rate and out-rate. In-rate is the number of units per time added into a level, and out-rate is the number of units per time deducted from a level. In an inventory system, in-rate can be an arrive order, and out rate is order dispatched or shipments. In system dynamics simulation modelling the symbol of rate is shown in part (2) of Figure 5-4.

c. Auxiliary

In system dynamics simulation modelling, this variable is a helper variable. It assists a modeller to combine and reformulate information present in the model. Auxiliary also helps a modeller to break a complex calculation or equation into smaller components to make it easier to understand. It is also able to show a

value of the affecting variables. The symbol of Auxiliary is presented in part (3) in Figure 5-4.

d. Constant

Constant is a special type of auxiliary variable that defines an initial value of a variable or as constant. The symbol of constant is shown in part (4) of Figure 5-4.

To demonstrate how these variables collaborate to develop a system dynamics simulation, an illustration is presented in Figure 5-5, which is a model of a simple inventory system. In this model, inventory is presented as a level with order received as the in-rate variable and shipment as the out-rate variable. As a level, the number of inventory is accumulated over time. In the early state of the simulation, an initial value of inventory should be set. In the model, the initial value is set in the constant variable named 'initial inventory'. The quantity of order received increases, and shipment made reduces the inventory level. The quantity of order received over a period of time is determined by the order quantity and the lead time of the order (both are symbolised in auxiliary). The amount of order quantity is calculated by comparing the desired inventory level with the current number of inventory. For instance, if the desired inventory level is 100 units and the current inventory level is 25 units, thus 75 units is put as the amount of the order quantity. After an order is made, there will be a lead time (the interval between the order placed and the order arriving). At the time the order arrives, it will increase the inventory level. The calculation and logic to determine the order quantity and the order arrival can be inserted in the order received variable in the in-rate part of the model. However, it is difficult to determine what factors or variables affect the order received, so it is essential to break down the calculation into several auxiliaries.

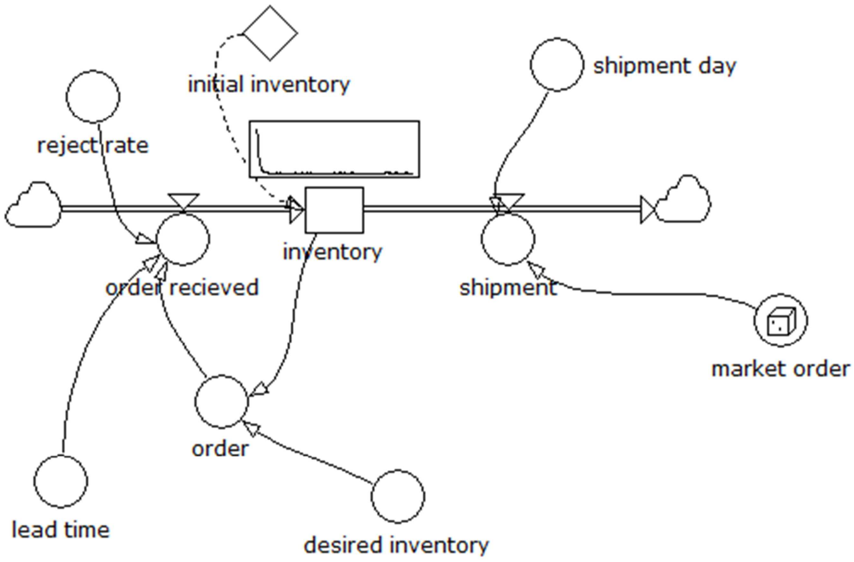


Figure 5-5 Illustration of the variables collaboration in system dynamics simulation

On the out-rate part of the model, the number of shipments is deducted from the inventory level. Variables that influence the shipment are market order and shipment day. Market order specifies the amount of order from the market that should be delivered from the inventory, and the shipment day determines when the order should be delivered. Similar to the order arrival, shipment can be inserted into the shipment out-rate. In order to gain a better understanding at the system structure, the related variables are then presented into auxiliary variables.

5.2.2 Simulation sub model development for maintenance programs

The first step of developing a system dynamics simulation model for the maintenance resource-provisioning in a maintenance program is creating a simulation sub model for the units within an asset. As seen in the CLD in Figure 5-2, asset performance is specified by the asset uptime (which is influenced by asset failure); the longer asset failure, the lower the asset uptime. Asset failure is affected by failure rate. In the simulation model, failure rate is then converted into time-to-failure and represented as a level, as shown in Figure 5-6.

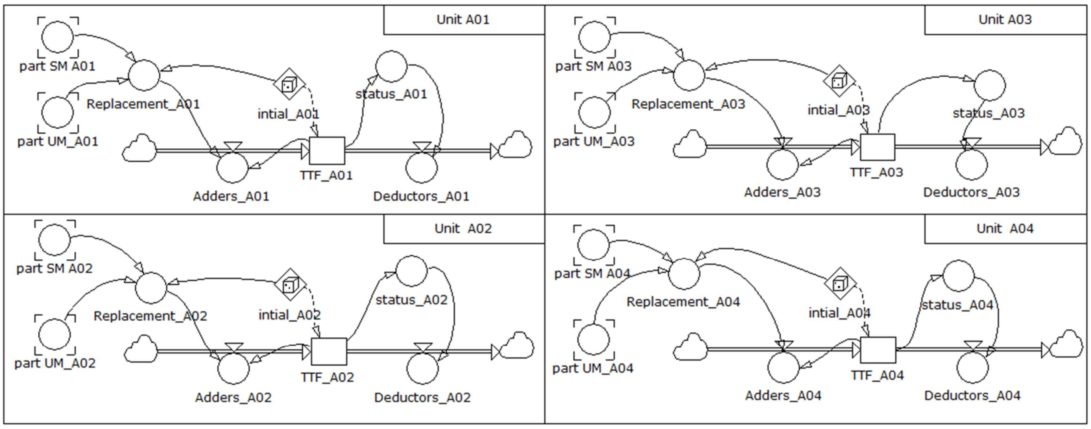


Figure 5-6 System dynamics sub model for units in an asset

The level for time-to-failure is called TTF_A0n, where A0n is the identity number of the unit. For instance, Unit A01 is selected. To start the simulation, initial time-to-failure (TTF_A01) is determined from a constant variable named initial_A01, and then the value is inserted into TTF_A01. The initial_A01 contains a formula to generate a random value for time to failure. For instance, if the probability of failure follows an exponential distribution, the equation will be as shown in Eq. 5-1.

$$\mathrm{P} = 1 - e^{-\lambda \mathrm{t}} \quad \text{Eq. 5-1}$$

where:

P : probability of failure

λ : exponential distribution parameter

t : time

Then, the time-to-failure can be calculated by finding t as shown in Eq. 5-2, where P is a generated random number between 0 and 1.

$$\mathrm{t}_{\mathrm{TTF}} = -\frac{1}{\lambda}\ln(1 - \mathrm{P}) \quad \text{Eq. 5-2}$$

During the simulation, the TTF is decreased by the deduction out-rate variable. When the TTF level reaches zero, this means that the unit fails. Auxiliary variable status_A01 represents the status of the unit. It has two values: 1 represents failure and 0 represents operational. If the status_A01 shows 1, it will stop the deduction to reduce the TTF and send an order for an unscheduled maintenance as

seen in Figure 5-8. Further, sending an order for unscheduled maintenance, the status_A01 variable also creates the required parts/components or consumables for the replacement. The sub model for the creating required parts/ components or consumables is shows in Figure 5-7.

In Figure 5-6, four units are presented in an asset. The requirement of parts/components or consumables in each scheduled maintenance or unscheduled maintenance will be based on the accumulated requirements of all units.

The number of required parts/components or consumables is required in order to complete the unscheduled maintenance. After required parts/components or consumables for the unscheduled maintenance are received (shown as part UM_A01), these are used to replace the failed units. The auxiliary named Replacement_A01 represents the replacement part and is given a new random TTF by the initial_A01. The value of the TTF is then added to the TTF level by the Adders_A01 in-rate variable, so, the TTF level will have a new TTF.

A similar replacement process also occurs in scheduled maintenance activities. In the replacement process for scheduled maintenance, not all units are replaced; only units with TTF that are smaller than the threshold variable are to be replaced. The sub model to determine the number of parts/components or consumables required for scheduled maintenance is shown in Figure 5-7. The variable which represents the number of required units for scheduled maintenance is Reg_for_SM auxiliary. The number of parts required for scheduled maintenance is then supplied to the purchasing and inventory sub model. Then after the required parts/components are obtained from purchasing and inventory, the scheduled replacement is performed with a similar process for the unscheduled replacement based on Figure 5-6.

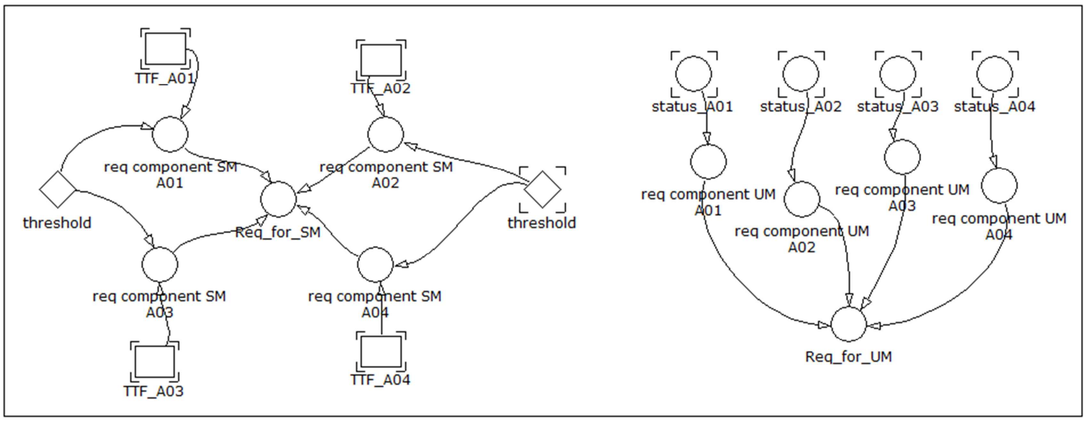


Figure 5-7 Simulation sub model to create parts/ components or consumables required for maintenance actions

In Figure 5-7, the required parts/components or consumables for unscheduled maintenance are accrued from the required parts from all unscheduled maintenance requirement at all units. The requirement in each unit can be indicated from the status of each unit. If the status shows that there is a failure, then a component is required for the particular unit. The variable which represents the amount of components required for unscheduled maintenance is Req_for_UM auxiliary.

To maintain the unit, a maintenance program will be included in the model. Each scheduled maintenance and unscheduled maintenance is modelled in a level variable. In the scheduled maintenance order level, the scheduled maintenance (SM) order is the in-rate and SM execution is the out-rate. The SM order level represents the required/delayed SM variable in the CLD in Figure 5-2. The SM order is created from a SM generator, based on the SM interval and SM preparation (SM_prep). For example, if the SM interval is 30 days and it takes 5 days to prepare the required resources (e.g. human resources, components), then the scheduled maintenance will be done at day 30, but the SM order is submitted at day 25 (5 days before the scheduled maintenance).

When there is an order for scheduled maintenance, it will generate a value for the dispatch order auxiliary. This order is requested to maintenance resources provision to provide the required resources for scheduled maintenance. After maintenance resources provisioning provides the required resources, the scheduled maintenance is then performed. In Figure 5-8, the out-rate of the SM order level and the scheduled maintenance are executed after the required parts/components or

consumables are provided (in the SM buffer), and man-hours are also provided (in the MH SM buffer). Otherwise, no scheduled maintenance will be executed.

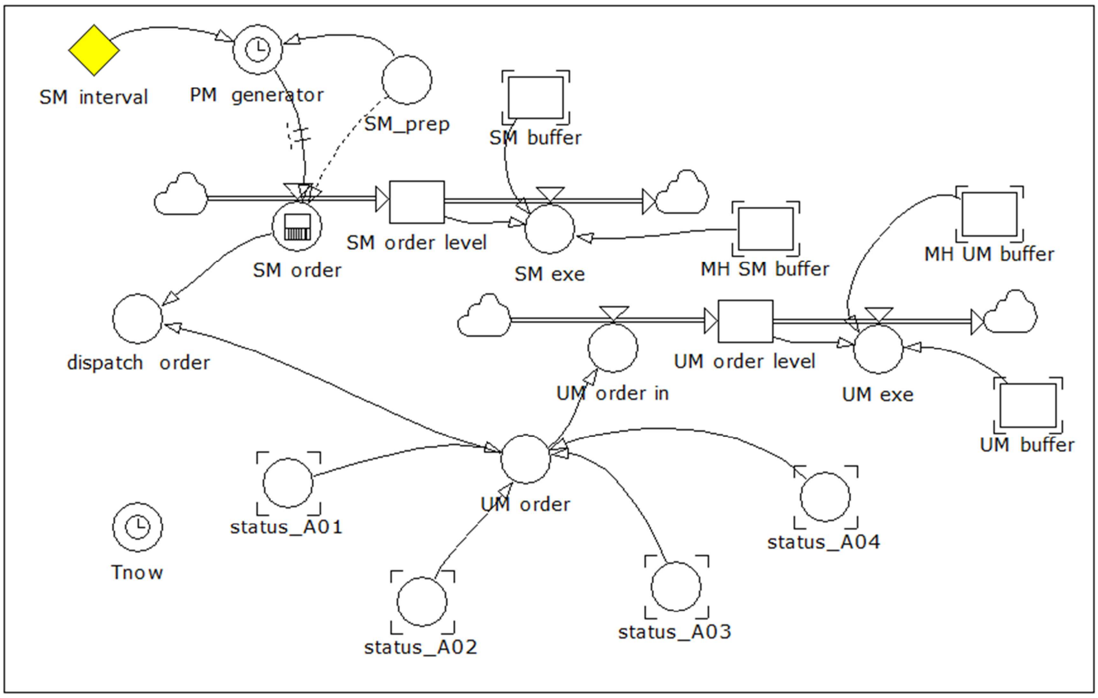


Figure 5-8 A simulation sub model to generate maintenance orders and actions

Slightly different to the scheduled maintenance, unscheduled maintenance orders are generated when there is a unit failure. The failure is seen from the status of each unit. The failure status of one or more units generates an UM order, which is transmitted as an input for the UM order in the in-rate for the UM order level. When there is a value in the UM order auxiliary, it will transmit a dispatch order to demand for maintenance resources. The UM order level will remain until there is UM execution and the required resources in the UM buffer are provided by the associated sub model. After the required maintenance resources are provided, unscheduled maintenance actions will be executed. This execution reduces the value of the UM order level.

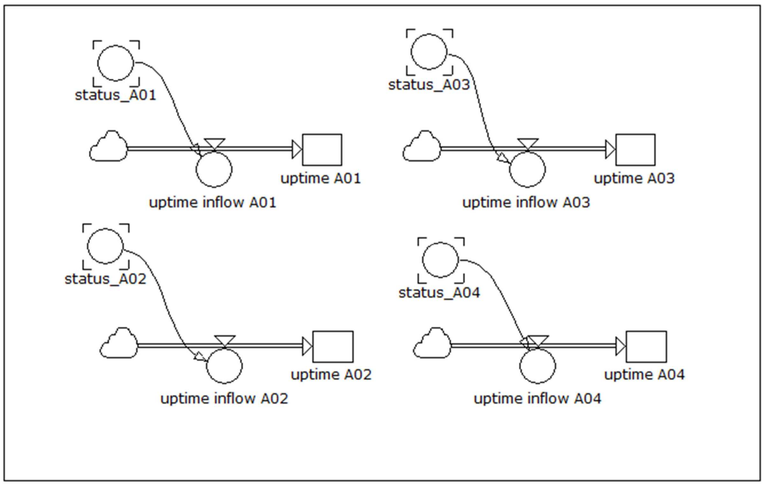


Figure 5-9 Simulation sub model to calculate asset uptime

In the maintenance sub model, calculation for the asset uptime is also included in the model, as presented in Figure 5-9. For each unit, the uptime is considered as a level with one in-rate variable. The uptime is accrued daily from the in-rate unless there is failure represented by the status of the unit.

5.2.3 Simulation sub model for purchasing and inventory

This sub model represents the process of parts/components or consumables provisioning for maintenance purposes. It covers purchasing, inventory, and provisioning for any request from maintenance activities. As shown in Figure 5-10, six levels of variables which are represented which are:

a. Available component: represents the number of available parts/components or consumables in the inventory for maintenance purposes.

b. Order Quantity: this variable is an in-flight order, the amount of ordered parts/components or consumables have not yet arrived.

c. Total component required: this level shows the total amount of required parts/components or consumables, which is the accumulation of the requirement for scheduled and unscheduled maintenance.

d. Scheduled maintenance (SM) required: is the amount of required parts/components or consumables for the scheduled maintenance.

e. Unscheduled maintenance (UM) required: is the amount of required parts/components or consumables for the unscheduled maintenance.

f. Backlog: shows the amount of shortage in the provision program. It happens when the amount of available components is lower than required.

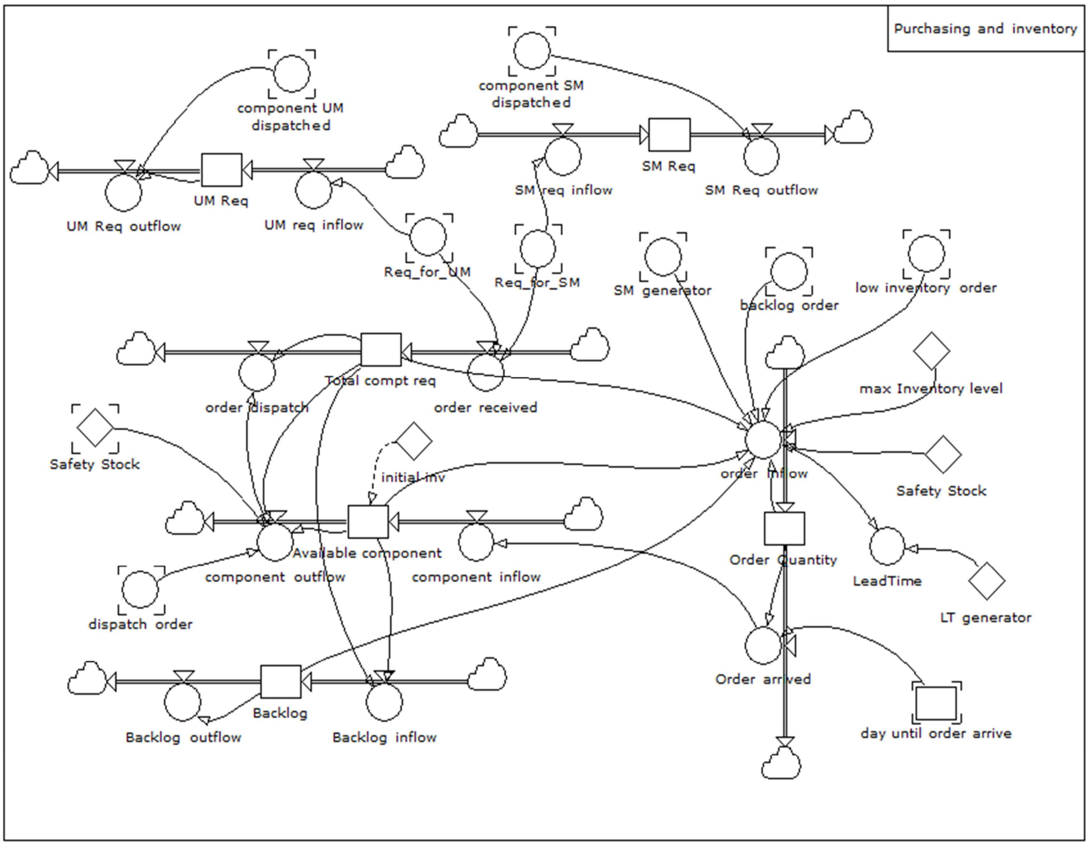


Figure 5-10 Simulation sub model for purchasing and inventory

In the available component, two attributes are initialised at the early stages of simulation. These attributes are initial inventory level and safety stock. Safety stock refers to the minimum number of parts/components or consumables that should be kept in the inventory. Usually it is used as spares to fulfil the requirement during the lead time (the period between the purchase order being issued and the order arriving). When the inventory level reaches the safety stock, a purchase order will be issued to maintain the inventory to the desired level. The safety stock level is also known as the re-order point (ROP). The in-rate for available parts/components or consumables is component inflow, which is the number of ordered components arriving from the purchasing process. The out-rate is component outflow, which is the amount of parts/components or consumables withdrawn from the available component for replacement purposes. It will be calculated if there is a dispatch order

from the maintenance sub system. The amount of component outflow depends on the number of total components required and the available components. The formula inserted in the component outflow is:

IF('dispatch order'>0, IF('Available component'>='Total compt req', 'Total compt req' ,IF('Available component'<'Total compt req' ,'Available component'),0))

A number of parts/components or consumables will be withdrawn from the available component when there is a dispatch order of maintenance and the required number of components for maintenance activities. When the amount of available parts/components or consumables is less than the required parts/components or consumables or after components withdrawn for maintenance, a purchasing order will be issued.

The issued purchasing order is calculated based on several variables, as shown at the order inflow in-rate in Figure 5-10. These variables are SM generator, total components required, available components, backlog, safety stock, max inventory level, low inventory order, and backlog order. Some of these variables have been discussed previously; those variables not previously discussed are explained in the following:

a. SM generator is a variable that is used to generate the scheduled maintenance order. When the value of SM generator is greater than 0, a scheduled maintenance order will be issued.
b. Max inventory level is the desired amount of inventory level. In this model, it excludes the safety stock.
c. Low inventory order is a purchase order issued whenever the number of inventory is equal to or less than safety stock.
d. Backlog order is a purchase order issued when backlog occurs.

Generally, there are three situations in which a purchase order will be issued: (1) when available components are less than the sum of total required components and safety stock, (2) when the level of inventory is equal to or less than the safety stock, and (3) when there is a backlog. Briefly, the formula inserted in the order inflow in-rate variable is:

IF('Order Quantity'>0,0, IF('SM generator'>0 AND 'Available component'<=('Total compt req'+'Safety Stock'), ('max Inventory

level'+'Safety Stock'-'Available component'), IF('low inventory order'>0,('max Inventory level'+'Safety Stock'-'Available component'), IF('backlog order'>0,('max Inventory level'+'Safety Stock'+Backlog),0))))

The main objective of the inventory policy is to keep the level of inventory at the desired level, including the level of safety stock. This policy may produce different order quantities in every purchase, depending on the inventory level when the purchase order is issued. After the number of orders is calculated, the lead time for the order is then generated randomly by the LT (lead time) generator. From the generated lead time, the number of days untill order arrival can be determined. This variable is important to determine when the order arrives.

The order inflow in-rate is then converted into the order quantity level. The out-rate of the order quantity variable is order arrival. The order arrival reduces the order quantity. It is assumed that the amount of order which arrive is the same as the order quantity. The "day until order arrive variable" determines the number of days left until the order arrives. It is reduced by 1 every simulation day. When the value of this variable is zero, the number of purchased components arrives in the warehouse. This amount is then added to the component availability in the inventory by adding the value in the component inflow in-rate variable.

The next variable to discuss is the "total component required level variable". The in-rate for this variable is order received and the out-rate is order dispatch. The value of the order received in-rate variable is calculated from the accumulation of required components for scheduled maintenance (Req_for_SM) and unscheduled maintenance (Req_for_UM). This value is then accumulated into the total components required. As discussed, the amount of total components required is required to calculate the number of components withdrawn from the available components; as components outflow out-rate. Once the component outflow out-rate is determined, it generates a number in the order dispatch out-rate. This number is the same as the number in components outflow. Then, this number is deducted from the level of total components required.

The number in the component outflow variable is also distributed to fulfil the component requirements for scheduled and unscheduled maintenance. The component distribution is shown in Figure 5-11. Here, the number of withdrawn

components is used to meet the requirement for unscheduled maintenance if the orders for scheduled maintenance and unscheduled replacement come at the same time. The number of components for unscheduled maintenance is distributed into the part for UM auxiliary and then included into UM buffer in in-rate to be accumulated in the UM buffer. Based on the maintenance sub model in Figure 5-8, once there is a value in the UM buffer and assumed MH UM buffer is also fulfilled, an unscheduled maintenance is executed. This unscheduled maintenance action creates a withdrawal event of components in the UM buffer by components in the UM dispatched out-rate in Figure 5-11. A similar process is applied in the component distribution for scheduled maintenance

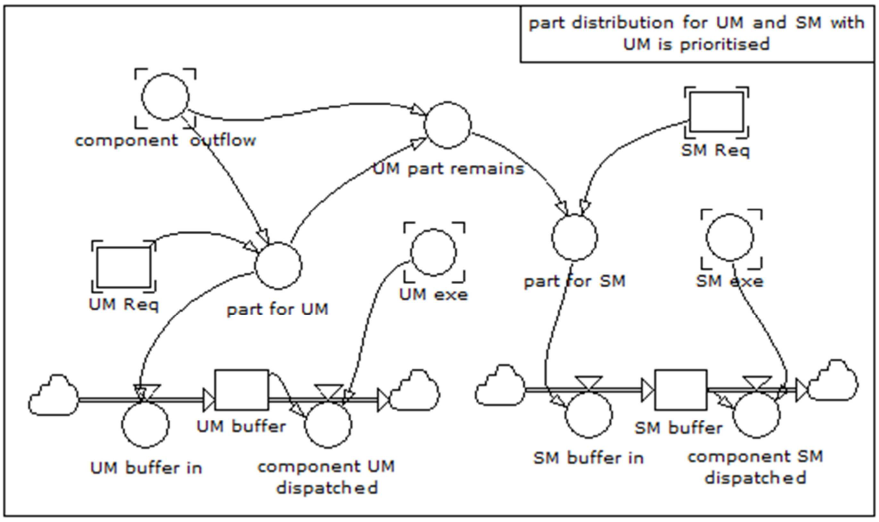


Figure 5-11 Simulation sub model for component distribution for scheduled and unscheduled maintenance

Recalling Figure 5-10, the level variables to store the required component for scheduled and unscheduled maintenance are named SM req and UM req, respectively. SM req has a SM req inflow in-rate variable that is determined by the total component requirement for scheduled maintenance (Req_for_SM), and a SM req outflow out-rate that is determined by the component SM dispatch from Figure 5-11. Also, an UM req has Um reg inflow in-rate that has a value from Req_for_UM and the out-rate is UM req outflow that is determined from the component UM dispatched out-rate shown in the Figure 5-11.

The last level variable in Figure 5-10 is backlog. The in-rate is backlog inflow which is calculated from a comparison of available component and the total

components required. The backlog level is employed to set the purchase order for a shortage condition. Once the purchasing for the shortage condition is issued, the backlog level is reduced to zero by the backlog outflow out-rate variable.

In Figure 5-11, the component requirement for scheduled and unscheduled maintenance is dispatched at the component SM dispatched and component UM dispatched out-rate variables.

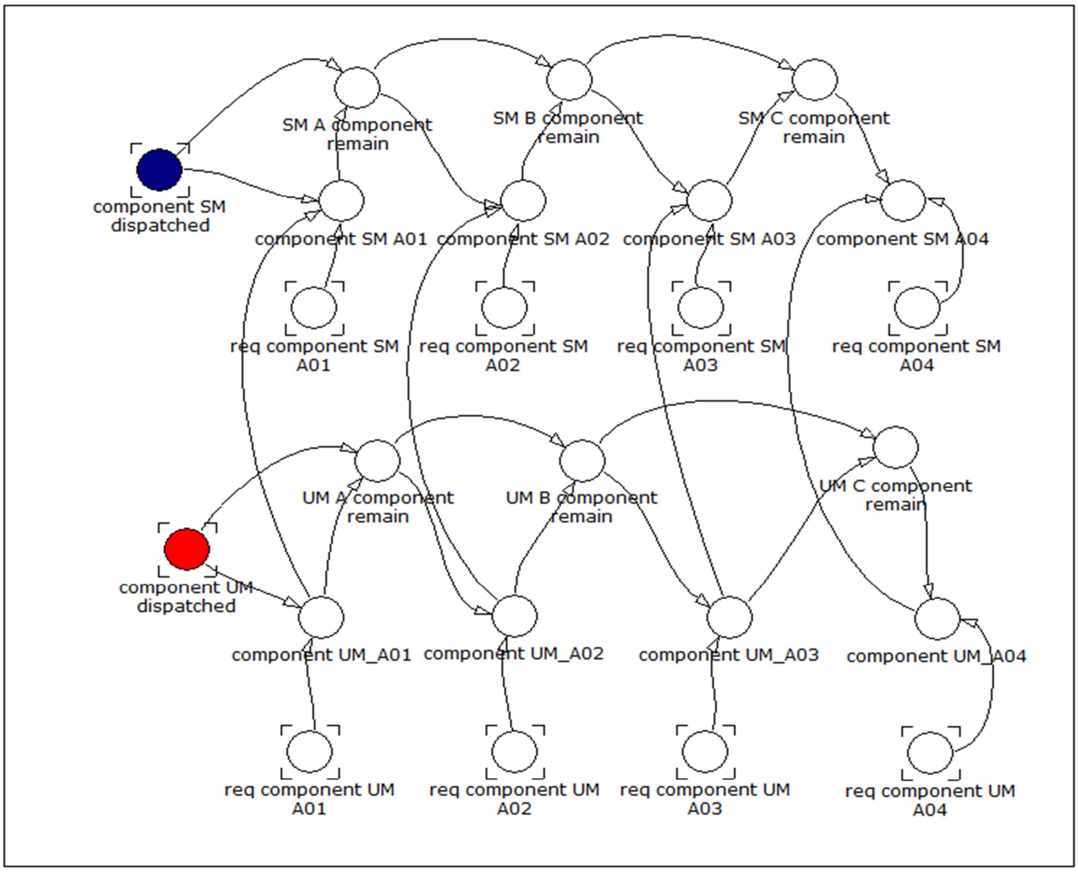


Figure 5-12 Simulation sub model for component distribution to each technical system

The dispatched components for scheduled and unscheduled maintenance need to be distributed to the particular requiring unit. The simulation sub model for distributing the components to each unit is presented in Figure 5-12. The first priority for the component distribution is for unscheduled maintenance purposes. Then the replacement either for scheduled or unscheduled maintenance will be done from the first technical system to the second, and so on in consecutive order to the last requiring unit.

5.2.4 Simulation sub model for human resources

In the human resources sub model, there are two options for selecting the unit of measurement for human resource availability: the number of people (mechanic/technician), or man-hours. In this research, man-hours is selected because it is easier to convert man-hours from or to other variables. For instance, man-hours is selected to be the unit of measure in available human resource. Because the trainees are not yet fully skilled, the number of trainees can be converted into FTE (full time equivalent) of skilled worker in term of man-hours. The system dynamics sub model for human resources is presented in Figure 5-13.

In Figure 5-13, three levels are developed. First level is available man-hours (MH) that represents the amount of man-hours available over time. The second level is MH UM buffer that is assigned to represent the amount of man-hours dispatched from the available man-hours to perform unscheduled maintenance. The third level is MH SM buffer that is allocated for the assigned man-hours from the available man-hours to complete the scheduled maintenance.

The available man-hours level variable has MH inflow as the in-rate variable and MH outflow as the out-rate variable. The constant variable named Provided MH is the initial value of the available MH level. The MH outflow specifies the number of man-hours assigned for maintenance purposes and is determined by the required MH. As shown in Figure 5-13, the required man-hours auxiliary is calculated when there is an order either for scheduled maintenance or unscheduled maintenance. The required man-hours is then compared to the available man-hours in the MH outflow out-rate to determine the number of man hours assigned. If the required man-hours is less than or equal to the available man-hours, the number of assigned man-hours will be equal to the required man-hours, otherwise it will be as much as the available man-hours.

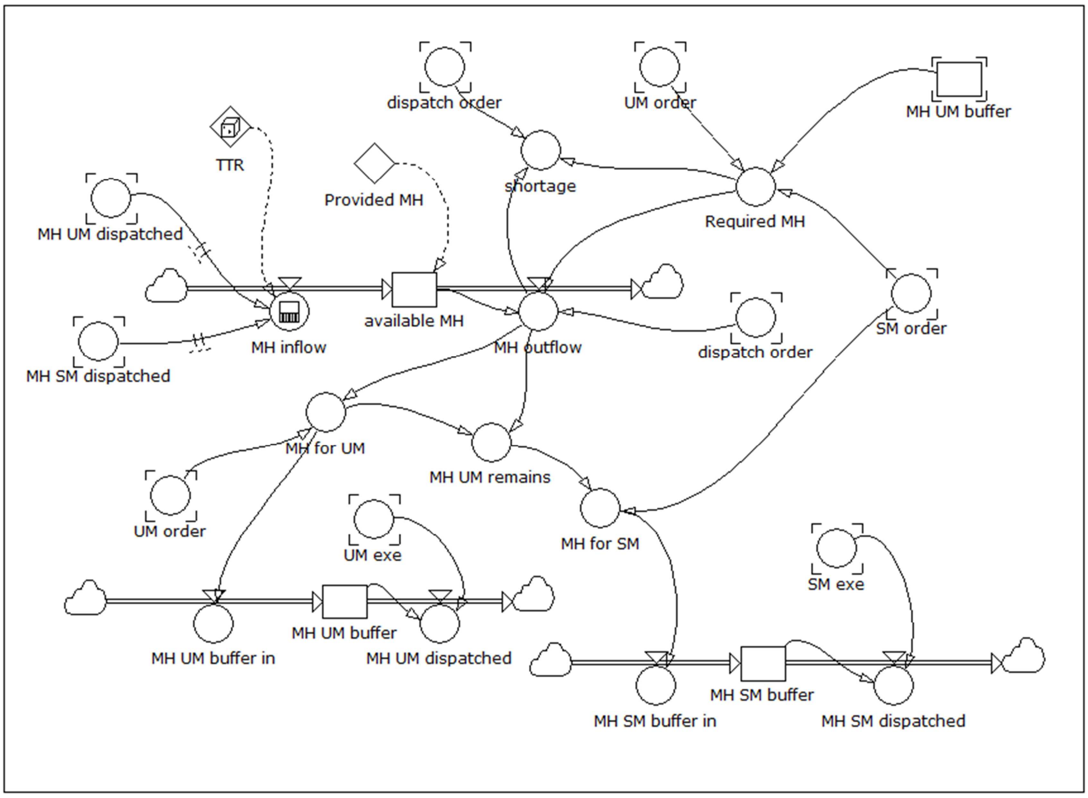


Figure 5-13 Simulation sub model for human resource provisioning sub system

After the number of assigned man-hours for maintenance is determined in the MH outflow out-rate, it is distributed to do the maintenance order. As unscheduled maintenance is prioritised ahead of scheduled maintenance, the allocation of man-hours is also firstly assigned for unscheduled maintenance if required. The amount of man-hours in the MH outflow is distributed to MH for UM auxiliary first and then the remaining man-hours (in MH UM remains) is distributed for scheduled maintenance in MH for SM.

In the MH for UM, the allocated number of man-hours for unscheduled maintenance is added to the MH UM buffer through the MH UM buffer in the in-rate. In the MH UM buffer, the number of assigned man hours is kept waiting until an unscheduled maintenance execution order is issued. Once it is issued, the assigned man-hours will be dispatched. After completing the unscheduled maintenance, the assigned man-hours is returned to the available man-hours through the MH inflow in-rate. There is a time delay between the dispatches of man-hours until it is returned to the available man-hours. This time delay is the time to repair or complete the unscheduled maintenance job. Similar logic is also applied to the assigned man-hours

for scheduled maintenance from allocation for scheduled maintenance, dispatched until returning to the available man-hours.

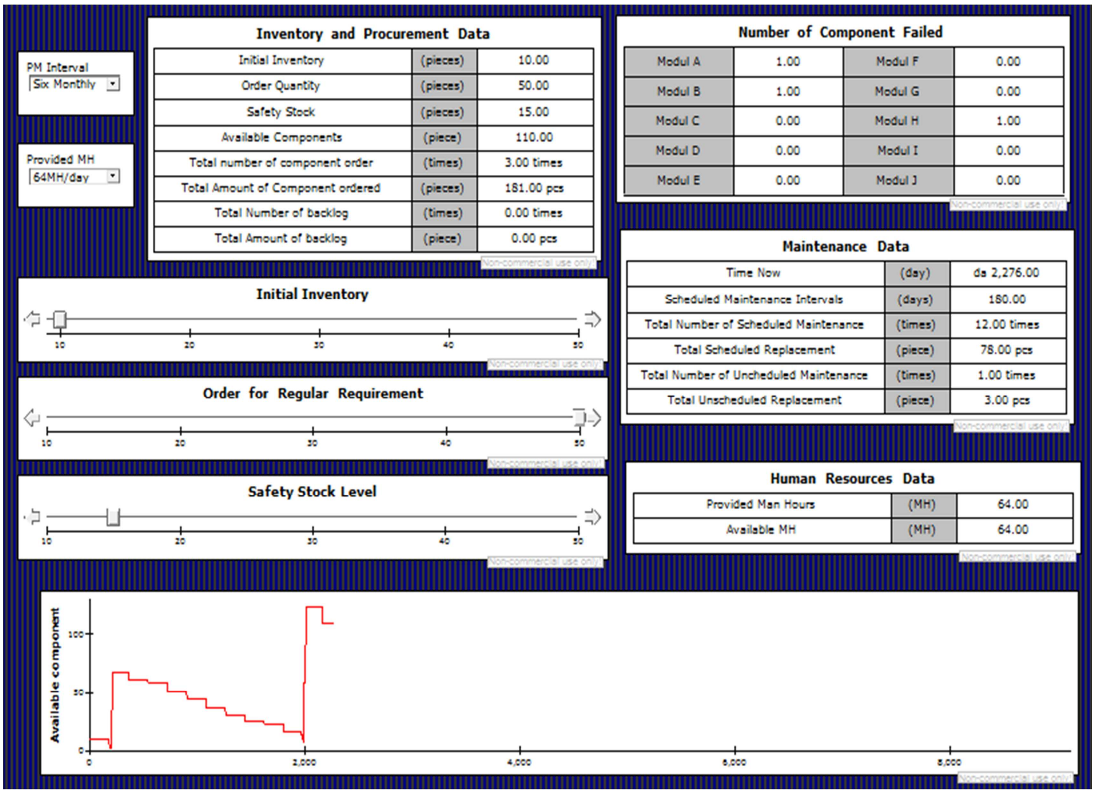


Figure 5-14 Simulation dashboard

For convenience when running the simulation, a simulation dashboard is created and shown in Figure 5-14. It displays a brief view of parameters on the running simulation tabulated as information about purchasing and inventory data, the number of failed components, maintenance, and human resources. On the other parts of the dashboard (i.e. combo box menu for SM interval and provided MH, slider menu for Initial inventory, order for regular requirement, and safety stock) there are some facilities used to change the simulation input of certain variables in order to generate different scenarios implemented in the model. Table, combo box menu and slider menu can be added for other input variables if required. If necessary, a graph showing the dynamics over time of one or several variables can also be shown. The graphic can help a decision modeller or decision maker to analyse the system when the simulation is run. The overall system dynamics model can be adjusted based on

selected case studies. In the following chapter, some case studies are presented to verify the system dynamics model.

5.3 Model Validation

Validation is meant to ensure that sufficient confidence in the model's "soundness and usefulness" is obtained before it can be used for policy analysis (Maani and Cavana, 2000). In other words, after the model is verified as being valid, the model is sufficient to represent the structure and behaviour of the system for policy analysis purposes. The model validation process in this research adopts the guideline suggested by Coyle (1996). Coyle (1996) recommends a guideline for validation process as quoted in Maani and Cavana (2000) that includes:

1. Ensuring that the CLD corresponds with the statement of the problem.
2. The model must be dimensionally valid: the dimension is usually also called 'unit of measurement'. Some simulation programs have features to automatically check the validity of the dimensions.
3. The model must not produce unrealistic values: in the case of maintenance resource provisioning, unrealistic values can be negative available man-hours or inventory, or the value of available man-hours being more than provided man-hours.
4. The model should maintain conservation flow: maintaining conservation of flow means that the total quality of such variables entering, departing, and remaining in the system should be analysed. In an inventory system for instance, if the number of inventory is 10 units and 5 purchased units arrive at the same time and there are 8 units requested, the number of inventory should be 7 units left. If the model indicates that inventory is not 7 units, the model could be considered as not sufficiently valid.

5.3.1 Ensuring that the CLD corresponds with the statement of the problem

The first step of the recommended validation process is ensuring that the CLD fits with the statement of the problem. The main objective of the system dynamics modelling in this research is to represent the structure, behaviour, and interaction between variables in integrated maintenance and its resource-provisioning

system. The CLD in Figure 5.2 presents the feedback structure of three sub-systems: maintenance, human resources, and purchasing & inventory. The CLD describes how a maintenance system relates to human resources; and purchasing & inventory system. It can provide a preliminary analysis of the effect of a particular policy on the resources-provisioning system to the maintenance system, and vice versa. For instance, management shortens the interval for scheduled maintenance. From the CLD, a shorter scheduled maintenance interval leads to a higher requirement for part/resources and a higher demand for part/resources from inventory. This condition requires changing inventory policy on the number of order quantity.

Changing policy in human resources may also affect the maintenance system, for instance, policy in man-hours lay off. This policy generates a lower availability of man-hours. When the number of provided man-hours is lower, the number of man hours assigned to the maintenance jobs is also less. It may lead to delay of a maintenance job, and/or higher asset failure to lower asset availability.

In general, from the aforementioned elaboration, it is concluded that the CLD provided in Figure 5.2 is capable of representing the structure, behaviour, and interaction between variables in the integrated maintenance and its resource-provisioning system as required for this research.

5.3.2 The model must be dimensionally valid

The system dynamics model in this research is developed using Powersim Studio 9. The software has the capability of automatically checking the dimension of the equations. This feature enables receiving error messages every time the dimension of the equations is invalid and the model could not be run. This process ensures every equation inserted in the model was inspected for dimensional validity.

5.3.3 The model must not produce unrealistic values

For this purpose, the model was run to discover the availability pattern of man-hours and inventory. The number of provided man hours inputted in this run is 32 man-hours per day and the maximum level of inventory is 5 units. The simulation outputs are presented in Figures 5.15 and 5.16. Figure 5.15 shows that the value of available man-hours from the beginning to the end of simulation time varies from 0 to 32.

There is no unrealistic value during the simulation. Also in Figure 5.16, which provides the information about part availability during the simulation, the value of the inventory level from the beginning to the end of simulation is sufficiently realistic.

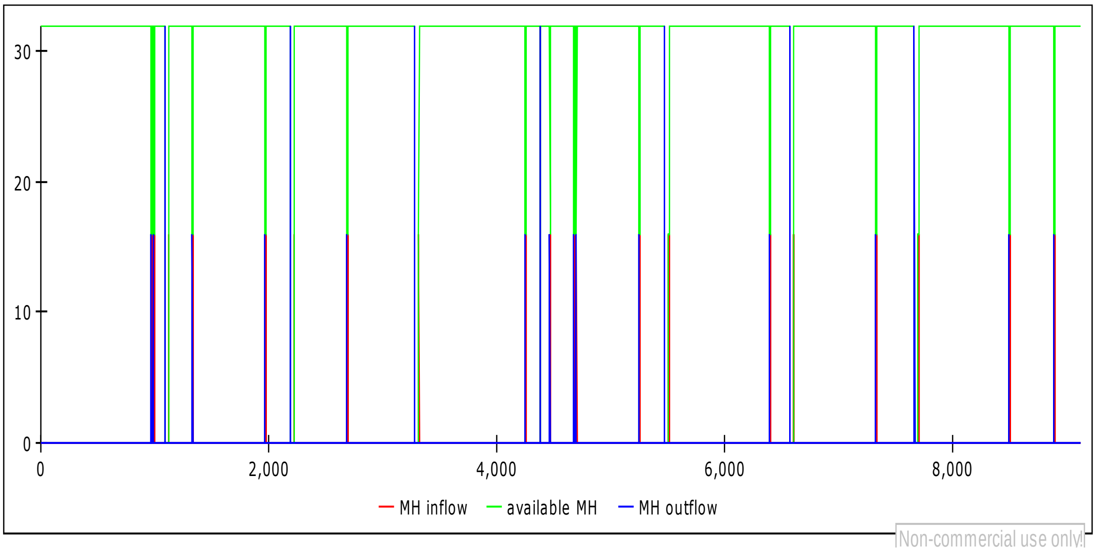


Figure 5-15 Man-hours availability

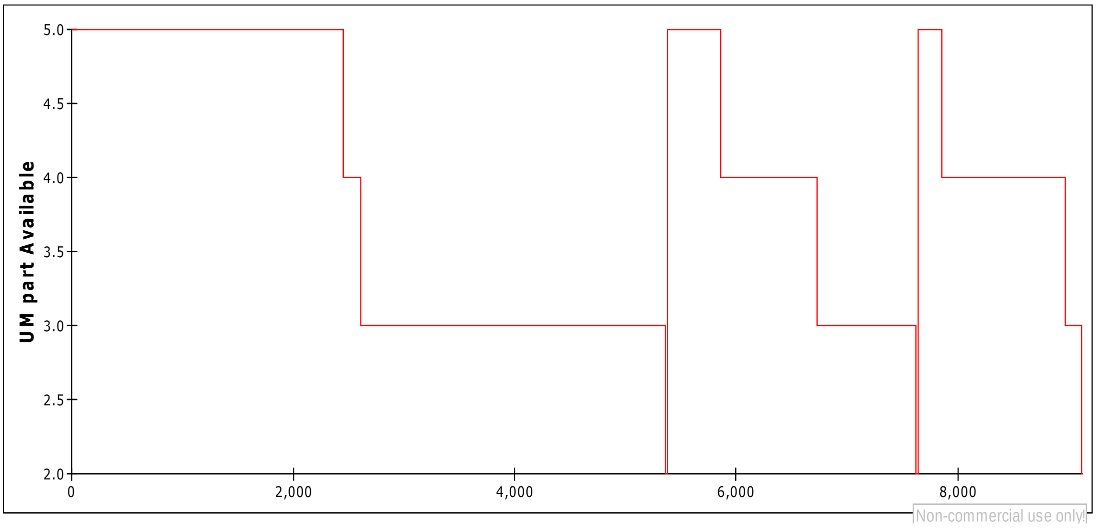


Figure 5-16 Inventory Level

5.3.4 The model should maintain conservation flow

To assess the conservation of flow in the model, the level of provided man-hours and inventory are examined. The inflow and outflow of man-hours are presented in Figure 5.15. It is seen that all values of outflown-man-hours returns as inflow man-hours after every completion of maintenance activities. More details of the conservation of flow are provided in Table 5.1, which presents values of inflow variable, outflow variable and available parts variable for maintenance purposes, and is calculated every 1000 days. The values of the variables show that there is consistency in maintaining the conservation of flow for inventory level.

Table 5-1 Conservation of Flow in inventory level

day	Accum part inflow	UM part Available	Accum part outlow
0	0.00	5.00	0.00
1,000	0.00	5.00	0.00
2,000	0.00	4.00	1.00
3,000	0.00	3.00	2.00
4,000	3.00	5.00	3.00
5,000	12.00	11.00	6.00
6,000	12.00	10.00	7.00
7,000	12.00	8.00	9.00
8,000	12.00	7.00	10.00
9,000	12.00	4.00	13.00

From all the analysis performed based on the guideline, it can be concluded that the model is valid and capable for further analysis. As mentioned in Maani and Cavana (2000), a valid model is ready for further policy analysis purposes. The application of the developed model and how it is used for policy analysis are presented in Chapter 6.

6 CASE STUDIES APPLICATION FOR DEVELOPING INTEGRATED MAINTENANCE RESOURCE-PROVISIONING POLICIY

6.1 Case study overview

This case study presents utilising the developed integrated model from system dynamics simulation and LCCA to arrive at a combined maintenance and resource provisioning policy for a wind farm. A wind farm can be composed of tens to hundreds of wind turbines. In general, each wind turbine as an engineered complex asset consists of several units: blades, gearbox, generator, nacelle, tower, and a set of converter modules in the transformer, as shown in Figure 1-2 in Chapter 1. More details about how a wind turbine works are shown in Figure 6-1.

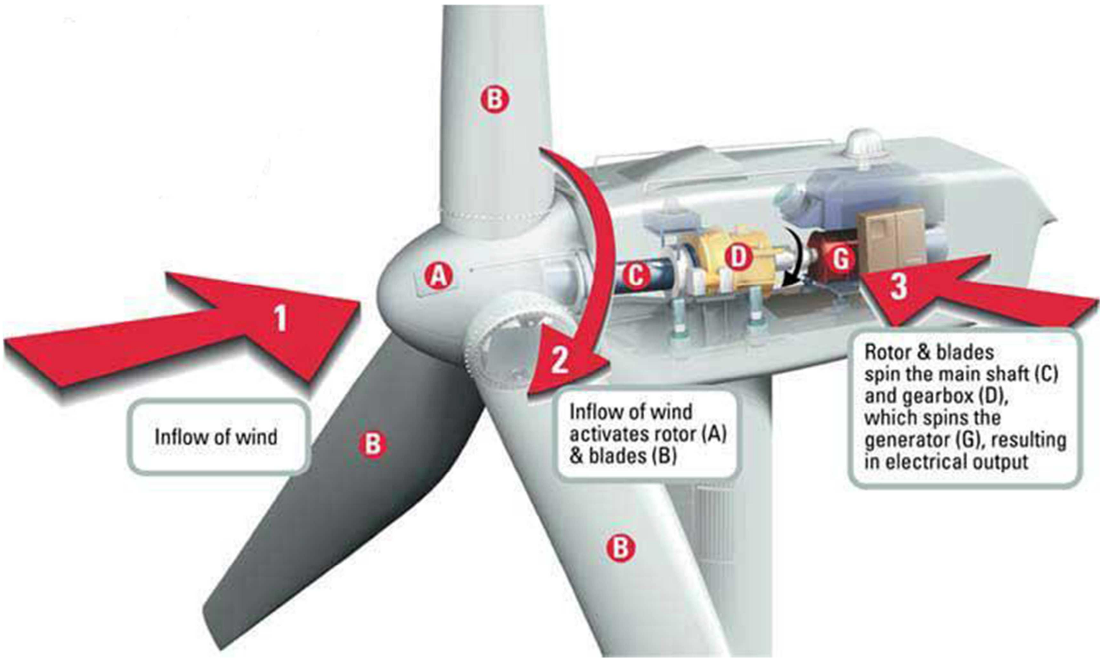


Figure 6-1 How a Wind Turbine Works
(http://www.ecoplanetenergy.com/all-about-eco-energy/overview/wind/)

The blades are designed to capture wind energy. The blades spin at a slow rate of about 6 to 20 rpm, but at the tip the speed can be over 240 kilometres per hour. The nacelle is a house of two main mechanical units: the gearbox and the generator. These two units convert the rotation of the blades from 20 revolutions per minute to more than 1,500 revolutions per minute in the generator. The rotations in the generator produce electricity. The frequency of the produced electricity varies and

needs to be adjusted before it can be transmitted to the grid. For this purpose, a transformer is set up and placed in the base of the tower. The tower is a white steel cylinder, about 45 to 60 meters tall and up to 3 meters in diameter. The wind turbine starts operating at a wind speed of 9 kilometres per hour and reaches its maximum power at 49 kilometres per hour. In conditions when the wind speed is more than 120 kilometres per hour, the wind turbine shuts down to avoid damage or fire hazard.

According to Hau (2006), there are five units/parts which establish the mechanical-electrical functional chain in a wind turbine as presented in Figure 6-2. From those five units/parts, three are inside the wind turbine: gearbox, generator, and transformer.

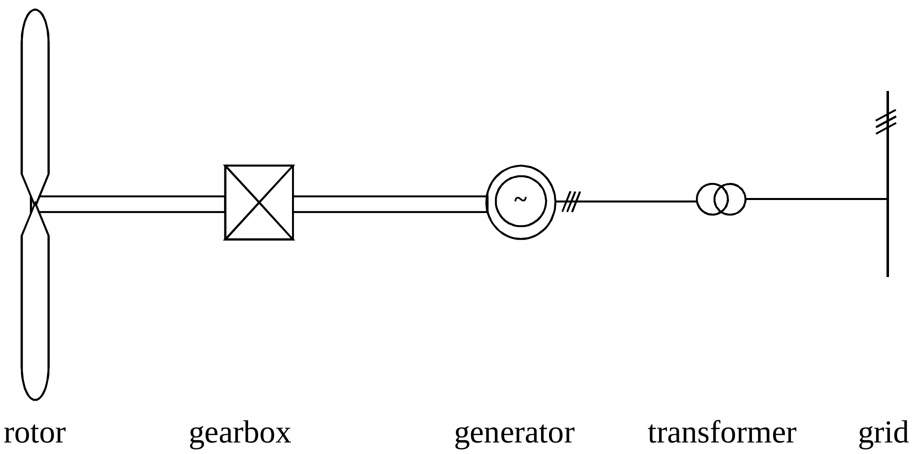


Figure 6-2 Mechanical-electrical functional chain in a wind turbine (adopted from Hau (2006))

In this case study, the developed system dynamics simulation model and the new LCC model are tailored for each unit independently covering the major three units: the generator, the gearbox, and the converter module in the transformer, respectively. Then, these tailored models for the units are merged together accounting for all identical units in all the turbines in the wind farm. This case study covers a wind farm that consists of 10 wind turbines which are considered as engineered complex assets. The schematic presentation of the case study is presented in Figure 6-3.

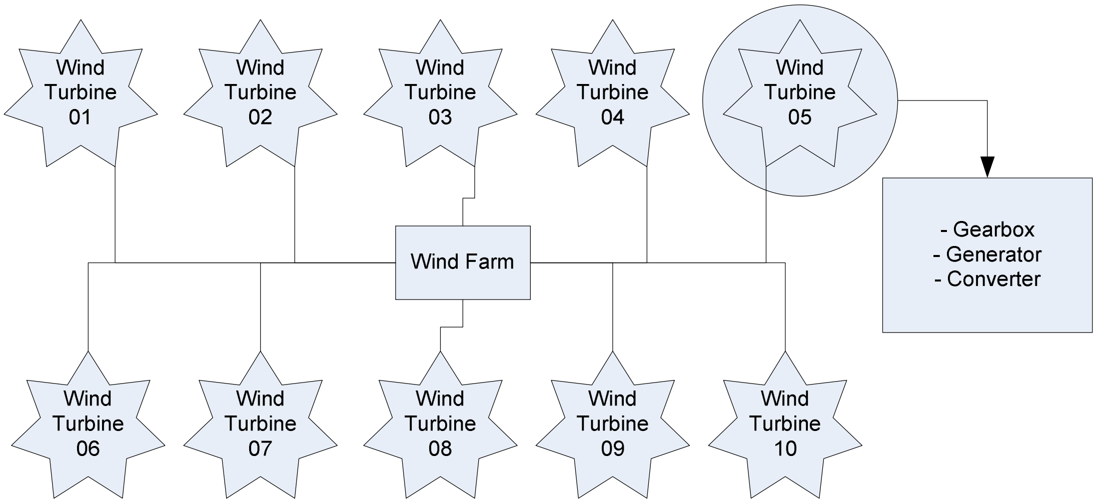


Figure 6-3 the schematic model of 10 wind turbines in a wind farm

As the focus of the modelling is on the generator, gearbox, and converter, the resource provisioning policy for the maintenance program for each unit is analysed. Three approaches to tailoring the developed model are presented for generator, gearbox, and converter. Each case includes case description, and system dynamics simulation to generate possible scenarios in terms of maintenance and resource provisioning parameters/variables, that in turn establish a set of alternative options reflecting the alternative combined maintenance and resource provisioning policies. At the same time the developed model engages these resulting alternative options/policies through the LCCA and presents the results.

6.2 Case Study 1: Resource provisioning Policy for Wind Farm Generator Maintenance Program

6.2.1 Case Description

A generator is a major unit in a wind turbine. Its function is to convert kinetic energy into electrical energy. Each wind turbine has one generator contained in a nacelle. Failure of the generator constitute a failure of the wind turbine to produce electricity. When the wind turbine is in a failure state, a maintenance job is required to be performed. In regards to generator failure, it can be questioned whether repair or replacement is the better option. According to a comparison of the costs of repair and replacement, repairing a failed unit seems to be a better approach, because it is usually cheaper compared to buying a new unit for replacement. However,

practically considering a cost-benefit analysis of all involved costs, such as transportation and logistics over the longer period of the unit's lifetime, the replacement option is more cost effective (Abb, 2006). Therefore maintenance activities in this case are limited to replacement of units. Both scheduled and unscheduled maintenance are done in terms of unit replacement. Unscheduled maintenance (UM) will be performed to replace the generator when a failure occurs in the generator.

6.2.2 Assumptions in the Maintenance Program and Resource provisioning for the Simulation of the Generator Case

The aim of the system dynamics simulation in this case will focus on generating scenarios based on different intervals of replacement that reflect alternative maintenance policies involving scheduled and unscheduled maintenance. Tian et al. (2011) recommend scheduled replacement for generators every 4 years. However in this case study, the interval for the scheduled replacement associated with the model is extended to between 5 and 7 years. This assumption considers the lifespan of the wind turbines to be approximately 25 years. By selecting 5 years and 7 years, there will be 4 or 3 times scheduled replacement during the assets' lifespan. To replace the generator during scheduled maintenance, replacement criteria need to be provided. The unit is to be replaced if the unit reaches a particular number of days after the last replacement (t_{sr}), which is calculated based on the interval of scheduled maintenance and a threshold. The threshold is a variable to determine the minimum t_{sr}. In this case study, the threshold is determined to be 180 days and 365 days. For instance, if the scheduled maintenance interval is selected once every 5 years (1,825 days) with 365 days of threshold, then the value of t_{sr} is 1460. Based on this t_{sr} value, all generators with a t_{sr} more than 1,460 days will be considered for a new replacement. All generators with t_{sr} is less than 1,460 days will not be replaced.

According to Tian et al. (2011), the lifetime of the generators follows a Weibull distribution with λ = 3300 days and β = 2.

$$P_f(t) = 1 - e^{-(\frac{t}{\lambda})^\beta} \quad \text{...Eq. 6-1}$$

where:

$P_f(t)$: Probability of failure in time t

λ : Generator life span (days)

β : Weibull shape parameter

To generate a random lifetime of the generators, the value of *t* is calculated, where,

$$t = \lambda(-ln\left(1 - P_f(t)\right))^{1/\beta} \quad \text{Eq. 6-2}$$

For the human resource provisioning policy, the model is needed to find the optimum level of man-hours. Initially, 48 man-hours and 64 man-hours are set in the scenario development. In the purchasing and inventory, initial inventory is pre-set as 2 units, likewise the safety stock level. When the inventory level reaches 2 units, a purchasing order will be released to fulfil the desired inventory level according to the particular scenario. Details of the simulation input data and its sources are resumed and presented in Table 6-1.

The number of man-hours in this case study is not only provided in particular for generator maintenance, but also for the maintenance for other types of units in the wind turbine. The main issue is how to share the fixed cost of provided man-hours to each type of unit in the wind turbine. To simplify the analysis, the fixed cost for man-hours will be distributed, based on the percentage of the cost breakdown for each types of unit in the wind turbine. Based on the data in Irena (2012), the generator contributes approximately 5% in the cost breakdown for each wind turbine. This information will be used as a basis to determine the composition of fixed costs for man-hours for the maintenance of generator. The fixed man-hours cost for the generator is determined to be 5% of total annual salary for the provided man-hours.

Table 6-1 Generator simulation input data, its sources, and assumptions

No	Input data	Value	Source
1.	Generator life time/unit (days)	Weibull (3300,2)	(Tian et al., 2011)
2.	Generator price/unit	AUD 16,250	(Fingersh et al., 2006)
3.	Unscheduled maintenance cost/ event	AUD 187,500	(Tian et al., 2011)
4.	Scheduled maintenance cost/ event	AUD 42,188	
5.	Currency converter USD to AUD	1 USD = 0.8 AUD	
6.	Inflation / annum	2.69 %	Australian Bureau of Statistics
7.	Interest / annum	2.49 %	Australian Reserve Bank
8.	Average Revenue / kWh	AUD 0.075	(Lesmerises and Crowley, 2013)
9.	Stock keeping cost / annum	0.5 %	(Tracht et al., 2013)
10.	Assumed operation time /day	8 hours	(Lesmerises and Crowley, 2013)
11.	Technician Annual salary/ per person	AUD 55,000	http://www.payscale.com/
12.	Repair time distribution (days)	Normal (5,2)	
13.	Wind Turbine Power Grade	2MW	

6.2.3 Application of the Model Developed in the Generator Case

In this case, the application of the developed model involves tailoring the system dynamics simulation developed in chapter 5 to generator maintenance and its resource provisioning program. The application of system dynamics generates some scenarios to be run in the simulation model. The scenarios are compared with the LCC analytical model presented in chapter 4 in order to determine the optimum alternative for maintenance and its resource provisioning policy.

Before developing the system dynamics model, it is necessary to present the modelling logic. The modelling logic for generator maintenance and its resource provisioning is presented in the flowchart shown in Figure 6-4. There is one generator in each wind turbine; failure of this unit makes the whole wind turbine fail.

In the beginning of the simulation, initial states of simulation are set. The initial set parameters include initial lifetime for each generator; scheduled maintenance event and interval; initial unit inventory level; and initial man-hours level.

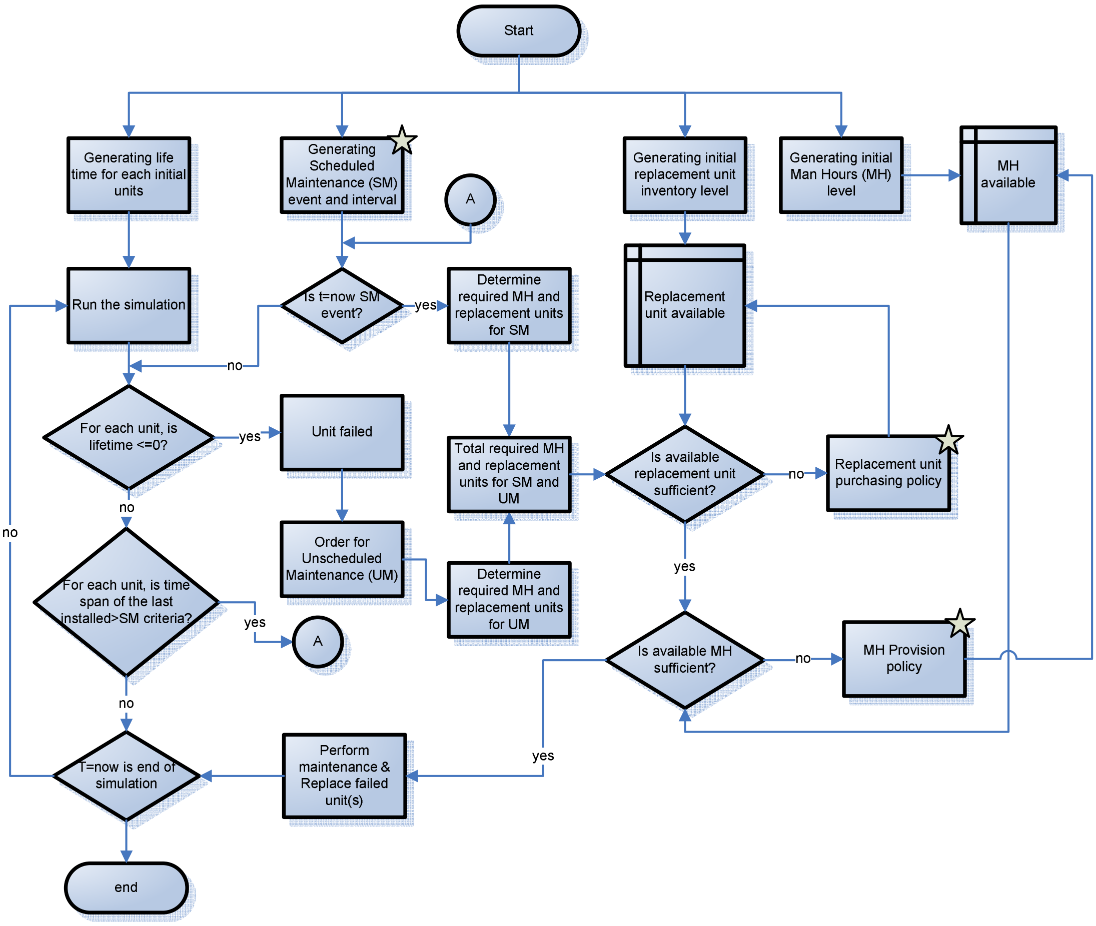


Figure 6-4 The modelling logic of the generator maintenance and its resource provisioning

The first variable for which values are generated in the beginning of the simulation for each generator as a unit in each wind turbine is the lifetime variable. In the generator simulation model, only 10 random lifetime values will be generated for 10 generators, as units in 10 wind turbines in the wind farm. The number of failed units in the wind farm is monitored during the simulation as shown in Figure 6-4. If the unit fails, the wind turbine is considered not to be working, and an unscheduled maintenance job is required to replace the failed unit. Otherwise, the failed units will be replaced during the scheduled maintenance. This process continues until the end of the simulation time.

The second variable for which values are generated in the initial simulation state is the interval of scheduled maintenance. The value of scheduled maintenance interval variable determines when the scheduled maintenance will be executed. At the instance of scheduled maintenance, data about the units requiring replacement is collected and also the man-hours requirements are determined.

This information is then used in the maintenance and resource provisioning plans of the related functions. The scheduled maintenance is executed after sufficient amount of required resources is provisioned. Unscheduled maintenance process simulation is similarly done, however the order is only triggered when there is a unit failure.

The third variable is the level of inventory. Generating values for initial inventory level determines the initial level of provided units in the inventory. At the time when there is an order to supply units for maintenance purposes, the required number of units should be provided and withdrawn from the inventory. After the units are withdrawn, the level of inventory may reach a safety stock level. Safety stock level is a level where the number of units in the inventory is just enough to fulfil the requirement during the lead time. When the safety stock level is reached or the number of required units to be provided is more than the available units in the inventory, a purchasing order is issued. Values of variables in the purchasing and inventory process, such as safety stock and the number of units in each order, are used for setting the provision policy.

The fourth value of variable to be generated is the level of provided man-hours. A maintenance order will determine the number of required man-hours. In the model, after a sufficient number of required units for the maintenance order is provided, a number of man-hours also will be provided. The number of provided man-hours will be deducted from the number of available man-hours. Once the maintenance action is finished, the number of provided man-hours will be returned and added to the number of available man-hours.

After the modelling logic is presented, the system dynamics model can be developed based on the logic. The developed model in chapter 5 is tailored to model this generator maintenance and its resource provisioning program. The tailored model is composed of three sections. The first section deals with simulation of the maintenance program. The second section deals with simulation of the purchasing

and inventory provision programs. The third section deals with the human resource provisioning program. This model requires developing some sub models assigned as buffers to allocate maintenance resources for maintenance actions. The function of the buffers is to temporary store the maintenance resources after being dispatched from the inventory or human resource department until the maintenance jobs are finished.

Starting with the first section of this model, a simulation sub model for the generator maintenance program is presented in Figure 6-5. The Figure provides an example for the maintenance program of two units of generators in two wind turbines only: wind turbine 01 and 02.

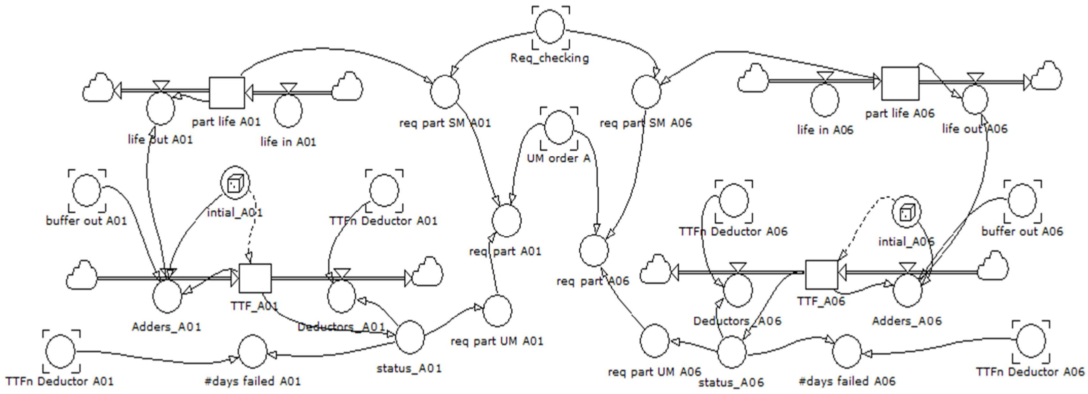
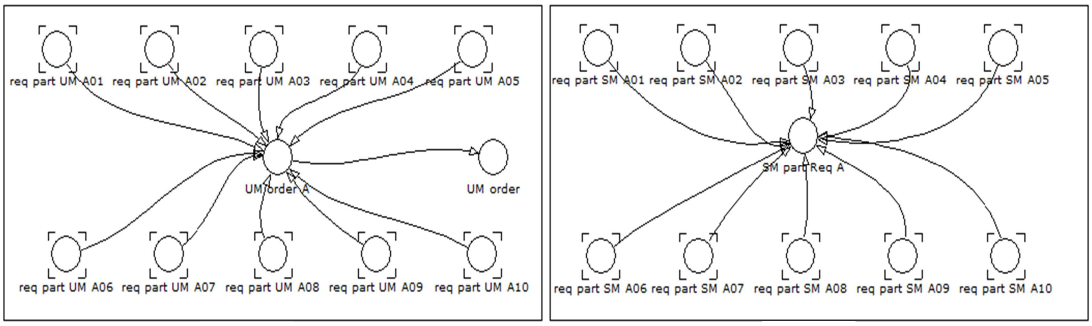


Figure 6-5 Simulation sub model for the generator maintenance program

The model in Figure 6-5 is a modified version of the general model developed in Figure 5-6. The sub model in Figure 6-5 is a combination of the sub models in Figure 5-6 and Figure 5-7. The initial lifetime for the generator is set based on Eq. 6-2. In Eq. 6-2, there is a variable for the probability of failure in time t ($P_f(t)$), which has a value between 0 and 1. By generating a random number between 0 and 1 to replace $P_f(t)$ in Eq. 6-2, a random lifetime for the generator will be produced. The generated lifetime is then assigned to a variable named *initial_A0x,* where x represents the unit number.

For the purpose of scheduled maintenance, one level variable is presented in each unit to store the information about the number of days after the last replacement of the unit in each wind turbine. The variable is called *part life A0x*. The value in this variable is increased by 1 every simulation day and decreased by the whole amount in the part life level whenever there is scheduled or unscheduled maintenance, which takes the value in the part life level back to zero. A few days before the scheduled

maintenance event, the number of units required for scheduled maintenance is calculated based on this level variable, and accrued as the *SM part Req A* variable, as shown in Figure 6-6 part 2. The number of units required for unscheduled maintenance is accrued in Figure 6-6 part 1.



(1) (2)

Figure 6-6 Simulation sub model to accrue the number of unit required for maintenance jobs

The second section of the generator system dynamics simulation model is purchasing and inventory. The sub model for purchasing and inventory is shown in Figure 6-7. The purchasing and inventory sub model is different from the sub model developed in chapter 5, as it is tailored to this case by introducing two types of purchasing: purchasing for regular inventory to maintain the inventory level and purchasing for scheduled maintenance requirements.

The accumulation of requested units for maintenance from the sub model in Figure 6-6 is then inserted into the purchasing and inventory sub model to determine the number of units required for each scheduled and unscheduled maintenance event. The *UM order* variable is the number of units required for unscheduled maintenance, and the *SM part req A* variable is the number of units required for scheduled maintenance.

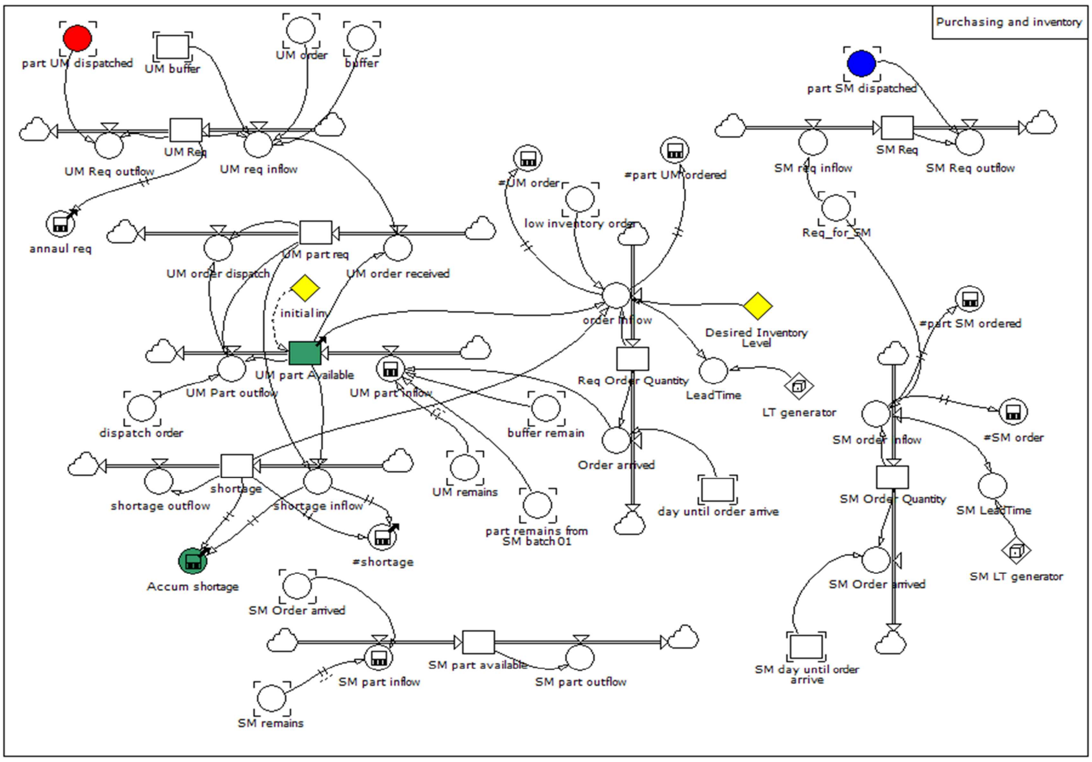


Figure 6-7 Simulation sub model for purchasing and inventory

On the top left corner of Figure 6-7, *UM order* creates *UM req* level to store the total amount of required units for unscheduled maintenance. A similar process is applied in the *SM req* level to store the total amount of required units for scheduled maintenance. The next process is fulfilling the requirements of maintenance jobs and purchasing following the logics presented in the model. Then, the allocation of the unit either to scheduled and unscheduled maintenance is presented in Figure 6-8 and 6-9.

As discussed in the beginning of section 6.2.2; that the system dynamics simulation model for generators requires buffers to store the allocated maintenance resources after being dispatched from their origin until the maintenance job is accomplished. The variable shortcuts for replacing unit buffers can be seen in Figure 6-9; buffers are used as indicators: they indicate whether the requirements for a particular unit have been fulfilled.

Take unit A01 for instance, the requirement for unit A01 is stored in the *req partA01* variable. If the value of this variable is 1, this means that the unit A01 requires replacement. Then after the replacing units are allocated from the inventory, the unit is temporarily stored in *buffer A01*. Therefore, if the value of *buffer A01*

shows 1, this means that the requirement for unit A01 has been fulfilled. Details about the buffers for each maintenance resource are shown in sub model 6-13 and 6-14.

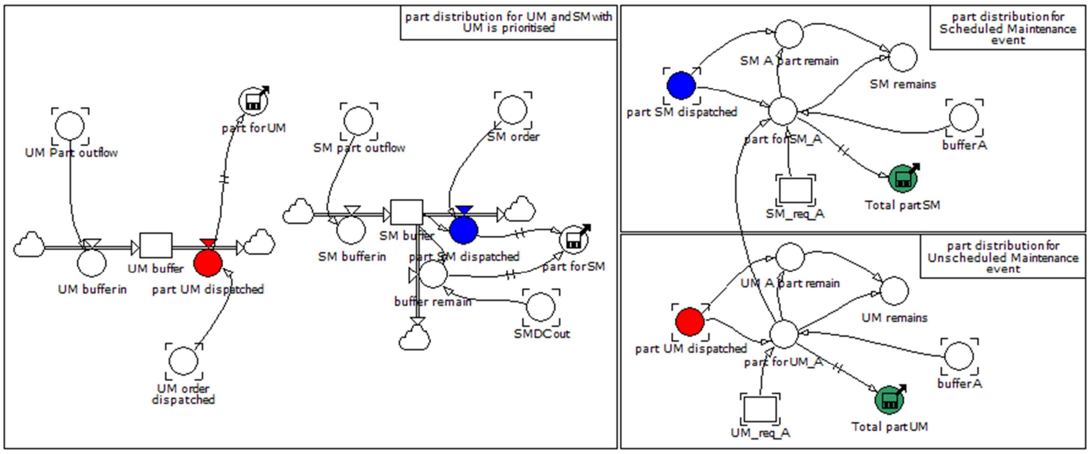


Figure 6-8 Simulation sub model for allocating units to scheduled or unscheduled maintenance

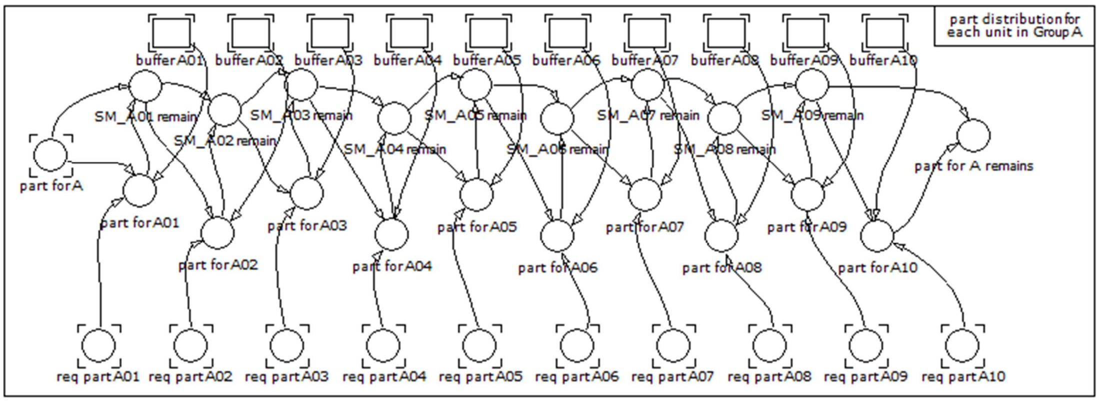


Figure 6-9 Simulation sub model for allocating units to each unit

The third section of the model is for human resources management. The basic model in Figure 5-13 is tailored for the human resource provisioning case by some adjustment as presented in Figure 6-10. The first adjustment is made to accommodate a different random time to repair for each unit. In this generator model, the time to repair is generated randomly for every maintenance event in each unit, as shown in Figure 6-12. The second one is for the returning man-hours after maintenance event. In the generator model, the returning man-hours are first collected in the *MH for A*

remains variable before being added into *MH inflow*. *MH for A remains* is a variable to collect the rest of the allocated man-hours used to finish the maintenance job. The process of generating this variable can be seen in Figure 6-11.

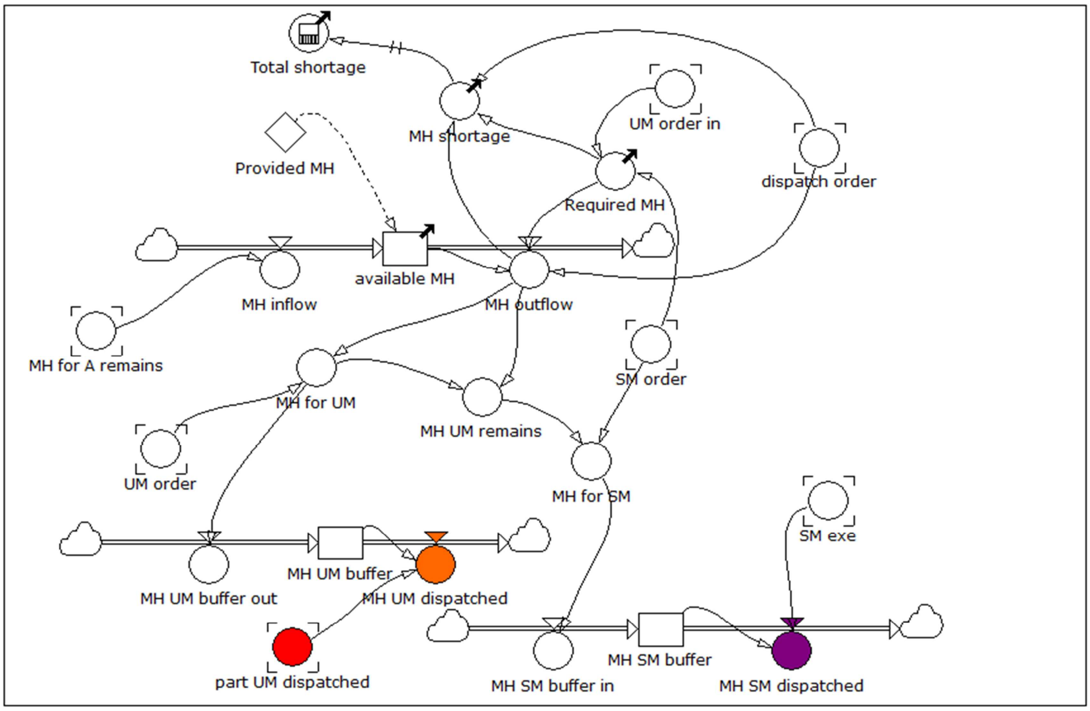


Figure 6-10 Simulation sub model for human resource provisioning

Similar to the sub model for purchasing and inventory, the dispatched man-hours also need to be allocated to each requiring unit. Figure 6-11 shows the process of allocating man-hours into each requiring unit. The requirement for man-hours in each unit is based on the allocated replacement unit to the particular wind turbine. The logic behind using the allocated requiring unit in each wind turbine as the basis for man-hours requirement is when a particular unit requires a maintenance action, the first thing that should be fulfilled is unit requirement, then man-hours requirement. Once a replacing unit is provided, man-hours have to be allocated for the maintenance action to the particular wind turbine being replaced. As shown in Figure 6-11, the allocated unit in the buffers is used as a variable to determine the man-hours requirement for each wind turbine.

As mentioned previously in the example for the unit allocation in unit A01, after a replacing unit is allocated in buffer A01, then man-hours are required. In such a case, it is assumed that every maintenance job in each unit requires two technicians

that each work 8 hours per day, or a total of 16 man-hours per day. Then, after the allocated man-hours are dispatched from the human resource sub model, the man-hours are then allocated to each requiring unit based on its requirement. The allocated man-hours in each unit are stored in the MH buffer in every associated unit, as shown in Figure 6-11.

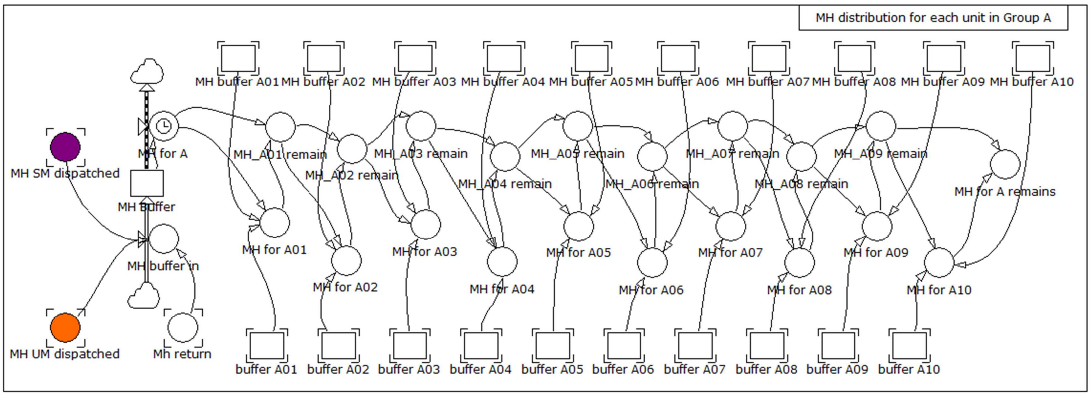


Figure 6-11 Simulation sub model man-hours allocation to each unit

Figure 6-12 shows a sub model for generating repair times for each unit and defining when the maintenance action ends. As shown in Figure 6-12, the allocated units for unit A01 will trigger auxiliary variable *mttr gen A01* to generate a random maintenance time. In the case where weather is considered in the maintenance job, an auxiliary variable named *weather adjA01* is inserted into the model. *Weather adjA01* is a variable used to adjust the time to repair if the weather significantly affects the time to repair. But in this model, the weather adjustment is not considered, so the value of this variable is zero. The generated time to repair is assigned in the *mttr A01* rate variable. The logic associated with the *mttr A01* is:

IF('TTFinish A01'>0,0,IF('part for A01'>0, 'mttr gen A01'+'wheather adjA01',0))

The value in the mttr A01 rate variable is then stored in the *TTFinish A01* level. *TTFinish A01* is a level which stores the random value of generated time to repair. At the same time after the replacing unit is allocated, the process for allocating man-hours is performed. After unit A01 is provided with the required man-hours stored in the *MH buffer A01*, maintenance action is started which triggers the *TTFn Deductor A01* to start working by deducting the value in *TTFinish A01* by 1 day. When the

value in *TTFinish A01* become less than or equal to zero, this is an indication that the maintenance job for this particular unit has been accomplished.

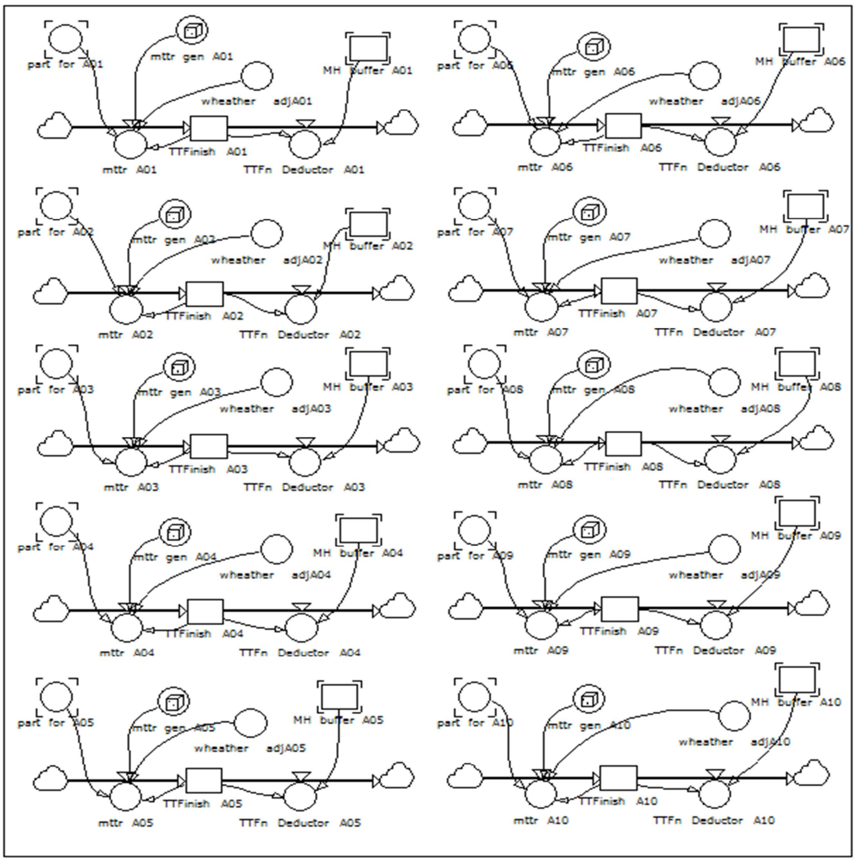


Figure 6-12 Simulation sub model for generating time to repair

The other addition sub models for this case are buffers for replacing units and man-hours, as shown in Figure 6-13 and Figure 6-14, respectively. When a replacing unit or a number of man-hours is allocated to the requiring unit, it fills the associated level. The replacing unit or man-hours is temporarily stored in the associated level until the maintenance action is completed. This will be indicated by the value of the TTFinish variable. When the maintenance action is finished, this means that the replacing unit has been installed, and the man-hours are then returned to the human resource sub model to increase the number of available man-hours.

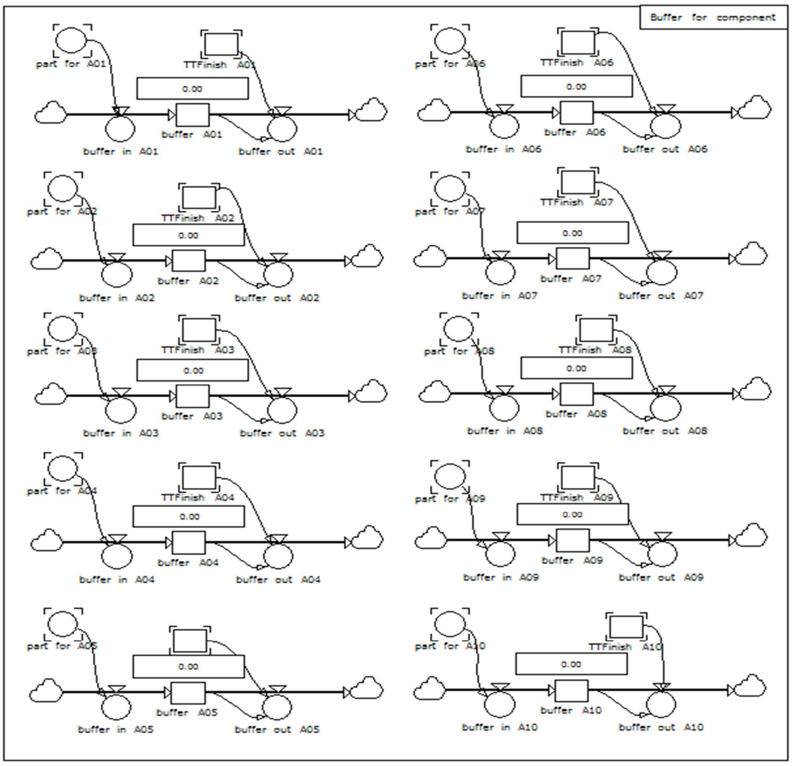


Figure 6-13 Buffers for allocated replacing units

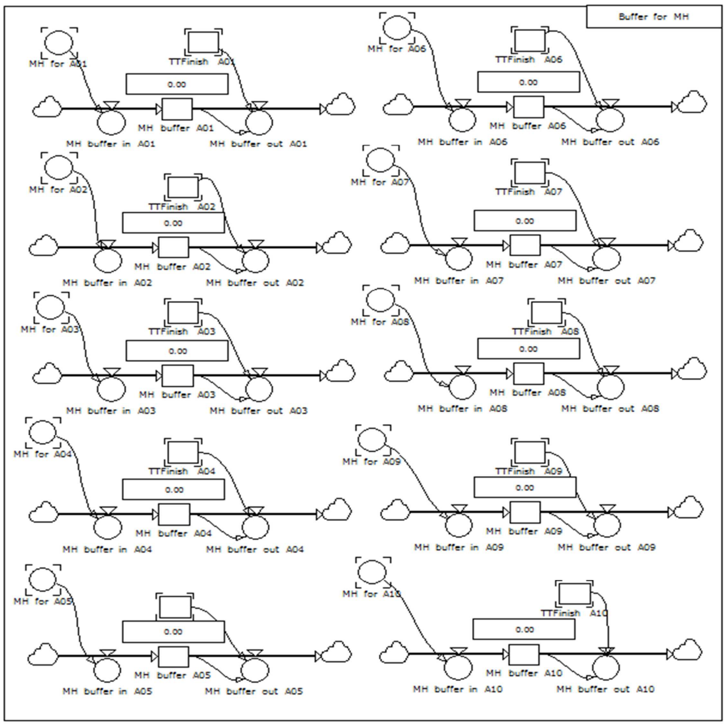


Figure 6-14 Buffers for allocated man-hours

6.2.4 Scenarios Generation in System Dynamic Simulation

Based on the research objective presented in chapter 1, there are two criteria that should be considered in the simulation of scenario planning and performance optimisation: efficiency of the resource provisioning, and the target level of asset performance. In other words, the selected scenario is an option in terms of generated values of a of set variables that achieve the desired asset performance with minimum cost. The simulation model output is a set of combined options for the maintenance program and maintenance resource-provisioning. As shown in the framework for integrated maintenance resource analysis in Figure 3-1, the scope of the analysis covers four divisions: maintenance, human resources, purchasing and inventory, and finance and budgeting. Therefore, in the model, the combined policies are composed of policies from maintenance, human resources, and purchasing and inventory. The analysis also involves finance and budgeting relationships to perform the LCCA, which is promoted to the objective function of the model output in minimizing the LCC through the combined policies of maintenance, human resources, purchasing and inventory.

In this case study, sixteen scenarios are generated. The scenarios are set as alternative values of certain input variables for generating policies in the simulation. This set of variables for generating policies for the integrated maintenance programs and their resource provisioning are scheduled maintenance interval, inventory level, provided man-hours, and threshold. The proposed scheduled maintenance interval values selected as the set of alternative policy values in the model are 5 years and 7 years. The inventory level variable affects the number of replacement units purchased for regular requirement, because the number of purchased replacement units is calculated from the desired inventory level subtracted by the available number of units in the inventory. The desired inventory level is the maximum number of units stored for inventory. Alternative values for desired inventory level variable for this simulation are 5 units and 8 units.

The provided man-hours and threshold are the other variables to be set in terms of alternative values for the simulation. In the scenarios, the suggested alternative sets of values for man-hours provided are 48 man-hours and 64 man-hours per day (equivalent to 6 and 8 people per day). The alternative set of values for the threshold variable is 180 days and 365 days. The threshold variable affects the

time span criteria of the unit for scheduled maintenance. There are also other initial values that need to be set in the state as a set of preliminary scenarios, namely the initial inventory level and safety stock level. The initial inventory level is set as 5 units, and the safety stock level is set as 2 units. Detailed combinations for all alternative values of the set of variables for initially generated scenarios are shown in Table 6-2.

Table 6-2 Detail for suggested preliminary scenario

Scenario	SM interval	Desired inv level	Provided MH	Threshold
	years	unit	man hours/day	days
1	5	5	48	365
2	5	5	64	365
3	5	8	48	365
4	5	8	64	365
5	7	5	48	365
6	7	5	64	365
7	7	8	48	365
8	7	8	64	365
9	5	5	48	180
10	5	5	64	180
11	5	8	48	180
12	5	8	64	180
13	7	5	48	180
14	7	5	64	180
15	7	8	48	180
16	7	8	64	180

The combination of all alternative sets of values for the variables produces sixteen scenarios, as shown in Table 6-2, which are set as input for the simulation model. The simulation model generates values for 13 output variables, these being:

1. # of SM order : Total number of scheduled maintenance order
2. # unit performed SM : Total number of unit performed scheduled maintenance
3. # unit performed UM : Total number of unit performed unscheduled maintenance
4. Total Part for SM : Total component required for scheduled maintenance
5. Total Part for UM : Total component required for unscheduled maintenance
6. Total # of order : Total number of purchasing performed during the simulation

7.	Total unit ordered	:	Total number of components ordered during the simulation
8.	Average daily available component	:	The average available component in the inventory
9.	Total time to repair	:	The total repair time for both scheduled and unscheduled maintenance during an asset's lifespan
10.	# turbines days loss	:	The total number of days the turbines failed.
11.	# backlog	:	The number of orders caused by component shortage (available component is less than required).
12.	Accum BL	:	Total number of components purchased because of the shortage.
13.	Daily MH available	:	The number of man-hours available daily.

6.2.5 Simulation Model Output and Life Cycle Cost Analysis

The generated scenarios in the simulation are obtained from a combination of different simulation inputs. These generated scenarios in terms of sets of parameters/variables represent alternatives or options that reflect different maintenance resource-provisioning policies. For example, a set of variables in a scenario reflects maintenance and its resource provisioning policy in terms of different scheduled maintenance interval (I), an order quantity (Q), Re-order Point (ROP) in a purchasing and inventory program, and the number of man-hours provided (MH) in a human resource provisioning program. The output variables of the simulation constitute the input variables for the new devolved LCC model. Then, Eq. 4-14 can be tailored to this case study with the input provided from system dynamics simulation, as seen in Eq. 6-3.

$$LCC\ (I,\ f\text{-}1(t),q,ROP,MH) = \sum_{t=1}^{td}[C_{u,t}(MTBF, MTTR)(m, t+s, t) + F_{o,t} + A_{sys}C_{o,t}m + \sum_{r=1}^{n_{SM,t}}(F_{SM,r,t} + C_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t} + C_{UM,s,t}) + n_{d,t}.F_{SL,t} + T_{d,t}.C_{S,t} + (n_{HR,t}.L_t) + \sum_{l=1}^{n_{p,t}}(\frac{t_{p,l,t}}{365}.L_t) + [(n_{R,t}.F_{R,t}) + \sum_{p=1}^{n_{R,t}}(n_{NHR,p,t}.\frac{t_{NHR,p,t}}{365}.L_t)] + [(n_{RO,t}.F_{RO,t}) + \sum_{q=1}^{n_{RO,t}}(n_{o,q,t}.C_{o,q,t})] + F_{i,t} + (n_{p,t}.C_{p,t}) + (n_{c,t}.C_{i,t}) + (\frac{n_{i,t}+n_{c,t}}{365}.C_{inv,t}) - S_{a,t}(m, t+s, t)]\ (1+\pi)^{t-1}(1+r)^{-t} \quad \text{Eq. 6-3}$$

To simplify the modelling, simulation approach and application, the LCC model development is tailored to the case application to eliminate the cost elements that do not change or have no effect on optimizing the LCC. Therefore, the integrated simulation and LCC model development approach is based on tailoring the LCC model to the application, first to eliminate all unnecessary variables, and then to develop the system dynamics simulation to account for the resources and maintenance policy variables, in order to achieve the overall resource provisioning and maintenance policy optimization.

In some cases, the scenario comparison purpose allows some variables in the formula to be ignored, because in every scenario the values of those variables are equal. Considering the acquisition cost for instance, all scenarios include the same number of assets, resulting in the same value of acquisition cost for all scenarios. In the simulation, the proposed scenarios combine different maintenance policies, purchasing and inventory policies, and human resource policies. For scenario comparison purposes in the simulation, the costs elements in Eq. 4-16 that can be ignored are: (1) Acquisition cost; (2) Fixed operating cost; (3) unit annual operating cost; and (4) Salvage cost. After eliminating these cost elements in Eq. 6-3, the cost elements left in the basic LCC for comparison purposes are: (1) maintenance cost; (2) stoppage loss; (3) human resource provisioning cost; and (4) purchasing and inventory cost. Eq.6-4 is the LCC equation derived from Eq. 6-3 by eliminating the four cost elements as stated.

$$LCC\ (I, f\text{-}1(t),q,ROP,MH)= \sum_{t=1}^{td}[\sum_{r=1}^{n_{SM,t}}(F_{SM,r,t} + C_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t} + C_{UM,s,t}) + n_{d,t}.F_{SL,t} + T_{d,t}.C_{S,t} + (n_{HR,t}.L_t) + \sum_{l=1}^{n_{p,t}}\left(\frac{t_{p,l,t}}{365}.L_t\right) + [(n_{R,t}.F_{R,t}) + \sum_{p=1}^{n_{R},t}\left(n_{NHR,p,t}.\frac{t_{NHR,p,t}}{365}.L_t\right)] + [(n_{RO,t}.F_{RO,t}) + \sum_{q=1}^{n_{RO,t}}(n_{o,q,t}.C_{o,q,t})] + F_{I,t} + (n_{p,t}.C_{p,t}) + (n_{c,t}.C_{I,t}) + (\frac{n_{i,t}+n_{c,t}}{365}.C_{inv,t})]\ (1+\pi)^{t-1}(1+r)^{-t}$$

……………………………………….... Eq. 6-4

The LCC can be calculated during the asset life time (td) from t=1 to t=td, where the cost components of LCC can be represented and elaborated as follow:

a. Maintenance cost : $\sum_{r=1}^{n_{SM,t}}(F_{SM,r,t} + C_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t} + C_{UM,s,t})$

   The maintenance cost consists of scheduled maintenance (SM) cost and unscheduled maintenance (UM) cost, and is calculated from the number of scheduled maintenance events (r) and unscheduled maintenance events (s) in the year t. The SM cost includes a fixed cost for every event of scheduled maintenance (F_{SM}), and the variable cost of every event of scheduled maintenance (C_{SM}). The UM cost includes a fixed cost for every event of unscheduled maintenance (F_{UM}), and the variable cost of every event of unscheduled maintenance ($C_{U\,M}$).

b. Stoppage loss : $n_{d,t}.F_{SL,t} + T_{d,t}.C_{S,t}$

   The stoppage loss is composed of fixed cost whenever a stoppage occurs, and a variable cost per measured time due to the asset failure. The fixed cost for every stoppage ($n_{d,t}.F_{SL,t}$) can be calculated from the number of stoppages which occur at time t, multiplied by the fixed cost of stoppage at time t. The Variable cost per measured time ($T_{d,t}.C_{S,t}$) is the duration of the asset failure at time t, multiplied by the loss per measured time of duration.

c. Cost for human resources : $(n_{HR,t}.L_t) + \sum_{l=1}^{n_{p,t}}\left(\frac{t_{p,l,t}}{365}.L_t\right) + [(n_{R,t}.F_{R,t}) + \sum_{p=1}^{n_{R},t}\left(n_{NHR,p,t}.\frac{t_{NHR,p,t}}{365}.L_t\right)] + [(n_{RO,t}.F_{RO,t}) + \sum_{q=1}^{n_{RO,t}}(n_{o,q,t}.C_{o,q,t})]$

   Basically, the cost for human resources can be divided into cost for personnel salary ($(n_{HR,t}.L_t) + \sum_{l=1}^{n_{p,t}}\left(\frac{t_{p,l,t}}{365}.L_t\right)$); cost for recruitment at time t ($[(n_{R,t}.F_{R,t}) + \sum_{p=1}^{n_{R},t}\left(n_{NHR,p,t}.\frac{t_{NHR,p,t}}{365}.L_t\right)]$); and cost for outsourcing

$([(n_{RO,t}.F_{RO,t}) + \sum_{q=1}^{n_{RO,t}}(n_{o,q,t}.C_{o,q,t})])$. Details of this cost is presented in section 4.1.3.

d. Purchasing & inventory cost: $F_{I,t} + (n_{p,t}.C_{p,t}) + (n_{c,t}.C_{I,t}) + (\frac{n_{i,t}+n_{c,t}}{365}.C_{inv,t})$

The costs that develop the purchasing and inventory cost are fixed inventory cost at time t ($F_{I,t}$); purchasing cost ($(n_{p,t}.C_{p,t})$; which is the cost that occurs at every purchasing event (e.g. handling and delivery cost, administration cost); cost for component$(n_{c,t}.C_{I,t})$; and inventory cost ($\frac{n_{i,t}+n_{c,t}}{365}.C_{inv,t}$).

All scenarios are generated in terms of input values, as summarised in Table 6-2. The number of replications is determined to be 30 replications for the purpose of this study. After the simulation is run, the output of the simulation is tabulated. The summary of the simulation output for all scenarios with a 5 year scheduled maintenance interval is shown in Table 6-3 and the summary for all scenarios with a 7 year scheduled maintenance interval is shown in Table 6-4.

The simulation is run for 25 years (9,125 days) of asset life time, and the output values of variables are recorded annually, except for available man-hours and inventory level, which are recorded daily. Tables 6-3 and 6-4 present the values of average and standard deviation of several simulation output variables for 30 replications of simulation.

The analysis to find optimum scenario is performed based on two variables: (1) Total cost and (2) Asset availability. In this case study, the performance of the wind farm is based on asset availability. Higher asset availability is reflected by a lower number of days loss of the wind turbines in the wind farm. The number of turbine days loss variable is used to calculate the lost profit due to unavailability of the turbines, which is included in the developed LCC model in Eq.6-4. By including the lost due to the unavailability of turbines, the criteria for optimisation becomes the minimum LCC.

Table 6-3 Simulation summary for all scenarios with 5 year scheduled maintenance interval

5 yearly SM scenarios

		Scenario 01		Scenario 02		Scenario 03		Scenario 04		Scenario 09		Scenario 10		Scenario 11		Scenario 12	
variables	unit of measure	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
SM order	times	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00
SM exe	times	29.00	3.52	29.00	2.89	30.00	2.83	29.00	2.75	30.00	3.41	30.00	3.31	30.00	2.67	29.00	3.09
UM exe	times	17.00	4.60	17.00	3.52	16.00	4.14	18.00	3.46	17.00	4.90	16.00	3.61	16.00	3.78	18.00	4.21
Total part SM	pcs	26.00	5.10	25.00	5.30	27.00	5.39	26.00	4.98	25.00	6.22	27.00	4.67	27.00	5.01	24.00	6.38
Total part UM	pcs	17.00	4.63	17.00	3.50	16.00	4.10	18.00	3.35	17.00	4.84	16.00	3.66	16.00	3.78	18.00	4.25
#order	times	9.00	1.70	9.00	1.30	7.00	0.76	7.00	0.52	8.00	1.61	8.00	1.68	7.00	0.75	7.00	0.83
acuum order	pcs	42.00	3.33	41.00	3.57	43.00	3.84	43.00	3.67	40.00	4.45	42.00	3.34	43.00	4.20	42.00	4.36
average daily available component	pcs	5.00	0.60	5.00	1.25	6.00	1.24	6.00	0.66	6.00	1.73	5.00	0.90	6.00	1.78	7.00	1.80
Time To Repair	days	209.87	22.85	206.93	24.71	204.57	19.48	207.80	20.62	200.60	21.24	209.13	20.44	204.30	17.60	203.27	28.17
#turbines days loss	turbine days	294.17	36.13	291.67	24.86	283.00	29.92	294.40	23.60	294.27	67.47	287.27	29.32	282.70	25.27	290.63	32.49
#backlog	times/30 replications	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Accum BL	pcs/ 30 replication	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	

Table 6-4 Simulation summary for all scenarios with 7 year scheduled maintenance interval

7 yearly SM scenarios

		Scenario 05		Scenario 06		Scenario 07		Scenario 08		Scenario 13		Scenario 14		Scenario 15		Scenario 16	
variables	unit of measure	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
SM order	times	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00
SM exe	times	17.00	2.69	15.00	3.68	16.00	3.19	16.00	3.46	16.00	3.25	16.00	3.64	16.00	3.05	15.00	3.24
UM exe	times	19.00	3.87	21.00	5.00	21.00	4.39	21.00	4.65	21.00	3.98	21.00	4.63	20.00	4.41	21.00	3.72
Total part SM	pcs	16.00	3.28	14.00	3.93	16.00	4.07	15.00	3.98	15.00	3.73	14.00	4.14	15.00	3.57	15.00	3.46
Total part UM	pcs	19.00	3.83	21.00	4.98	21.00	4.41	21.00	4.57	21.00	4.01	21.00	4.64	20.00	4.40	21.00	3.77
#order	times	8.00	1.28	10.00	1.92	7.00	0.60	7.00	0.88	10.00	1.52	10.00	1.56	7.00	0.78	7.00	0.68
acuum order	pcs	34.00	2.20	34.00	3.54	36.00	2.82	36.00	4.21	34.00	2.58	34.00	2.45	34.00	2.90	35.00	3.09
average daily available component	pcs	5.00	0.25	5.00	0.32	6.00	0.45	6.00	0.69	5.00	0.27	5.00	0.28	6.00	0.58	6.00	0.55
Time To Repair	days	172.27	20.48	172.47	20.37	171.00	15.16	171.97	23.37	172.53	15.81	171.03	19.21	167.47	15.18	171.40	18.06
#turbines days loss	turbine days	264.23	32.99	276.70	38.12	274.10	25.72	277.37	40.11	275.17	28.22	275.77	35.50	264.87	32.67	274.20	30.15
#backlog	times/30 replications	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Accum BL	pcs/ 30 replication	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	

Tables 6-3 and 6-4 are accumulations of simulation values based on the lifespan of the asset. As stated, the output of the simulation is used as the input in the LCC equation. The developed LCC model is developed to accommodate the simulation but not all variables in Eq. 6-4 are generated from the system dynamics simulation in this case study. In addition, in some cases the terms in Eq. 6-4 need to be tailored to the case. This circumstance leads to adjustment of the LCC to fit the output of the system dynamics simulation presented in Tables 6-3 and 6-4. In this case study, the inventory cost component is adjusted based on estimating the annual inventory cost as 5% of the value of the average number of stored units for a wind farm (Tracht et al., 2013). Based on this information, the adjustment relates back to the inventory cost in Eq. 4-9 which is adjusted and presented in Eq. 6-5. Considering the output variables from the system dynamics simulation and inventory cost in Eq. 6-5, the LCC analytical model for this case study is presented in Eq. 6-6.

$$\frac{n_i+n_c}{365}.(C_c * 0.05) \quad \text{Eq. 6-5}$$

$$\text{LCC}(\text{I}, \text{f-1(t)},\text{q},\text{ROP}) = \sum_{t=1}^{td}\Big[\sum_{r=1}^{n_{SM,t}}(F_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t}) + T_{d,t}.C_{S,t} + (n_{p,t}.C_{p,t}) + (n_{c,t}.C_{i,t}) + \Big(\frac{n_i+n_c}{365}.C_c.5\%\Big)\Big](1+\pi)^{t-1}(1+r)^{-t} \quad \text{Eq. 6-6}$$

In the studies in this chapter, the value of interest and inflation is assumed to be constant. The data of the interest rate is obtained from the Reserve Bank of Australia (rba.gov.au), and the data for inflation is obtained from rateinflation.com. The data obtained for this model development shows that from September 2013 to March 2014, the interest rate is steady at 2.49%. The latest data for inflation is 2.69%. As mentioned in the previous chapter, the value of the discount rate (r) is equal to the interest rate, so in this LCC calculation the value of the discount rate is 2.49%.

Eq. 6-6 is used to calculate the LCC for each scenario, so they can be compared to find the optimum scenario based on selecting the one with minimum LCC. As an example, the average values of output variables and their associated cost for Scenario 01 are presented in Tables 6-5 through Table 6-7. Table 6-5 presents the

average values of the output variables for scenario 01. The values are calculated from 30 replications and presented on an annual basis. Table 6-5 also presents the costs for each year for associated output variables. The cost increases annually, and considers the annual inflation. Table 6-6 presents the annual cost for scenario 01. The values in this table are calculated from the multiplication output variables and their associated costs in Table 6-5. Then, the present value cost is calculated from Table 6-6 and presented in Table 6-7. The result of the LCC calculations is based on Eq. 6-6 for all scenarios are obtained and presented in Table 6-8. The values in Table 6-8 are presented in a chart form in Figure 6-15.

The results obtained from the LCC analysis shows that scenario 5 has the lowest LCC. This indicates that scenario 5 is the optimum alternative for integrated maintenance and its resource provisioning policy for this case study.

Table 6-5 Average values of output variables and its associated cost for Scenario 01

		Year		1	2	3	4	5	6	7	8	9	10	11	12	13
Variables	a	# Scheduled maintenance	(unit)	0	0	0	0	7	0	0	0	0	7	0	0	0
	b	#Unscheduled maintenance	(unit)	0.20	0.50	0.70	1.03	0.73	0.33	0.53	0.77	0.93	0.97	0.20	0.47	0.67
	c	# order	(times)	0.00	0.00	0.30	1.20	7.70	0.30	0.70	0.70	1.20	7.67	0.10	0.60	0.70
	d	# component ordered	(pcs/year)	4.93	4.56	4.10	3.96	3.88	3.82	3.92	3.92	3.93	4.07	3.92	3.93	3.90
	e	# days of stoppage	(days)	1.97	5.10	7.23	10.77	7.77	40.00	5.30	7.53	9.50	9.27	36.27	4.33	7.00
Cost	1	Scheduled maintenance Cost	($1000/unit)	42.19	43.32	44.49	45.69	46.92	48.18	49.47	50.81	52.17	53.58	55.02	56.50	58.02
	2	Unscheduled maintenance Cost	($1000/unit)	187.50	192.54	197.72	203.04	208.50	214.11	219.87	225.79	231.86	238.10	244.50	251.08	257.83
	3	Component Price	($1000/pcs)	16.25	16.69	17.14	17.60	18.07	18.56	19.06	19.57	20.09	20.64	21.19	21.76	22.35
	4	Inventory Cost	($1000/pcs)	0.08	0.08	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.11	0.11	0.11
	5	Stoppage Loss	($/day)	1.20	1.23	1.27	1.30	1.33	1.37	1.41	1.45	1.48	1.52	1.56	1.61	1.65

Table 6-5 Average values of output variables and its associated cost for Scenario 01 (continued)

		Year		14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
Variables	a	# Scheduled maintenance	(unit)	0	7	0	0	0	0	7	0	0	0	0	0	28.47
	b	#Unscheduled maintenance	(unit)	0.93	1.03	0.60	0.40	0.50	0.77	1.07	0.33	0.57	0.70	0.90	0.93	16.77
	c	# order	(times)	0.90	7.87	0.20	0.50	0.40	0.50	8.13	0.10	0.40	0.50	0.20	0.30	41.17
	d	# component ordered	(pcs)	4.02	3.94	4.88	4.60	4.67	4.49	4.12	6.17	6.01	5.75	5.28	4.56	111.34
	e	# days of stoppage	(days)	9.43	9.93	35.07	3.97	4.77	7.37	11.87	29.00	5.10	6.67	8.87	10.10	294.17
Cost	1	Scheduled maintenance Cost	($1000/unit)	59.58	61.18	62.82	64.51	66.25	68.03	69.86	71.74	73.67	75.65	77.69	79.78	1477.12
	2	Unscheduled maintenance Cost	($1000/unit)	264.77	271.89	279.21	286.72	294.43	302.35	310.48	318.83	327.41	336.22	345.26	354.55	6564.57
	3	Component Price	($1000/pcs)	22.95	23.56	24.20	24.85	25.52	26.20	26.91	27.63	28.38	29.14	29.92	30.73	568.93
	4	Inventory Cost	($1000/pcs)	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.14	0.14	0.15	0.15	0.15	2.84
	5	Stoppage Loss	($/day)	1.69	1.74	1.79	1.83	1.88	1.94	1.99	2.04	2.10	2.15	2.21	2.27	42.01

Table 6-6 Annual cost calculation Scenario 01

		Year		1	2	3	4	5	6	7	8	9	10	11	12	13
Sub-total	1a	Scheduled maintenance Cost	($1000)	0.00	0.00	0.00	0.00	337.80	0.00	0.00	0.00	0.00	373.24	0.00	0.00	0.00
	2b	Unscheduled maintenance Cost	($1000)	37.50	96.27	138.41	209.81	152.90	71.37	117.27	173.10	216.40	230.16	48.90	117.17	171.89
	3c	Purchasing Cost	($1000)	0.00	0.00	5.14	21.12	139.14	5.57	13.34	13.70	24.11	158.20	2.12	13.06	15.64
	4d	Inventory cost	($1000)	0.40	0.38	0.35	0.35	0.35	0.35	0.37	0.38	0.40	0.42	0.42	0.43	0.44
	3c+4d	Purchasing & inventory Cost	($1000)	0.40	0.38	5.49	21.47	139.49	5.92	13.71	14.08	24.51	158.62	2.53	13.48	16.08
	5e	Stoppage Loss	($1000)	2.36	6.28	9.15	13.99	10.36	54.81	7.46	10.89	14.10	14.12	56.75	6.96	11.55
	6	HR Cost	($1000)	16.50	16.94	17.40	17.87	18.35	18.84	19.35	19.87	20.40	20.95	21.52	22.09	22.69
		Annual Cost :	($1000)	57.16	120.26	175.94	284.60	798.40	156.87	171.50	232.02	299.92	955.72	132.24	173.20	238.28

Table 6-6 Annual cost calculation Scenario 01 (continued)

		Year		14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
Sub-total	1a	Scheduled maintenance Cost	($1000)	0.00	426.21	0.00	0.00	0.00	0.00	512.33	0.00	0.00	0.00	0.00	0.00	1649.58
	2b	Unscheduled maintenance Cost	($1000)	247.12	280.95	167.52	114.69	147.21	231.80	331.18	106.28	185.53	235.35	310.74	330.91	4470.44
	3c	Purchasing Cost	($1000)	20.65	185.37	4.84	12.42	10.21	13.10	218.86	2.76	11.35	14.57	5.98	9.22	920.47
	4d	Inventory cost	($1000)	0.46	0.46	0.59	0.57	0.60	0.59	0.55	0.85	0.85	0.84	0.79	0.70	12.90
	3c+4d	Purchasing & inventory Cost	($1000)	21.11	185.83	5.43	13.00	10.80	13.69	219.41	3.62	12.20	15.41	6.78	9.92	933.37
	5e	Stoppage Loss	($1000)	15.98	17.29	62.66	7.28	8.98	14.25	23.58	59.18	10.69	14.35	19.59	22.92	495.54
	6	HR Cost	($1000)	16.51	16.54	16.58	16.61	16.64	16.67	16.71	16.74	16.77	16.80	16.84	16.87	412.05
		Annual Cost :	($1000)	217.93	645.99	175.54	105.45	123.90	179.45	681.06	117.61	138.10	167.38	203.65	213.55	5783.94

Table 6-7 Annual cost after present value projection for Scenario 01

		Year		1	2	3	4	5	6	7	8	9	10	11	12	13
PV Projection	7	Scheduled maintenance Cost	($1000)	0.00	0.00	0.00	0.00	298.71	0.00	0.00	0.00	0.00	291.86	0.00	0.00	0.00
	8	Unscheduled maintenance Cost	($1000)	36.59	91.65	128.56	190.15	135.21	61.58	98.72	142.18	173.43	179.98	37.31	87.22	124.85
	9	Component Price	($1000)	0.00	0.00	4.78	19.14	123.04	4.80	11.23	11.25	19.33	123.71	1.62	9.72	11.36
	10	Purchasing Cost	($1000)	0.39	0.36	5.10	19.45	123.35	5.11	11.54	11.57	19.64	124.04	1.93	10.04	11.68
	11	Stoppage Loss	($1000)	2.30	5.98	8.50	12.68	9.16	47.29	6.28	8.94	11.30	11.04	43.30	5.18	8.39
	12	HR Cost	($1000)	16.10	16.13	16.16	16.19	16.23	16.26	16.29	16.32	16.35	16.38	16.42	16.45	16.48
		Annual Present Value :	($1000)	55.38	114.13	158.33	238.48	582.66	130.24	132.83	179.01	220.72	623.30	98.96	118.89	161.40

Table 6-7 Annual cost after present value projection for Scenario 01 (continued)

		Year		14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
PV Projection	7	Scheduled maintenance Cost	($1000)	0.00	294.72	0.00	0.00	0.00	0.00	313.27	0.00	0.00	0.00	0.00	0.00	1198.55
	8	Unscheduled maintenance Cost	($1000)	175.13	194.27	113.02	75.50	94.55	145.27	202.50	63.41	108.00	133.67	172.20	178.93	3143.90
	9	Component Price	($1000)	14.64	128.18	3.27	8.18	6.56	8.21	133.82	1.65	6.61	8.28	3.32	4.98	667.65
	10	Purchasing Cost	($1000)	14.96	128.50	3.66	8.55	6.94	8.58	134.16	2.16	7.10	8.75	3.75	5.36	676.69
	11	Stoppage Loss	($1000)	11.33	11.95	42.28	4.79	5.77	8.93	14.42	35.30	6.22	8.15	10.86	12.39	352.75
	12	HR Cost	($1000)	16.51	16.54	16.58	16.61	16.64	16.67	16.71	16.74	16.77	16.80	16.84	16.87	412.05
		Annual Present Value :	($1000)	217.93	645.99	175.54	105.45	123.90	179.45	681.06	117.61	138.10	167.38	203.65	213.55	5783.94

Table 6-8 LCC for all generator's scenarios

5 yearly SM scenarios

		SC 01	SC 02	SC 03	SC 04	SC 09	SC 10	SC 11	SC 12
Scheduled maintenance Cost	($1000)	1198.55	1191.17	1259.85	1216.16	1224.51	1239.92	1239.13	1190.94
Unscheduled maintenance Cost	($1000)	3143.90	3160.07	2892.41	3252.64	3131.88	2924.83	2940.74	3263.23
Purchasing Cost	($1000)	667.65	655.37	689.66	689.25	643.89	666.45	688.21	669.63
Inventory Cost	($1000)	9.05	9.51	12.27	11.91	10.40	9.47	12.27	12.89
Stoppage Loss	($1000)	352.75	349.95	339.60	353.51	353.41	344.83	339.30	348.85
HR Cost	($1000)	412.05	549.39	412.05	549.39	412.05	549.39	412.05	549.39
Total PV	($1000)	5783.94	5915.47	5605.84	6072.86	5776.14	5734.88	5631.69	6034.93

7 yearly SM scenarios

		SC 05	SC 06	SC 07	SC 08	SC 13	SC 14	SC 15	SC 16
Scheduled maintenance Cost	($1000)	698.81	630.03	667.26	648.67	658.14	636.86	656.91	621.13
Unscheduled maintenance Cost	($1000)	3468.04	3884.09	3823.40	3920.57	3844.28	3918.86	3626.07	3829.70
Purchasing Cost	($1000)	541.13	540.36	578.33	572.04	548.14	544.93	552.31	557.94
Inventory Cost	($1000)	8.40	8.67	11.19	11.11	8.39	8.52	11.12	11.35
Stoppage Loss	($1000)	317.51	332.25	329.00	333.18	330.70	331.40	318.05	329.46
HR Cost	($1000)	412.05	549.39	412.05	549.39	412.05	549.39	412.05	549.39
Total PV	($1000)	5445.93	5944.79	5821.23	6034.97	5801.70	5989.95	5576.51	5898.97

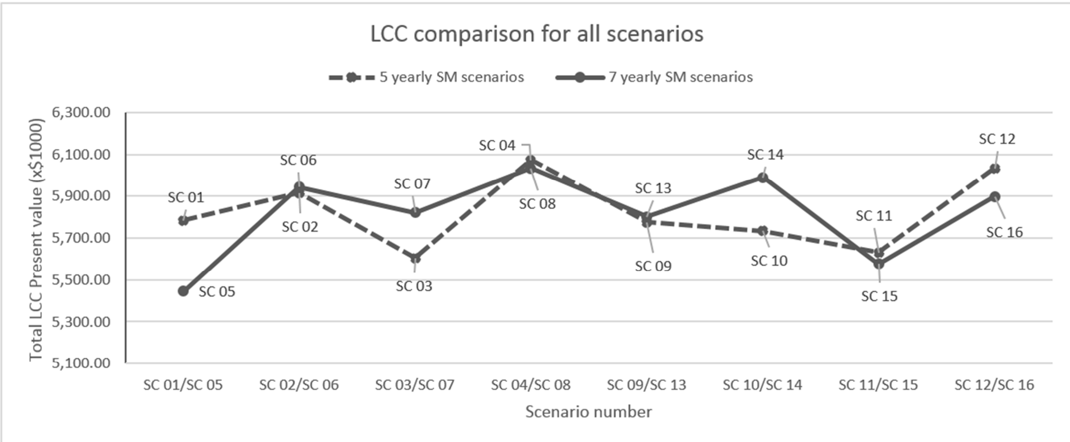


Figure 6-15 LCC comparison for all scenarios

After determining the optimum scenario, it is necessary to explore the relationships between variables and to identify the policy variables which have significant impact to an asset's performance. For this purpose, a statistical analysis is performed to identify the variables that have most impact on the criteria of minimum LCC. The statistic used in this analysis is the Z-test: two sample for means. This test will compare the means of the turbine days loss for two different scenarios in order to find the effect of different inputs. In regards to different policies of desired inventory level, man-hours provided and different threshold, the LCC model is able to find how significantly the different policies affect the LCC.

The first step in the analysis to find the significant variables is to compare the LCC of all scenarios in different scheduled maintenance intervals. The analysis

compares scenarios in 5 and 7 year scheduled maintenance intervals. The employed statistical method is the t-test for small samples. The hypotheses used in this test are:

H_0: There is no mean difference between the LCC of all scenarios in 5 year and 7 year scheduled maintenance intervals.

H1: The mean of the LCC for a 5 year scheduled maintenance interval is different to a 7 year scheduled maintenance interval.

Using the t-test in Microsoft Excel with α=0.05, the results are shown in Table 6-24.

Table 6-9 t-test: Two sample assuming Unequal variances

	5 years SMI	*7 years SMI*
Mean	5819.468194	5814.257237
Variance	30148.46579	42313.02436
Observations	8	8
Hypothesized Mean Difference	0	
df	14	
t Stat	0.054753126	
P(T<=t) one-tail	0.478554417	
t Critical one-tail	1.761310136	
P(T<=t) two-tail	0.957108834	
t Critical two-tail	2.144786688	

The result in Table 6-24 shows that the result of the calculation (t Stat) is 0.0547 which is between –t Critical two-tail and t Critical two-tail (-2.144<0.0733<2.144). Also, the P(T<=t) two-tail is 0.957 which is greater than α. From this result, it can be concluded that H_0 cannot be rejected. This reflects that the means for the LCC of the scenarios in 5 and 7 year interval are statistically equal.

After the LCC comparison for all scenarios, each simulation input variable is tested to find the impact to the simulation output. For this purpose, the mean comparison with the hypothesis test is employed. The mean comparison test assessments follow the hypotheses:

1. There is no mean difference between the turbine days loss for different man-hours provided in the scenarios.
2. There is no mean difference between the turbine days loss for different desired inventory level in the scenarios.
3. There is no mean difference between the turbine days loss for different threshold in the scenarios.

4. There is no mean difference between the turbine days loss for different scheduled maintenance interval in the scenarios.

The formula to test the means comparison is adopted from Waller (2008), and is presented in Eq. 6-7. The test is also utilised hypothesis test.

$$Z = \frac{(\overline{x_1} - \overline{x_2}) - (\mu_1 - \mu_2)_{H_0}}{\sqrt{\frac{\hat{\sigma}_1^2}{n_1} + \frac{\hat{\sigma}_2^2}{n_2}}} \quad \text{……………..…………………….…..….....} \text{ Eq. 6-7}$$

where :

$\overline{x_1}$	: Mean for sample 1
$\overline{x_2}$	: Mean for sample 2
$(\mu_1 - \mu_2)_{H_0}$	: The difference between the hypothesized means of the population
$\hat{\sigma}_1^2$	: Variance for sample 1
$\hat{\sigma}_2^2$	: Variance for sample 2
n_1	: the number of samples for population 1
n_2	: the number of samples for population 2

For example, the means of the turbine days loss of scenario 1 and scenario 2 are tested. This test is to answer the question whether different levels of man-hours affect the turbine days loss. In those two scenarios, the value of the other variables are kept the same, except for the provided man-hours, where scenario 1 has 48 man-hours provided and scenario 2 has 64 hours provided. The simulation output data for scenarios 1 and 2 is provided in Table 6-10.

Table 6-10 30 replication data of the turbine days loss of scenario 1 and 2

No	SC01	SC02	No	SC01	SC02	No	SC01	SC02
1	303.00	332.00	11	269.00	329.00	21	355.00	308.00
2	291.00	269.00	12	264.00	295.00	22	286.00	270.00
3	241.00	274.00	13	294.00	339.00	23	272.00	270.00
4	327.00	303.00	14	289.00	312.00	24	343.00	256.00
5	235.00	295.00	15	280.00	328.00	25	360.00	262.00
6	309.00	304.00	16	361.00	300.00	26	279.00	277.00
7	286.00	268.00	17	262.00	253.00	27	277.00	296.00
8	269.00	326.00	18	279.00	294.00	28	245.00	275.00
9	289.00	256.00	19	275.00	300.00	29	334.00	268.00
10	337.00	277.00	20	263.00	303.00	30	351.00	311.00

Scenario 01	Scenario 02
Mean : 294.17	Mean : 291.67
Variance : 1305.25	Variance : 617.95

In the beginning of the test, H_0 and H_1 are presented as follows:

H_0 : There is no mean difference between the turbine days loss of scenario 1 and 2.

H_1 : The mean of the turbine days loss for scenario 1 is different to scenario 2.

With α = 0.05, H_0 cannot be accepted if $-1.95 \leq Z \leq 1.95$; otherwise, H_0 is rejected. Since the null hypothesis is to test no different mean, $(\mu_1 - \mu_2)_{H_0} = 0$. Inserting the value to each variable into Eq. 6-7 will show the calculation as follows:

$$Z = \frac{(294.17 - 291.67) - 0}{\sqrt{\frac{1305.25}{30} + \frac{617.95}{30}}}$$

$$Z = \frac{2.5}{8.006} = 0.312$$

The value of Z is between -1.95 and 1.95, because there is not enough proof to reject H_0. It can be concluded that in scenarios 1 and 2, the different man-hours provided

do not affect the number of turbine days loss. The other means comparison tests for the same purpose are performed using Microsoft Excel, and the results are shown in Tables 6-11 and 6-12.

Table 6-11 Mean comparison result for scenarios with 5 years SM interval

z-Test: Two Sample for Means

	SC01	SC02
Mean	294.1666667	291.6666667
Known Variance	1305.25	617.95
Observations	30	30
Hypothesized Mean Difference	0	
z	0.312239908	
P(Z<=z) one-tail	0.377429102	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.754858205	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC03	SC04
Mean	283	294.4
Known Variance	895.24	556.87
Observations	30	30
Hypothesized Mean Difference	0	
z	-1.638572722	
P(Z<=z) one-tail	0.050651139	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.101302277	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC09	SC10
Mean	294.2666667	287.2666667
Known Variance	4551.86	859.93
Observations	30	30
Hypothesized Mean Difference	0	
z	0.52118055	
P(Z<=z) one-tail	0.301120501	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.602241002	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC11	SC12
Mean	282.7	290.6333333
Known Variance	638.36	1055.62
Observations	30	30
Hypothesized Mean Difference	0	
z	-1.055752675	
P(Z<=z) one-tail	0.145540612	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.291081225	
z Critical two-tail	1.959963985	

Table 6-12 Mean comparison result for scenarios with 7 years SM interval (continued)

z-Test: Two Sample for Means

	SC05	SC06
Mean	264.2333333	276.7
Known Variance	1088.12	1453.32
Observations	30	30
Hypothesized Mean Difference	0	
z	-1.354475158	
P(Z<=z) one-tail	0.087792417	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.175584834	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC07	SC08
Mean	274.1	277.3666667
Known Variance	661.54	1608.45
Observations	30	30
Hypothesized Mean Difference	0	
z	-0.375537643	
P(Z<=z) one-tail	0.353630328	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.707260656	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC13	SC14
Mean	275.1666667	275.7666667
Known Variance	796.42	1259.98
Observations	30	30
Hypothesized Mean Difference	0	
z	-0.07246997	
P(Z<=z) one-tail	0.471113952	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.942227903	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC15	SC16
Mean	264.8666667	274.2
Known Variance	1067.57	909.06
Observations	30	30
Hypothesized Mean Difference	0	
z	-1.149832852	
P(Z<=z) one-tail	0.125106361	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.250212722	
z Critical two-tail	1.959963985	

Other means comparison tests are also conducted to test the effect of different desired inventory level to turbine days loss, different threshold to turbine days loss, and different scheduled maintenance interval to turbine days loss. The results are shown in Table 6-13, Table 6-14, and Table 6-15 respectively.

Table 6-13 Result of mean comparison for different desired inventory level

z-Test: Two Sample for Means

	SC01	SC03
Mean	294.1666667	283
Known Variance	1305.25	895.24
Observations	30	30
Hypothesized Mean Difference	0	
z	1.303840539	
P(Z<=z) one-tail	0.096143979	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.192287957	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC02	SC04
Mean	291.6666667	294.4
Known Variance	617.95	556.87
Observations	30	30
Hypothesized Mean Difference	0	
z	-0.436784843	
P(Z<=z) one-tail	0.331133696	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.662267392	
z Critical two-tail	1.959963985	

Table 6-14 Result of mean comparison for different threshold

z-Test: Two Sample for Means

	SC01	SC09
Mean	294.1666667	294.267
Known Variance	1305.25	4551.86
Observations	30	30
Hypothesized Mean Difference	0	
z	-0.007156801	
P(Z<=z) one-tail	0.497144874	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.994289748	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC06	SC14
Mean	276.7	275.767
Known Variance	1453.32	1259.98
Observations	30	30
Hypothesized Mean Difference	0	
z	0.098140552	
P(Z<=z) one-tail	0.460910344	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.921820687	
z Critical two-tail	1.959963985	

Table 6-15 Result of mean comparison for different scheduled maintenance interval

z-Test: Two Sample for Means

	SC11	SC15
Mean	282.7	264.866667
Known Variance	638.36	1067.57
Observations	30	30
Hypothesized Mean Difference	0	
z	2.364898748	
P(Z<=z) one-tail	0.0090175	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.018035001	
z Critical two-tail	1.959963985	

z-Test: Two Sample for Means

	SC12	SC16
Mean	290.6333333	274.2
Known Variance	1055.62	909.06
Observations	30	30
Hypothesized Mean Difference	0	
z	2.030674802	
P(Z<=z) one-tail	0.021143997	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.042287994	
z Critical two-tail	1.959963985	

From the mean comparison analysis above, it can be concluded that the input variable that has the most significant impact on the asset's availability is scheduled

maintenance interval. The other variables: the different number of man-hours provided, desired inventory level, and threshold from the generated scenario, do not significantly affect the asset's availability. For the desired inventory level, another analysis should be performed because different policies of inventory level lead to different numbers of purchasing orders each year, which leads to different cost. Different policies of desired inventory level also produce different inventory levels, which lead to different inventory costs. Different purchasing costs and inventory costs may in turn lead to different annual costs leading to different LCC.

6.2.6 Case Study Results and Findings

In this case study, the developed integrated model: system dynamics simulation and the life cycle model is applied, and results verified for maintenance resource-provisioning policy setting for wind turbine generators in a wind farm. Sixteen scenarios are generated and run by system dynamic simulation, and the optimum scenario selected based on minimum life cycle cost through the developed LCC model

The LCC analysis shows that increasing asset availability, requires providing more resources to support the maintenance job, and therefore increases the cost. The optimum situation results from a trade-off between the cost of providing more resources to support the maintenance job and the stoppage loss as a result of insufficient provided resources. Application of the developed model is found capable of analysing this trade-off, and the result of the LCC indicates that scenario 5 in a 7 year scheduled maintenance interval has the lowest total cost during the asset's lifespan. The result of the LCC comparison of all scenarios shows that all scenarios in 7 year scheduled maintenance intervals generate better asset availability than those scenarios in 5 year scheduled maintenance intervals, but the difference is quite small some in instances, as shown in Figure 6-16. But there are close scenarios as shown in figure 6-16. The results presented in Figure 6-16 are explained by the high number of turbine days loss in 5 year scheduled maintenance intervals, which is due to asset unavailability; high stoppage loss caused by unit replacement in scheduled maintenance, more units purchased; high purchasing and inventory cost and high scheduled maintenance cost.

However, in a situation where availability is not a central concern and unscheduled maintenance cost is significantly high; in other words the ratio of UM cost to SM cost is considerably high, the decision may shift to selecting a 5 year scheduled maintenance interval to reduce unplanned failure. Conversely, in situations where low ratio of UM to UM cost and availability is the main issue, this will strengthen the decision to select a scenario from the 7 year scheduled maintenance interval.

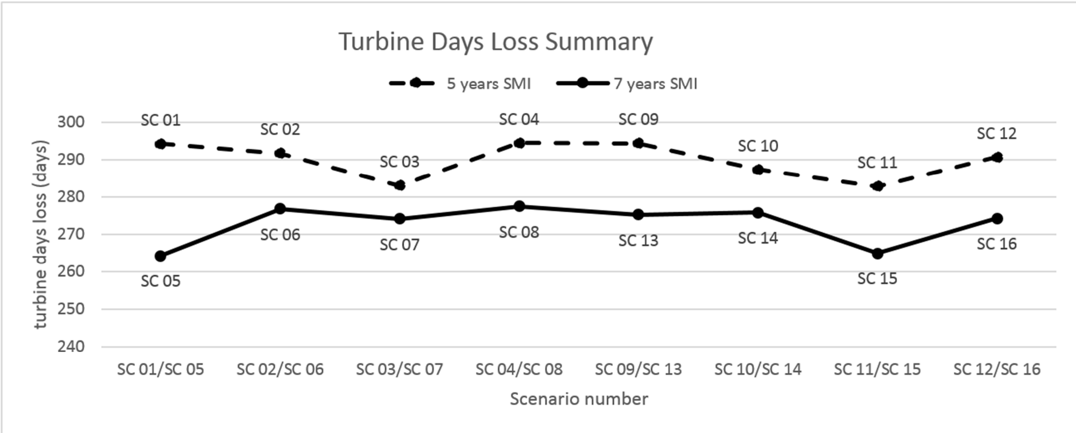


Figure 6-16 Turbine days loss summary

The statistical analysis performed on the resulting values of the various variables shows that there is impact of the variables of the resource provisioning and maintenance alternative policies on asset performance, but the variable that has the most significant impact is the scheduled maintenance interval.

The selection of scenarios 5 in 7 year scheduled maintenance as the optimum scenario for the combined maintenance and its resource provisioning policy can be explained in terms of its minimum LCC resulting from:

1. low stoppage loss
2. less maintenance activities
3. low purchasing and inventory cost

6.3 Case Study 2: Resource provisioning Policy for Wind Farm Gearbox Maintenance Program

6.3.1 Case Description

The second case study in this research is the wind turbine's gearbox. The main function of a gearbox in a wind turbine is to convert slow rotation speed from the blade to a faster speed of kinetic energy to be transferred to the generator to generate electrical energy (Meng-Na et al., 2012). As shown in Figure 6-1, the gearbox is located between the blade and the generator. The common speed at the blade is between 5 to 20 rotations per minute (rpm) and the structure of the bearings in the gearbox convert the rotation speed to 750 – 3600 rpm. According to Lesmerises and Crowley (2013), the structure of bearings in the gearbox consists of High Speed Shaft; Intermediate Speed Shaft; Low Speed Shaft; Planet Carrier; and Planet Gears.

In this case study, the lifetime of the wind turbine is also planned for 25 years. During the lifetime, some replacement may occur during scheduled or unscheduled maintenance. The main issues in gearbox replacement are: (1) whether the replacement of the faulty gearbox is for the whole gearbox or only the failed bearing (Lesmerises and Crowley, 2013, Meng-Na et al., 2012); and (2) the scheduled maintenance interval related to maintenance policy. For the first issue, Lesmerises and Crowley (2013) compared the LCC for these different policies, and found that replacing all bearings (the whole gearbox) generates lower LCC, compared with replacing only the failed bearing for either a 20 year or 25 year lifetime. In line with this result, the case study in Meng-Na et al. (2012) also recommends replacement of the whole gearbox. In this case study, replacement is made for one whole gearbox, which is regarded as one unit asset in the wind turbine. In the second issue, the developed model will simulate the effects of different maintenance interval policies.

6.3.2 Assumptions in the Maintenance Program and Resource provisioning for the Simulation of the Gearbox Case

The simulation model used in this case study is similar to the simulation model and sub models used in the generator case study with different input data. Details of the data input in the model are given in Table 6-16.

Table 6-16 Gearbox simulation input data and its sources.

No	Input data	Value	Source
1.	Generator life time/unit (days)	Weibull (3750,3.43)	(Lesmerises and Crowley, 2013)
2.	Gearbox price/unit	AUD 140,000	(Lesmerises and Crowley, 2013)
3.	Unscheduled maintenance cost/ event	AUD 252,500	(Tian et al., 2011)
4.	Scheduled maintenance cost/ event	AUD 46,750	
5.	Currency converter USD to AUD	1 USD = 0.8 AUD	
6.	Inflation / annum	2.69 %	Australian Bureau of Statistics
7.	Interest / annum	2.49 %	Australian Reserve Bank
8.	Average Revenue / kWh	AUD 0.075	(Lesmerises and Crowley, 2013)
9.	Stock keeping cost / annum	0.5 %	(Tracht et al., 2013)
10.	Assumed operation time /day	8 hours	(Lesmerises and Crowley, 2013)
11.	Technician Annual salary/ per person	AUD 55,000	http://www.payscale.com/
12.	Repair time distribution (days)	Normal (5,2)	
13.	Wind Turbine Power Grade	2MW	

Similar to the generator case study, there are 10 wind turbines observed in the wind farm. Each wind turbine has one gearbox. Thus, in this case study, ten units are observed. To calculate the fixed cost of man hour provided, the percentage of the cost breakdown is also applied. Irena (2012) indicates that a gearbox contributes approximately 10% of the value of a wind turbine.

6.3.3 Application of the Model Developed in the Gearbox Case

In the generator case study, a modelling logic flowchart is presented in Figure 6-4. The modelling logic provides a guideline to tailor the system dynamic model

developed in Chapter 5 to the case study. Generally the modelling logic of the gearbox case study is similar to the generator case study. This leads to a similar system dynamics simulation to that of the generator case study. The same simulation logic is used in this case study with different values of input variables. Therefore, the system dynamics simulation modelling for the gearbox maintenance program and its resource provisioning is the same as the model explained in Section 6.2.3.

6.3.4 Scenario Generation in System Dynamic Simulation

For this gearbox case study, sixteen preliminary scenarios are generated. The ranges of input variables covered in the scenario generation in this model are: scheduled maintenance interval; desired inventory level; provided man-hours; and threshold. Lesmerises and Crowley (2013) indicate that the optimum scheduled replacement for the gearbox is 10 years. In this case study, the scheduled maintenance intervals assessed by the developed integrated model are 7 and 10 years. The desired inventory levels considered are 4 and 6 units. The provided man-hours and threshold are 48 and 64 man-hours; and 180 and 365 days respectively. Details of the generated scenarios from the combination of those ranges of input are shown in Table 6-17.

Table 6-17 Detail for suggested preliminary scenario

Scenario	SM interval	Desired inv level	Provided MH	Threshold
	years	unit	man hours/day	days
1	7	4	48	180
2	7	4	48	365
3	7	4	64	180
4	7	4	64	365
5	7	6	48	180
6	7	6	48	365
7	7	6	64	180
8	7	6	64	365
9	10	4	48	180
10	10	4	48	365
11	10	4	64	180
12	10	4	64	365
13	10	6	48	180
14	10	6	48	365
15	10	6	64	180
16	10	6	64	365

Other fixed inputs applied in the model for every scenario are initial inventory level and safety stock level, which are predetermined as 2 units. Also, 13 output variables are generated, as elaborated in Section 6.2.4.

6.3.5 Simulation Model Output and Life Cycle Cost Analysis

All the input values of scenario variables are run for 30 replications by the system dynamics simulation. Each scenario is executed for a 25 year simulation time or 9,125 days. A summary of the output for all scenarios is given in Table 6-18 and Table 6-19.

Table 6-18 Simulation summary for all scenarios with 7 year scheduled maintenance interval

7 yearly SM scenarios

		Scenario 01		Scenario 02		Scenario 03		Scenario 04		Scenario 05		Scenario 06		Scenario 07		Scenario 08	
variables	unit of measure	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
SM order	times	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00	3.00	0.00
SM exe	times	22.00	2.85	22.00	2.99	23.00	2.85	22.00	2.71	23.00	3.58	22.00	2.78	23.00	2.76	22.00	2.96
UM exe	times	11.00	3.89	11.00	3.68	10.00	3.93	11.00	3.77	11.00	4.71	11.00	3.83	11.00	3.33	11.00	3.69
Total part SM	pcs	21.00	4.64	20.00	4.40	22.00	3.85	20.00	4.25	21.00	6.14	21.00	4.08	20.00	4.20	21.00	4.03
Total part UM	pcs	11.00	3.82	11.00	3.66	10.00	3.87	11.00	3.75	11.00	4.79	11.00	3.88	11.00	3.26	11.00	3.70
#order	times	7.00	1.16	7.00	1.77	7.00	1.54	7.00	1.42	5.00	0.68	6.00	0.80	5.00	0.73	6.00	0.86
acuum order	pcs	29.00	2.67	29.00	2.40	29.00	1.39	29.00	1.96	30.00	3.07	31.00	1.81	30.00	1.94	30.00	2.61
average daily available component	pcs	5.00	0.73	5.00	0.80	4.00	0.37	5.00	0.88	5.00	0.58	5.00	0.55	5.00	0.80	5.00	0.69
Time To Repair	days	149.13	19.44	147.90	17.95	152.23	10.50	147.37	13.78	142.40	16.30	151.07	13.15	139.90	15.80	153.33	14.83
#turbines days loss	turbine days	202.77	13.49	200.23	24.11	201.53	21.39	200.50	17.85	195.70	18.55	203.53	24.27	191.50	19.93	203.50	20.89
#backlog	times/30 replications	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Accum BL	pcs/ 30 replication	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	

Table 6-19 Simulation summary for all scenarios with 10 year scheduled maintenance interval

10 yearly SM scenarios

		Scenario 09		Scenario 10		Scenario 11		Scenario 12		Scenario 13		Scenario 14		Scenario 15		Scenario 16	
variables	unit of measure	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
SM order	times	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00
SM exe	times	7.00	2.65	7.00	2.73	8.00	2.16	7.00	2.30	8.00	2.33	8.00	2.46	8.00	2.47	7.00	2.22
UM exe	times	18.00	3.35	18.00	3.87	17.00	2.81	18.00	3.63	17.00	3.38	17.00	3.27	18.00	3.24	18.00	3.22
Total part SM	pcs	7.00	2.66	7.00	2.99	7.00	1.93	7.00	2.30	7.00	2.39	8.00	2.79	8.00	2.59	7.00	2.32
Total part UM	pcs	18.00	3.37	18.00	3.75	17.00	2.79	18.00	3.57	17.00	3.24	17.00	3.29	18.00	3.24	18.00	3.22
#order	times	10.00	1.77	10.00	1.89	10.00	1.59	10.00	1.72	7.00	0.85	6.00	0.76	7.00	0.87	6.00	0.91
acuum order	pcs	23.00	1.72	23.00	1.67	23.00	1.65	23.00	2.01	24.00	1.86	24.00	1.77	24.00	2.00	23.00	2.30
average daily available component	pcs	4.00	0.20	4.00	0.24	4.00	0.24	4.00	0.19	5.00	0.36	5.00	0.24	5.00	0.22	5.00	0.26
Time To Repair	days	118.80	13.09	118.33	11.23	117.13	11.48	118.60	12.01	121.50	12.92	117.13	8.83	117.50	10.37	117.93	12.75
#turbines days loss	turbine days	204.97	25.21	206.63	25.35	201.57	20.17	206.27	26.76	207.30	25.32	199.93	20.65	203.57	20.38	205.40	25.54
#backlog	times/30 replications	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Accum BL	pcs/ 30 replication	0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	

After the simulation outputs are generated and summarized, Eq. 6-6 is used in the calculation of the LCC for a comparison for the two alternative scheduled maintenance intervals. The results of the calculation for all scenarios are shown in Table 6-20 and charted in Figure 6-17.

Table 6-20 Present value cost for all gearbox scenarios

7 yearly SM scenarios

		SC 01	SC 02	SC 03	SC 04	SC 05	SC 06	SC 07	SC 08
Scheduled maintenance Cost	($1000)	1274.01	1256.50	1290.09	1280.45	1295.03	1276.50	1288.22	1254.84
Unscheduled maintenance Cost	($1000)	2685.16	2615.65	2438.01	2675.66	2654.24	2556.51	2599.56	2536.56
Purchasing Cost	($1000)	3952.17	3974.73	4027.31	4003.29	4114.21	4237.10	4132.33	4202.12
Inventory Cost	($1000)	74.91	74.84	69.18	74.51	86.15	81.96	86.22	84.36
Stoppage Loss	($1000)	243.86	240.70	242.31	241.11	235.49	244.78	230.25	244.61
HR Cost	($1000)	824.09	824.09	1098.79	1098.79	824.09	824.09	1098.79	1098.79
Total PV	($1000)	9054.20	8986.50	9165.70	9373.79	9209.21	9220.95	9435.37	9421.28

10 yearly SM scenarios

		SC 09	SC 10	SC 11	SC 12	SC 13	SC 14	SC 15	SC 16
Scheduled maintenance Cost	($1000)	405.50	403.37	415.59	405.73	411.30	354.75	421.47	387.90
Unscheduled maintenance Cost	($1000)	4354.76	4440.43	4259.38	4376.98	4304.49	4683.98	4344.09	4429.80
Purchasing Cost	($1000)	3108.82	3103.82	3093.76	3122.11	3251.11	3397.81	3293.35	3193.69
Inventory Cost	($1000)	67.33	66.92	66.42	65.55	80.12	79.17	80.04	79.67
Stoppage Loss	($1000)	246.65	248.66	242.44	248.07	249.45	258.37	244.91	247.10
HR Cost	($1000)	824.09	824.09	1098.79	1098.79	824.09	824.09	1098.79	1098.79
Total PV	($1000)	9007.15	9087.29	9176.39	9317.23	9120.55	9598.17	9482.64	9436.95

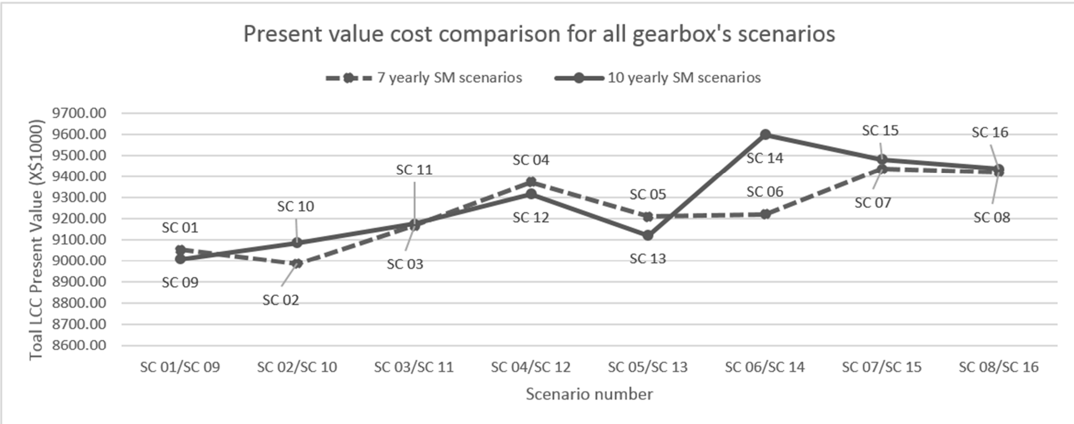


Figure 6-17 Present value cost for all gearbox scenario

Figure 6-17 shows that scenario 2 has the lowest LCC. It also indicates that the results of the calculation of both interval of scheduled maintenance are close to each other, with only a slight difference. However, it is difficult to say that one scheduled maintenance interval is better than another. This highlights that the impact of the scheduled maintenance interval on the LCC is not significant.

Having determined the optimum scenario and seen the close tie between scenarios in both scheduled maintenance intervals, it is necessary explore the relationships between variables and to identify the policy variables which have significant impact on the asset's performance. For this purpose, a statistical analysis

is performed to identify the variables that have most impact on the criteria of minimum LCC. A t-test statistical analysis is used for this purpose and the result of the test is presented in Table 6-21.

Table 6-21 t-test result for comparing mean of the present value

	7 years SMI	*10 years SMI*
Mean	9233.37578	9278.295546
Variance	27742.1448	45148.07497
Observations	8	8
Hypothesized Mean Difference	0	
df	13	
t Stat	-0.47059555	
P(T<=t) one-tail	0.32286379	
t Critical one-tail	1.7709334	
P(T<=t) two-tail	0.64572758	
t Critical two-tail	2.16036866	

The result of the test shows that the value of t Stat is between the acceptance intervals. This result shows that the cost generated by 7 year scheduled maintenance scenarios is similar to the cost of a 10 year scheduled maintenance interval. Although a 7 years scheduled maintenance interval produces less turbine days loss and higher asset availability as shown in Figure 6-18, the required cost to produce the asset availability makes it generate a similar cost to 10 years scheduled maintenance interval. From Table 6-20, in 7 year scheduled maintenance interval scenarios, the cost is dominated by purchasing and inventory costs. In the 10 year scheduled maintenance interval scenarios, the dominant cost is unscheduled maintenance cost.

As performed in the previous case study, a Z-test for mean comparison is also performed to find the effect of different policy variables on turbine days loss, as shown in Section 6.2.5. Based on this analysis for the system dynamics simulation output data, it is found that a combination of variables in terms of scenarios impacts on the turbine days loss; no single variable can be identified as having the most significant impact.

A further analysis is done to support policy selection despite the similarity of the LCC for both schedule maintenance intervals. This might be the case as a trade-off for high availability with high LCC. The turbine days loss output are separated

and plotted into two groups: 7 and 10 year scheduled maintenance interval. The result of the plotting is shown in Figure 6-18.

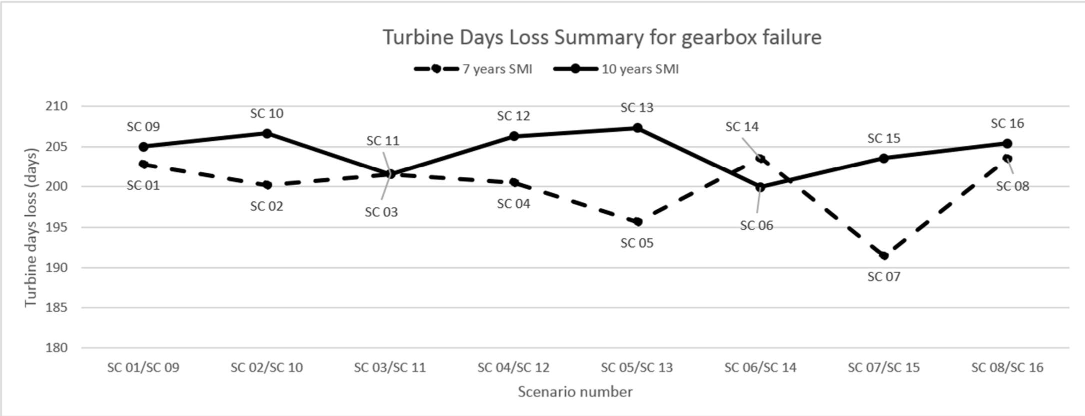


Figure 6-18 Summary of turbine days loss caused by gearbox failure

From Figure 6-18, most 7 year scheduled maintenance scenarios have a lower number of days loss. To support this judgement, a statistical analysis is performed to compare whether the turbine days loss from 7 year scenarios is different to 10 year scenarios. Because the data is less than 30, a t-test is used. The result of the comparison is provided in Table 6-22.

Table 6-22 t-test result for comparing mean of gearbox's turbine days loss

	7 years SMI	*10 years SMI*
Mean	199.9083333	204.4541667
Variance	17.95960317	6.693313492
Observations	8	8
Hypothesized Mean Difference	0	
df	12	
t Stat	-2.58955028	
P(T<=t) one-tail	0.011838759	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.023677518	
t Critical two-tail	2.17881283	

The result shows that the value of the t Stat (-2.589) is outside the acceptance area, which is between –t Critical two-tail and t Critical two-tail (-2.178<T Stat<2.178). From this analysis, it is verified that the turbine days loss of the 7 year scheduled maintenance scenarios is statistically different compared to the 10 year scenarios. It indicates that scenarios in a 7 year scheduled maintenance interval provides higher asset availability.

6.3.6 Case Results and Findings

In this case study, the developed integrated model: (system dynamics simulation and the life cycle model) is applied, and results verified for maintenance resource-provisioning policy setting for turbine gearboxes in a wind farm. Sixteen scenarios are generated and run by system dynamic simulation, and the optimum scenario selected based on minimum life cycle through the developed LCC model. The result of the application on the developed integrated model; (system dynamic simulation and LCC model) indicates that scenario 2 has lowest LCC and is the optimum alternative for maintenance and its corresponding resource provisioning policy in this case study.

The statistical analysis done on the resulting values of the various variables shows that there is impact of the variables on resource provisioning and maintenance alternative policies on asset performance, but no variable can be identified to have the most significant impact.

The result of the cost comparison analysis between scenarios on different scheduled maintenance intervals shows that both scheduled maintenance intervals produce similar cost but different asset availabilities. Therefore, this case study tends to fit situations where low ratio of UM to UM cost and availability is the main issue. Hence, the result tends to strengthen the decision to select a scenario from the 7 year scheduled maintenance interval. However, in a situation where availability is not a central concern, decision may shift to selecting from the 10 year scheduled maintenance interval.

6.4 Case Study 3: Resource provisioning Policy in Wind Farm Converter Maintenance Program

6.4.1 Case Description

The converter is a unit within the transformer in a wind turbine. It is used to convert electricity from AC to DC or vice versa, and from one voltage or frequency to another (Rivkin and Silk, 2013). Each wind turbine has a transformer that consists of 14 basic converter units (Zhang and Zain, 2010), and is able to tolerate 2 failed units at the same time. The failure of three converter units causes failure of the converter subsystem that takes the wind turbine into a failure state. As shown in

Figure 6-19, model 7-7, converters are present in each wind turbine. Model 7-7 means that there are 7 converter modules in the generator side and 7 converter modules in the grid side (Zhang and Zain, 2010).

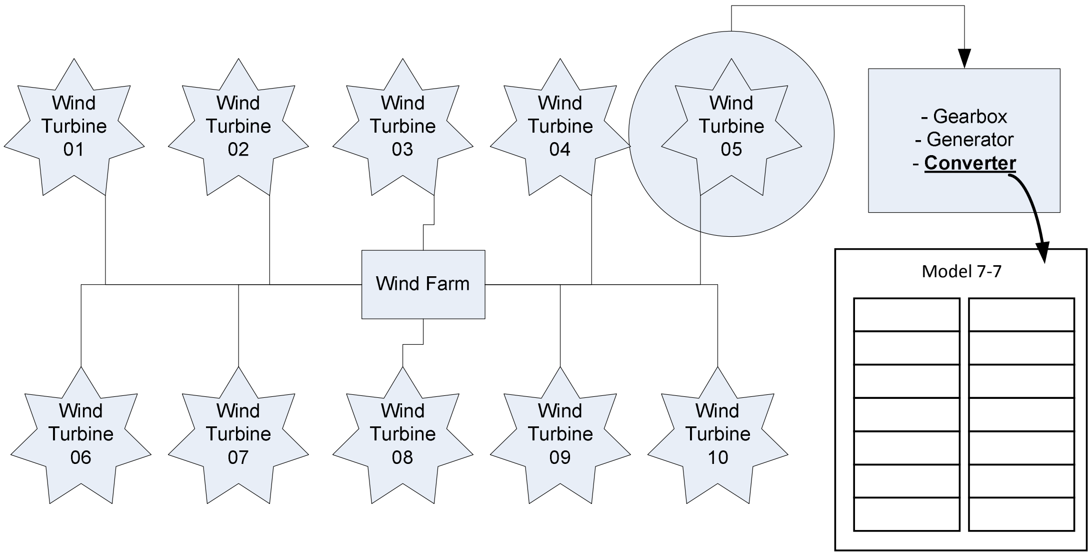


Figure 6-19 Converter 7-7 model in overall wind farm schematic model

6.4.2 Assumption in the Maintenance Program and Resource provisioning for Simulation of the Converter Case

According to records of the wind farm case study considered, a scheduled maintenance (SM) action is required in general. The assumption is for scheduled maintenance (SM) to be performed either every 6 months (180 days) or 12 months (365 days) to replace failed converter units found in the transformer. All maintenance is performed as required as long as some maintenance resources are available. It is assumed that each unit has a different random lifetime (hours) that follows an exponential distribution with $\lambda = 10^{-5}$ (number of failures per operating hour). Two maintenance resources of human resources measured in man-hours (MH), and spare parts measured in pieces (pcs), are involved in modelling. In modelling the human resource, it is assumed initially there are 8 persons available with 8 working hours per day. Thus, this results in 64 man-hours available each day. One maintenance task (SM or UM) requires 2 persons for 2 hours for one transformer in each wind turbine. To ensure the availability of maintenance resources in terms of spare parts, purchasing is regularly done based on their safety stock levels. When the stock level

is less than 15 units, a purchase order will be sent to the supplier, and the new parts will be received within 30 days after (Cahyo et al., 2014). In this case study, a unit refers to a converter component.

6.4.3 Application of the Model Developed in the Converter Case

In this case, the application of the developed model involves tailoring the system dynamics simulation developed in Chapter 5 for converter maintenance and its resource provisioning. The application of system dynamics simulation in this case study results in some scenarios. The scenarios are analysed based on the LCC analytical model presented in Chapter 4 to find the optimum scenario.

Similar to the previous case studies, a modelling logic is also presented as a guide for the system dynamics model development. The case description for the converter maintenance and its maintenance resource system is shown in the flowchart in Figure 6-20. It shows the logic in the system dynamics modelling. In the beginning of the simulation, an initial condition of the system is set. The initial condition set in the model consists of several variables: Unit lifetime, scheduled maintenance interval, inventory level of the unit, number of man-hours provided. After the initial values for input variables are set, the simulation is run throughout the lifespan of the wind farm.

Overall, the logic is similar to the logic of the generator case presented in Figure 6-20. The differences are the number of units in each asset and the cause of a unit’s failure. In the converter maintenance program, each transformer (within the wind turbine) has fourteen units, and the failure of three units causes stoppage of the wind turbine. These differences are reflected in the process of setting initial lifetime and decisions concerning simulating unit failures. The process in the purchasing and inventory and human resource system is similar to the process explained in section 6.2.3.

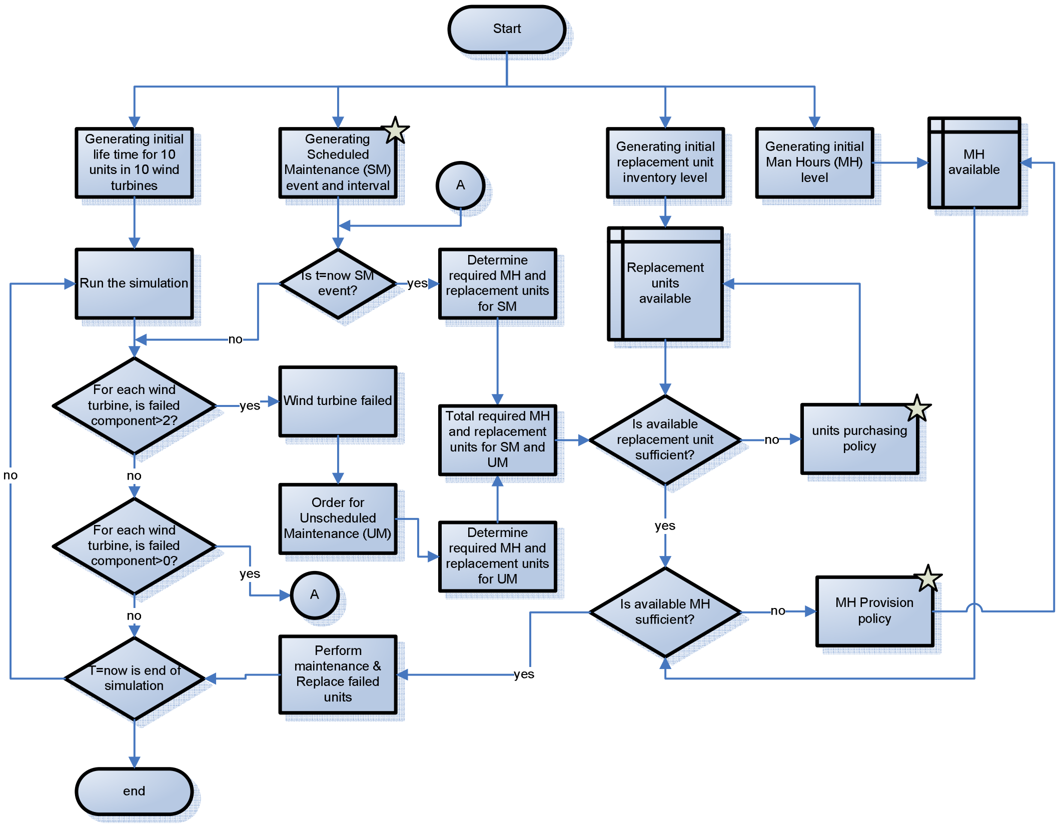
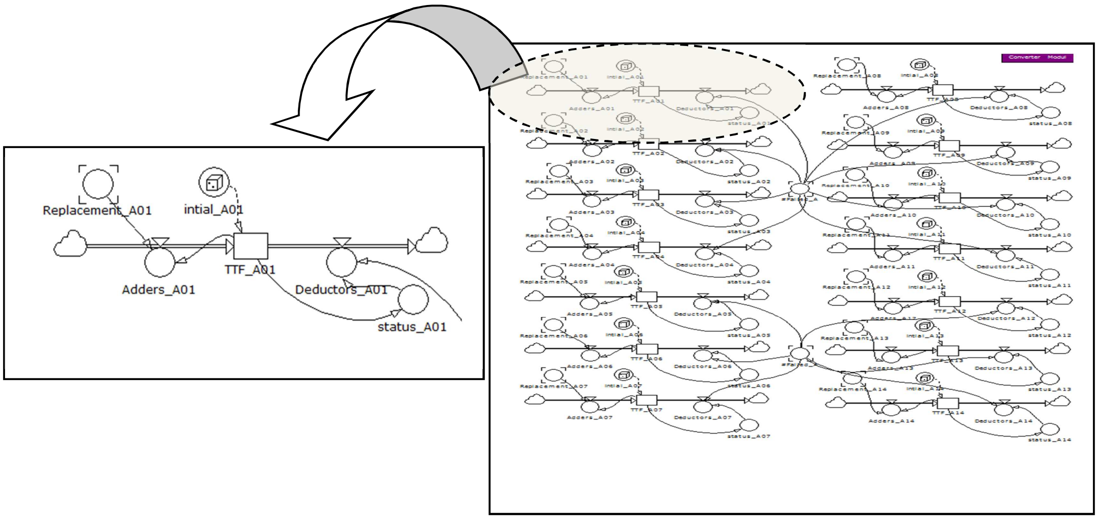


Figure 6-20 Model Flowchart

The developed model in Chapter 5 is adjusted to fit this converter maintenance program and its resource provisioning. As mentioned in the case description, in a wind turbine there are fourteen converter units. The right hand side of Figure 6-21 is the configuration of these converter models in a wind turbine (part (2)). The system dynamics simulation model representation of each converter in a wind turbine is shown on the left hand side of Figure 6-21. In a wind farm, there are ten turbines and therefore the representation for each is identical to the one in Figure 6-21. Since the simulation sub models for converters are identical, replication logic is used.



(1) (2)

Figure 6-21 Converter simulation sub model

The developed simulation to generate the required units for scheduled and unscheduled maintenance action is as shown in Figure 6-22. The figure only shows the representation of one wind turbine as an example.

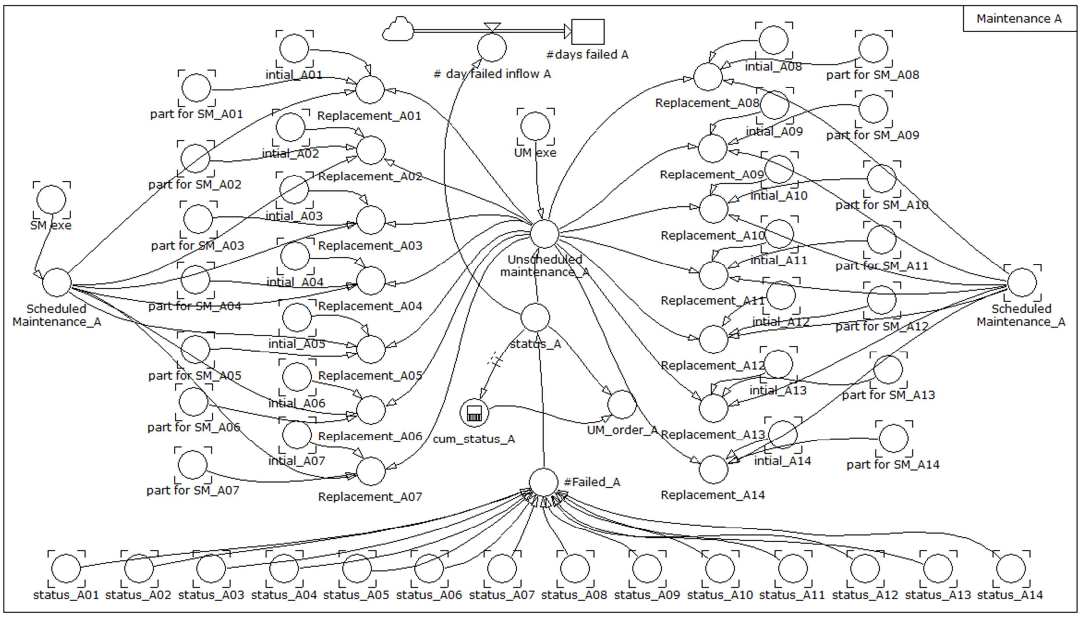


Figure 6-22 Simulation sub model for creating required component and replacement for each scheduled and unscheduled maintenance action for wind turbine A

Determining the number of units that need maintenance actions depends on the status of the number of failed units in each wind turbine. As described in Chapter 5, if the status shows “1” this means that the unit has failed. For an example in Figure 6-22, the status of all units in wind turbine A is accrued into an auxiliary named #Failed_A. If the amount in #Failed_A is equal to or more than three, this generates a failure status of the wind turbine in the auxiliary named status_A. This failure status indicates that the wind turbine unit A is in failure condition, and an unscheduled maintenance order (UM_order_A) will be issued with the required number of units to complete the unscheduled maintenance for unit A as in #Failed_A. Status_A is also used to calculate the number of failure days of the wind turbine. This information is stored in #days failed A level. Similarly, once a scheduled maintenance order is issued, the number of required components to complete the scheduled maintenance for unit A is also found from #Failed_A.

The simulation model in Figure 6-22 is also intended for distributing the replacement units in scheduled and unscheduled maintenance. After the number of units to be replaced is obtained from the inventory, each unit will be attributed with initial lifetime values. These replacements are distributed to the required converter modules as Replacement_A0X, where X is the unit number. The replacements can be seen in Figure 6-21 to add the components time to failure level.

Before every maintenance action, information about the required number of units is collected. The process of acquiring information about the required number of units in the whole wind farm is presented in a sub model in Figure 6-23. As shown at the top of Figure 6-23, after a scheduled maintenance order is issued, the system will generate the required number of units based on the number of failed units in each wind turbine. For instance in wind turbine A, the data is collected from #Failed_A. From #Failed_A, the required units for scheduled maintenance will be transferred into SM_req_A, which is a level to store unit requirements for scheduled maintenance at unit A. Similarly, in unscheduled maintenance, the requirement will be stored in UM_req_A. The accumulation of units required either for scheduled or unscheduled maintenance for all units is calculated at the bottom of Figure 6-23 and named Req_for_SM and req_for_UM respectively.

In the maintenance sub system, there is only a minor adjustment compared to the general simulation sub model presented in Figure 5-8. The representation of the maintenance program simulation sub model to generate converter maintenance orders and actions for all units in a wind turbine is shown in Figure 6-24. The adjustment of the general simulation model for tailoring to the case is done only for the number of wind turbines covered by the maintenance program. The simulation sub model is used to generate the number of performed scheduled maintenance and unscheduled maintenance as shown in the Total SM exe auxiliary variable.

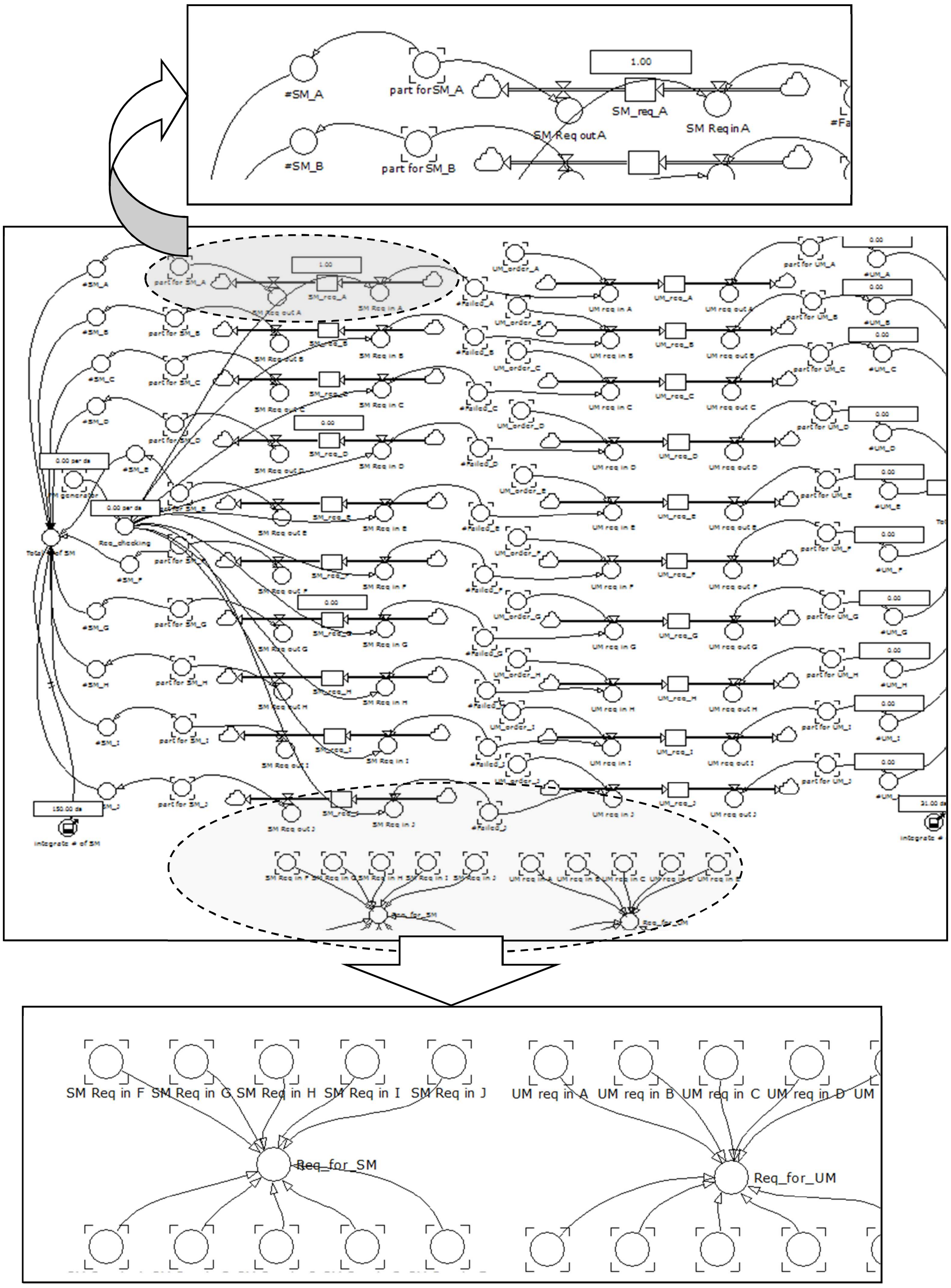


Figure 6-23 Simulation sub model to accrue required component for each maintenance action

The simulation sub model for purchasing and inventory used in this case study is the same as the simulation sub model presented in Figure 5-10. Also, for distributing the components from inventory to scheduled or unscheduled

maintenance purposes is as indicated in Figure 5-11. The complexity issue in this case arises from distribution of components to each requiring converter unit either for scheduled or unscheduled maintenance. The challenge is in developing logic for a simulation sub model to distribute components into 140 modules.

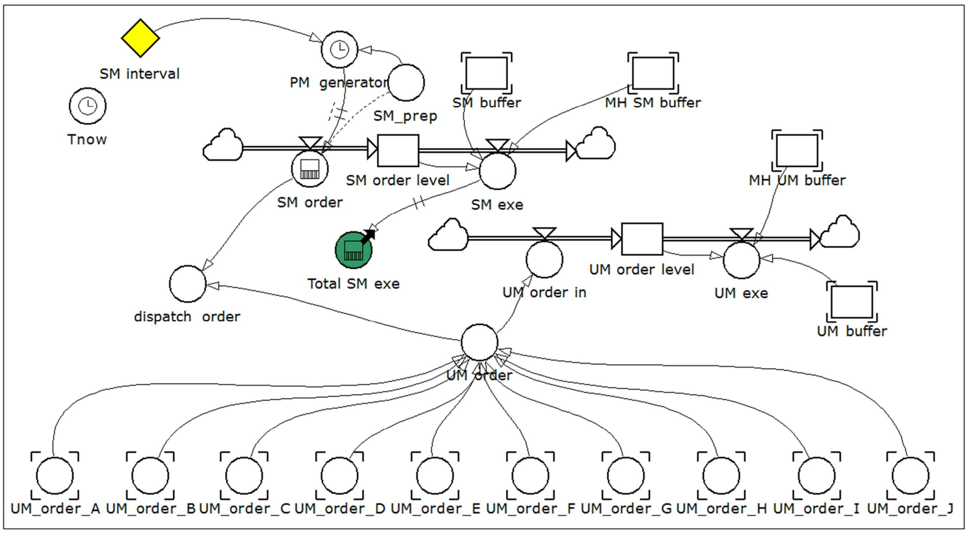


Figure 6-24 Simulation sub model to generate converters' maintenance orders and actions for all unit wind turbines

To simplify this allocation issue, the unit distribution to each requiring converter unit is developed in a hierarchical form. The logic is started by distributing the unit replacement to the requiring wind turbine, then distributing to the requiring units. The simulation sub model for allocating unit replacement to requiring units is shown in Figure 6-25. In a condition where scheduled and unscheduled maintenance occur at the same time, the unit allocation to unscheduled maintenance is prioritised in the simulation.

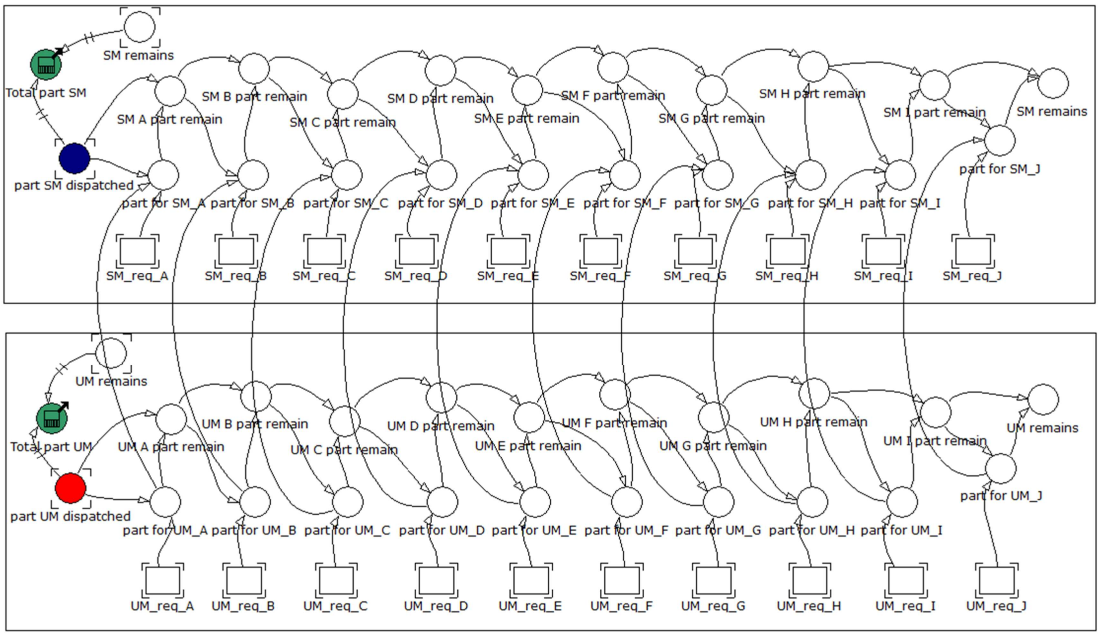


Figure 6-25 Simulation sub model for allocating component replacement to requiring units in scheduled and unscheduled maintenance

The allocation of the replacements to each wind turbine is based on the number of required units either for scheduled or unscheduled maintenance. For example, unit allocation for scheduled maintenance unit A is based on SM_req_A (see Figure 6-23). According to this hierarchy, the priority for unit replacement is from unit A, B, C respectively to J. After the replacement units are distributed to the requiring wind turbines, the number of required units is temporarily stored in an auxiliary variable associated with the type of maintenance. Auxiliary part for SM_A for instance, is an auxiliary to store the number of required units to support scheduled maintenance action for wind turbine A. The formula to determine the number of required units for the scheduled maintenance of wind turbine A is:

IF('part for UM_A'=>3,0, IF(SM_req_A=0,0, IF('part SM dispatched'>=SM_req_A,SM_req_A, 'part SM dispatched')))

As discussed, there is a possibility that at any time that scheduled and unscheduled replacements are performed at the same time. In that case, fulfilments for unscheduled replacement are prioritised. Therefore, in the formula above, the calculation starts after considering the requirement for unscheduled maintenance. If the number of allocated units for unscheduled maintenance is more than or equal to

three, no scheduled maintenance will be allocated to the particular wind turbine. Then, if the requirement for scheduled maintenance is zero, no scheduled maintenance is allocated either. Otherwise, the number of allocated units for unit A is based on the minimum number between the part SM dispatched and SM_req_A. A similar formula is applied to all auxiliary variables to determine the number of allocated units for scheduled and unscheduled maintenance for all associated wind turbines. After the units are distributed to the requiring wind turbine, then it will be distributed to the requiring modules as shown in Figure 6-26.

In Figure 6-26, the simulation sub model to distribute replacement units to the requiring units in a wind turbine is presented. Wind turbine units A and C are chosen as an example. Allocated units are temporarily stored in an auxiliary variable name part for SM_XYY where X is the wind turbine number and YY is the unit number. For instance, part for SM_A01 is an auxiliary to store allocated units to fulfil the requirement for scheduled maintenance in unit 01 wind turbine A. The formula applied in the part for SM_A01 is:

IF(status_A01=0,0,IF('part for A'>0,1,0))

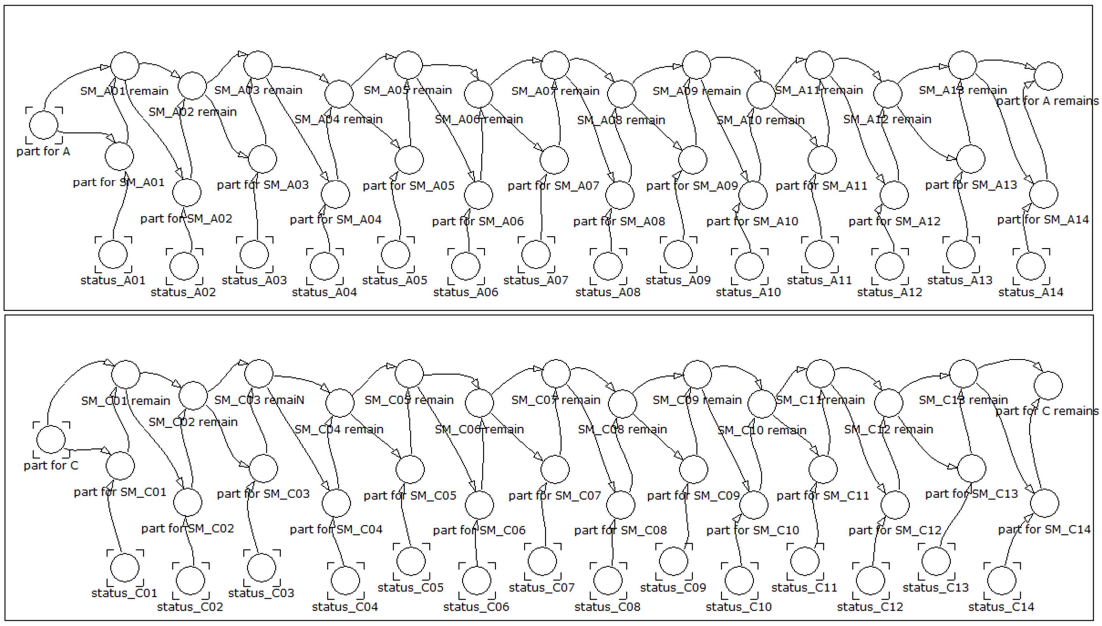


Figure 6-26 Simulation sub model for allocating units requiring modules of converters

The first step is checking the failure status of unit A01. If it has not failed then no replacing unit will be allocated Otherwise, if this unit has failed then a new unit is

allocated for maintenance purposes. The simulation checks whether a replacement unit is allocated for wind turbine A, if that is true the maintenance action is to be done in unit 01. The simulation logic is also applied to other units in the allocation auxiliary. The allocated units stored in every auxiliary are sent to the maintenance program simulation sub model. As shown in Figure 6-22 for instance, a unit to be replaced in wind turbine A unit 01 in a scheduled maintenance (part for SM A01) is given a random initial lifetime attribute and distributed to the replacement_A01 variable. In Figure 6-21, the replacement_A01 variable is added to the TTF_A01 (time to failure for unit A unit 01). Therefore, module A01 has a new unit with new time to failure attribute.

The simulation sub model for human resource provisioning used in this model is similar to the simulation sub model presented in Figure 5-13, and details of its logic has been explained in Section 5.2.4. In this converter case study, the human resource sub case is simple. The task here is to find out the optimum level of man-hours that should be provided by adding or reducing the number of technicians. This can be done by using the simulation sub model as in Figure 5-13 without adding any other variables.

6.4.4 Scenarios Generation by System Dynamic Simulation

The purpose of using system dynamics simulation in this research is to allow for generating alternative scenarios in terms of generated values for a set of variables that reflect different maintenance and resource provisioning policy or set of policies. In order to select the optimum policy, different output options of the simulation model are generated from different scenarios and analysed based on LCCA to find the best scenario for implementation.

For each policy, alternative sets of values for the input variables are selected and initial values for simulation variables are set in order to allow for generating values for scenario output variables. The scenarios cover different values of the variables set as alternative values for generating policies in the simulation. These set of variables for generating policies for the integrated maintenance programs and their resource provisioning are the interval of scheduled maintenance, initial inventory, safety stock level (or re-order point), maximum order quantity and provided man-hours. There are two alternative values to set for the variable of scheduled maintenance interval in this case: six monthly and annually.

For the purchasing and inventory policy, three variables are selected: initial inventory, safety stock level (or re-order point), and maximum order quantity. In this case study, initial inventory value is estimated by running the simulation to forecast the average annual requirement of the component. On average, the annual component requirement is 12 (twelve), pieces and therefore the initial inventory in the simulation is determined as 12 pieces to fulfil the requirement for the following year. This number is also selected as the number of safety stock or re-orders point. For the maximum order quantity, four different alternative numbers are set: 50 pieces, 30 pieces, 20 pieces, and 10 pieces. For the human resource division, the selected input for simulation is set as provided man-hours to support the maintenance order. The combinations of alternative values for all the above variables are tabulated in Table 6-23 to lay out all possible scenarios.

Table 6-23 Tabulation of all input variables

Input variables	SM Interval	Initial Inventory	Safety Stock Level	Max. Order Quantity	Provided Man-hours
Unit of measure	(days)	(piece)	(piece)	(piece)	(hours/day)
Scenario 1	**180**	12	12	**50**	64
Scenario 2	**180**	12	12	**30**	64
Scenario 3	**365**	12	12	**50**	64
Scenario 4	**365**	12	12	**30**	64
Scenario 5	**180**	12	12	**20**	64
Scenario 6	**180**	12	12	**10**	64
Scenario 7	**365**	12	12	**20**	64
Scenario 8	**365**	12	12	**10**	64

The combination of all alternative set of values for the variables produces eight scenarios as shown in Table 6-23, which are set as input for the simulation model. The simulation model generates values for 12 output variables as elaborated in Section 6.2.4, except the total time to repair variable. The consideration to eliminate this variable is because the time to repair for a converter is insignificant and can be ignored. Also in the previous case studies, the policy for inventory includes the desired inventory level variable, but in this case study this variable is replaced by maximum order quantity. This is because in converter purchasing, the optimum order

quantity is preferred instead of minimising the inventory cost. The price of each unit of converter is relatively small, so the inventory cost can be ignored.

6.4.5 Simulation Model Output and Life Cycle Cost Analysis

In this section, the output values of simulation are analysed. As a result of the simulation in terms of 30 replications for each scenario which represents 25 years of the wind farm lifetime, the outputs are presented in Table 6-24 and Table 6-25. The simulation output values of variables in all scenarios are accrued throughout each replication and adopted as an input into the LCC formula in Eq. 6-9 for LCCA to determine the optimum integrated maintenance and resource provisioning policy as one outcome of these simulation output scenarios.

Table 6-24 Output summary for all scenario with six monthly SM interval

input	unit of measure	Scenario 1	Scenario 2	Scenario 5	Scenario 6
Scheduled Maintenance interval	days	180	180	180	180
initial inventory	pcs	12	12	12	12
Safety stock level	pcs	12	12	12	12
Max. Order quantity	pcs	50	30	20	10
MH	hours/day	64	64	64	64

variables		Scenario 1		Scenario 2		Scenario 5		Scenario 6	
	unit of measure	average	stdev	average	stdev	average	stdev	average	stdev
# of SM order	times	50.00	0.00	50.00	0.00	50.00	0.00	50.00	0.00
# unit performed SM	times	215.00	11.47	216.00	12.30	217.00	9.64	215.00	9.86
# unit performed UM	times	12.00	3.85	12.00	3.90	11.00	3.12	12.00	3.38
Total part for SM	pcs	270.00	14.73	269.00	18.10	268.00	15.26	267.00	16.50
Total part for UM	pcs	35.00	11.64	35.00	11.70	33.00	9.39	35.00	10.14
Total # of order	times	7.00	0.47	10.00	0.76	14.00	0.88	25.00	1.70
Total unit ordered	pcs	329.00	25.04	318.00	25.27	311.00	20.47	307.00	21.13
average daily available component	pcs	37.00	1.14	27.00	0.68	22.00	0.55	17.00	0.36
#turbines days loss	turbine days	34.67	12.21	34.17	11.53	32.23	9.25	34.23	10.18

Table 6-25 Output summary for all scenario with annually SM interval

input	unit of measure	Scenario 3	Scenario 4	Scenario 7	Scenario 8
Scheduled Maintenance interval	days	365	365	365	365
initial inventory	pcs	12	12	12	12
Safety stock level	pcs	12	12	12	12
Max. Order quantity	pcs	50	30	20	10
MH	hours/day	64	64	64	64

variables		Scenario 3		Scenario 4		Scenario 7		Scenario 8	
	unit of measure	average	stdev	average	stdev	average	stdev	average	stdev
# of SM order	times	24.00	0.00	24.00	0.00	24.00	0.00	24.00	0.00
# unit performed SM	times	151.00	8.19	148.00	7.37	149.00	7.98	149.00	7.80
# unit performed UM	times	28.00	4.92	28.00	4.80	28.00	5.37	30.00	4.52
Total part for SM	pcs	208.00	11.10	203.00	11.02	204.00	12.15	205.00	12.72
Total part for UM	pcs	84.00	14.77	82.00	14.39	82.00	16.11	89.00	13.19
Total # of order	times	6.00	0.37	10.00	0.61	13.00	0.81	23.00	1.40
Total unit ordered	pcs	319.00	21.74	300.00	21.16	297.00	18.29	299.00	18.16
average daily available component	pcs	38.00	1.57	28.00	0.79	23.00	0.82	18.00	0.85
#turbines days loss	turbine days	83.23	15.17	81.80	14.23	83.87	21.47	88.73	13.30

The simulation output from all the scenarios are analysed and run through the LCC model. The result of analysis indicates that scenario 3 and scenario 5 turn out to be the best two scenarios. To illustrate the process of calculation, comparison and finding the optimum scenario through the LCC model, those two scenarios are selected.

On some occasions, it is difficult to obtain data or information from the actual system to be inputted into the LCC model. To cater for such situations, a cost ratio method is proposed. It is based on using sensitivity analysis on different cost ratios. The key point of using sensitivity analysis is observing how different values of observed variables affect the decision. According to (Pannell, 1997), there are 6 steps for sensitivity analysis:

a. Identify the parameters to be varied and the range for each parameter.
b. Perform sensitivity analyses for each parameter individually with the determined range. Then, record the result
c. On the basis of results so far, find a tentative optimum strategy.
d. Repeat steps b and c for every parameters.
e. Summarise these results, then identify the optimum scenarios where each strategy is optimal.
f. Attempt to draw conclusions.

The steps for sensitivity analysis are adjusted for the LCC calculation. The cost components in the LCC are considered as the parameters and the range is calculated based the pre-determined ratio of the cost based on one selected base cost. Then instead of repeating the steps for each cost component (or parameter), all possible combinations for ranges of the cost components are calculated and compared. In this research, the proposed adjusted approach for sensitivity analysis is called the cost ratio method.

As mentioned in the cost ratio method, each associated cost will be compared based on one promoted cost. For instance, the promoted base cost can be the price of the unit to be replaced. Then all the costs are defined as a ratio to the unit price. In general, the steps of this proposed method are detailed as follows:

1. Firstly, the base cost comparison is selected. It is argued that every associated cost can be selected as the base. However, it is important to select the cost that has a more stable value.
2. The second step of this method is determining the ratio for each associated cost to the base cost. The ratio for each associated cost can be set in terms of several ratio values to generate alternative options. For example, the unit price is selected as a base cost to determine maintenance cost. The estimated ratio values for maintenance cost to component price are 10; 12; 15. This means that the ratio range of maintenance cost is between 10, 12 or 15 times the unit price, and 3 ratio values are selected for the calculation, which are 10 times; 12 times; and 15 times of the unit price.
3. All cost ratio values for all associated costs are inserted into the LCC formula. In regards to the use of LCC in the scenario comparison in the system dynamics simulation, the cost ratio values are inputted to the LCC formula along with the output data from the simulation model.
4. The last step of this method is performing a sensitivity analysis. For a range of cost ratio values, sensitivity analysis needs to be done. In brief, sensitivity analysis is to find out how differently values of independent variables affect the output. The result of this analysis may help a decision maker to find the optimum scenario that should be selected in a particular condition of costs ratio.

To compare the promoted scenarios in this case study, the LCC formula needs to be tailored to this case. In this case study, tailoring is also done by removing cost elements which have the same value in all scenarios. It can be seen that the number of provided man-hours for the associated scenarios is the same. This means that human resource provisioning cost can be removed from the LCC for the cost comparison. Starting with Eq. 6-4, and removing the human resource provisioning cost, and considering the total cost formula in Eq. 4-10, the total cost formula for this case study scenario comparison is presented in Eq. 6-8. Then, the tailored LCC in terms of detailed variables after removing the human resource provisioning cost is presented in Eq. 6-9.

$$TC_t = C_{M,t} + C_{SL,t} + C_{PI,t} \quad \text{Eq. 6-8}$$

$$LCC\ (I,\ f\text{-}1(t),q,ROP) = \sum_{t=1}^{td}[\sum_{r=1}^{n_{SM,t}}(F_{SM,r,t} + C_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t} + C_{UM,s,t}) + n_{d,t}.F_{SL,t} + T_{d,t}.C_{S,t} + F_{i,t} + (n_{p,t}.C_{p,t}) + (n_{c,t}.C_{i,t}) + (\frac{n_{i,t}+n_{c,t}}{365}.C_{inv,t})](1+\pi)^{t-1}(1+r)^{-t} \quad \text{Eq. 6-9}$$

In this case study, the cost ratio method is used rather than using the actual value of cost elements. Following the steps of the cost ratio method, the first two steps are discussed in this section. First, the unit price of the unit to be replaced is selected as the base for the cost ratio. All cost elements are then presented in terms of a ratio to the price of the unit. Then, the cost elements in each scenario need to be determined as a ratio to the unit price. Based on the simulation output, the cost elements that need to be considered are: scheduled maintenance cost; unscheduled maintenance cost; delivery cost; purchasing cost (purchasing and delivery cost); stoppage loss.

The unit price is selected as the base of the cost ratio, and therefore the price of 1 unit is considered as 1 unit-price. The ratio of other cost elements range in value as follow:

1. Ratio ranges for the scheduled maintenance cost/unit price (SMC/C) between 3 unit-cost and 5 unit-cost. For example, SMC/C = 3 unit- cost means that the scheduled maintenance cost is 3 times higher than the unit price.
2. Ratio ranges for the unscheduled maintenance/unit price (UMC/C) between 10 unit- cost and 20 unit- cost.
3. Ratio ranges for the stoppage lost/unit price (SL/C) between 10 unit- cost and 15 unit- cost.
4. Ratio ranges for the delivery cost/unit price (DC/C) between 10 unit- cost and 20 unit- cost.

All the values of the cost ratio of all scenarios are used as input into the LCC model. As stated, scenario 5 and scenario 3 are selected to illustrate the process of finding the optimum scenario in the LCC model with the cost ratio method. By applying the combination of all ratio ranges of the cost elements to the two selected scenarios (scenario 3 and scenario 5) produces 32 unique combinations (32 runs) to calculate the LCC cost. The detail combination is presented in Table 6-26.

Based on the given data for the cost ratio, discount rate, and inflation, the formula in Eq. 6-9 can be simplified. The result of the simplification of Eq. 6-9 is shown in Eq. 6-10.

$$\text{LCC (I, f-1(t),q,ROP)} = \sum_{t=1}^{td}\Big[\sum_{r=1}^{n_{SM,t}}(F_{SM,r,t}) + \sum_{s=1}^{n_{UM,t}}(F_{UM,s,t}) + T_{d,t}.C_{S,t} + \left(n_{p,t}.C_{p,t}\right) + \left(n_{c,t}.C_{i,t}\right)\Big](1+\pi)^{t-1}(1+r)^{-t}$$

………………..………………..…...... Eq. 6-10

To simplify the calculation of the LCC, it is presented in the form of tables (Table 6-27 to Table 6-29). The formula in Eq. 6-10 accrues the cost during the design lifetime of the assets. In this case, t_d is determined for 25 years. The simulation is run in daily time steps for 25 years or 9,125 days. As discussed, the required simulation output values are generated annually. Then, all annual values are used to find the average value for calculation purposes. The average value is selected to represent the output values for the associated year. Run#1 is selected as an example. Run#1 is scenario 5 with maximum order quantity of 20 pcs, SMC/C : 3 unit-cost, UMC/C : 10 unit-cost, SL/C : 10 unit-cost, and DC/C : 1 unit-cost.

In the simulation, 30 replications are run for simulation output values generation. For instance, output from run#1 replication 01 is selected. To calculate the LCC, 5 types of output data are generated annually:

1. Required units for scheduled maintenance (#scheduled maintenance)
2. Required unit for unscheduled maintenance (#unscheduled maintenance)
3. Number of order (#order)
4. Number of components ordered (#component ordered)
5. Number of stoppage days (#days of stoppage)

The annual output values are presented in Table 6-27 in terms of variable rows and the cost ratio rows. Cost elements are determined from the cost ratio. All cells in the variable rows are then multiplied by associated cells in the cost rows. The results of these multiplications are annual cost, and are presented in Table 6-28. The annual cost is composed of annual cost for each output variable.

Table 6-26 Detail combination of ratio range to selected scenario

Run#		SMI	OQ	SMC/C	UMC/C	SL/C	DC/C
Scenario 5	1	180	20	3	10	10	1
	2	180	20	3	10	10	3
	3	180	20	3	10	15	1
	4	180	20	3	10	15	3
	5	180	20	3	20	10	1
	6	180	20	3	20	10	3
	7	180	20	3	20	15	1
	8	180	20	3	20	15	3
	9	180	20	5	10	10	1
	10	180	20	5	10	10	3
	11	180	20	5	10	15	1
	12	180	20	5	10	15	3
	13	180	20	5	20	10	1
	14	180	20	5	20	10	3
	15	180	20	5	20	15	1
	16	180	20	5	20	15	3
Scenario 3	17	365	50	3	10	10	1
	18	365	50	3	10	10	3
	19	365	50	3	10	15	1
	20	365	50	3	10	15	3
	21	365	50	3	20	10	1
	22	365	50	3	20	10	3
	23	365	50	3	20	15	1
	24	365	50	3	20	15	3
	25	365	50	5	10	10	1
	26	365	50	5	10	10	3
	27	365	50	5	10	15	1
	28	365	50	5	10	15	3
	29	365	50	5	20	10	1
	30	365	50	5	20	10	3
	31	365	50	5	20	15	1
	32	365	50	5	20	15	3

The next step is calculating the present value for each annual cost based on a predetermined interest rate of 2.49%. Table 6-29 shows the annual present value projection. Then, the annual present value projection is accumulated to find the LCC for run#1 replication 01. The result of the LCC calculation for run#1 replication 01 is 1,262.50 unit-cost and can be found at the bottom right of the continuation of Table 6-31. The total LCC is 1,262.50 times the unit price because it is based on a cost ratio to the unit price. Beside the LCC, the last column of continuation of Table 6-29 also provides the total amount of each cost element. This calculation process is repeated for all 30 replications in the simulation. The average of the annual cost and

annual present value projection for 30 replications are presented in Table 6-30 and 6-31 respectively. After 30 replications of run#1, it can be concluded that for run#1 the average LCC cost after present value projection is 1,403.46 unit-cost or 1,403.46 times the unit price.

The calculation process is repeated with different cost ratio based on the run number. The total cost for each cost element and the result of LCC calculation for all runs of scenario 5 and 3 are shown in Table 6-32 and 6-33 respectively. The next step is to plot the LCC from Table 6-32 and 6-33 into a chart to find the pattern of LCC in each scenario. The calculation results of the LCC from 16 runs in each scenario is shown in Figure 6-27. The figure indicates that in all combinations of cost ratio, scenario 5 has the lowest LCC.

Table 6-27 LCC calculation for run#1 replication 01

		Year		1	2	3	4	5	6	7	8	9	10	11	12	13
Variables	a	# Scheduled maintenance	(unit)	7.00	10.00	9.00	9.00	8.00	9.00	7.00	8.00	5.00	7.00	12.00	11.00	7.00
	b	#Unscheduled maintenance	(unit)	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00
	c	# order	(times)	1.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	0.00	1.00	1.00	0.00
	d	# component ordered	(pcs)	20.00	0.00	21.00	0.00	21.00	21.00	0.00	23.00	0.00	0.00	20.00	22.00	0.00
	e	# days of stoppage	(days)	0.00	0.00	0.00	0.00	0.00	3.00	0.00	3.00	0.00	0.00	0.00	0.00	3.00
Cost	1	Scheduled maintenance Cost	(unit cost/unit)	3.00	3.08	3.16	3.25	3.34	3.43	3.52	3.61	3.71	3.81	3.91	4.02	4.13
	2	Unscheduled maintenance Cost	(unit cost/unit)	10.00	10.27	10.55	10.83	11.12	11.42	11.73	12.04	12.37	12.70	13.04	13.39	13.75
	3	Ordering Cost	(unit cost/times)	1.00	1.03	1.05	1.08	1.11	1.14	1.17	1.20	1.24	1.27	1.30	1.34	1.38
	4	Component Price	(unit cost/pcs)	1.00	1.03	1.05	1.08	1.11	1.14	1.17	1.20	1.24	1.27	1.30	1.34	1.38
	5	Stoppage Loss	(unit cost/days)	10.00	10.27	10.55	10.83	11.12	11.42	11.73	12.04	12.37	12.70	13.04	13.39	13.75

Table 6-27 LCC calculation for run#1 replication 01 (continued)

		Year		14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
Variables	a	# Scheduled maintenance	(unit)	8.00	11.00	12.00	10.00	8.00	11.00	10.00	12.00	8.00	8.00	8.00	9.00	224.00
	b	#Unscheduled maintenance	(unit)	0.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.00
	c	# order	(times)	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00	14.00
	d	# component ordered	(pcs)	21.00	0.00	22.00	23.00	0.00	20.00	22.00	0.00	20.00	0.00	21.00	0.00	297.00
	e	# days of stoppage	(days)	0.00	3.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00	21.00
Cost	1	Scheduled maintenance Cost	(unit cost/unit)	4.24	4.35	4.47	4.59	4.71	4.84	4.97	5.10	5.24	5.38	5.52	5.67	105.03
	2	Unscheduled maintenance Cost	(unit cost/unit)	14.12	14.50	14.89	15.29	15.70	16.13	16.56	17.00	17.46	17.93	18.41	18.91	350.11
	3	Ordering Cost	(unit cost/times)	1.41	1.45	1.49	1.53	1.57	1.61	1.66	1.70	1.75	1.79	1.84	1.89	35.01
	4	Component Price	(unit cost/pcs)	1.41	1.45	1.49	1.53	1.57	1.61	1.66	1.70	1.75	1.79	1.84	1.89	35.01
	5	Stoppage Loss	(unit cost/days)	14.12	14.50	14.89	15.29	15.70	16.13	16.56	17.00	17.46	17.93	18.41	18.91	350.11

Table 6-28 Annual cost calculation for run#1 replication 01

			Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Sub-total	1a	Scheduled maintenance Cost	(unit cost)	21.00	30.81	28.47	29.24	26.69	30.83	24.63	28.90	18.55	26.67	46.94	44.19	28.88
	2b	Unscheduled maintenance Cost	(unit cost)	0.00	0.00	0.00	0.00	0.00	11.42	0.00	12.04	0.00	0.00	0.00	0.00	13.75
	3c	Ordering Cost	(unit cost)	1.00	0.00	1.05	0.00	1.11	1.14	0.00	1.20	0.00	0.00	1.30	1.34	0.00
	4d	Component Price	(unit cost)	20.00	0.00	22.14	0.00	23.35	23.98	0.00	27.70	0.00	0.00	26.08	29.46	0.00
	3c+4d	Purchasing Cost	(unit cost)	21.00	0.00	23.20	0.00	24.46	25.12	0.00	28.90	0.00	0.00	27.38	30.80	0.00
	5e	Stoppage Loss	(unit cost)	0.00	0.00	0.00	0.00	0.00	34.26	0.00	36.13	0.00	0.00	0.00	0.00	41.25
		Annual Cost :	(unit cost)	42.00	30.81	51.67	29.24	51.15	101.63	24.63	105.97	18.55	26.67	74.33	74.99	83.88

Table 6-28 Annual cost calculation for run#1 replication 01 (continued)

			Year	14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
Sub-total	1a	Scheduled maintenance Cost	(unit cost)	33.89	47.85	53.61	45.87	37.69	53.21	49.68	61.22	41.91	43.04	44.19	51.06	949.00
	2b	Unscheduled maintenance Cost	(unit cost)	0.00	14.50	29.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.91	100.40
	3c	Ordering Cost	(unit cost)	1.41	0.00	1.49	1.53	0.00	1.61	1.66	0.00	1.75	0.00	1.84	0.00	19.44
	4d	Component Price	(unit cost)	29.65	0.00	32.76	35.17	0.00	32.25	36.43	0.00	34.92	0.00	38.67	0.00	412.57
	3c+4d	Purchasing Cost	(unit cost)	31.07	0.00	34.25	36.70	0.00	33.86	38.09	0.00	36.67	0.00	40.51	0.00	432.02
	5e	Stoppage Loss	(unit cost)	0.00	43.50	89.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	56.73	301.21
		Annual Cost :	(unit cost)	64.96	105.86	206.98	82.57	37.69	87.08	87.76	61.22	78.58	43.04	84.70	126.69	2214.65

Table 6-29 Annual cost after present value projection for run#1 replication 01

		Year		1	2	3	4	5	6	7	8	9	10	11	12	13
PV Projection	6	Scheduled maintenance Cost	(unit cost)	20.49	29.33	26.45	26.50	23.60	26.60	20.73	23.74	14.87	20.85	35.82	32.90	20.97
	7	Unscheduled maintenance Cost	(unit cost)	0.00	0.00	0.00	0.00	0.00	9.85	0.00	9.89	0.00	0.00	0.00	0.00	9.99
	8	Ordering Cost	(unit cost)	0.98	0.00	0.98	0.00	0.98	0.99	0.00	0.99	0.00	0.00	0.99	1.00	0.00
	9	Component Price	(unit cost)	19.51	0.00	20.57	0.00	20.65	20.69	0.00	22.75	0.00	0.00	19.90	21.93	0.00
	10	Purchasing Cost	(unit cost)	20.49	0.00	21.55	0.00	21.63	21.68	0.00	23.74	0.00	0.00	20.89	22.93	0.00
	11	Stoppage Loss	(unit cost)	0.00	0.00	0.00	0.00	0.00	29.56	0.00	29.67	0.00	0.00	0.00	0.00	29.96
		Annual Present Value :	(unit cost)	40.98	29.33	48.00	26.50	45.23	87.69	20.73	87.04	14.87	20.85	56.71	55.82	60.93

Table 6-29 Annual cost after present value projection for run#1 replication 01 (continued)

		Year		14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
PV Projection	6	Scheduled maintenance Cost	(unit cost)	24.02	33.09	36.17	30.20	24.21	33.35	30.38	36.52	24.40	24.44	24.49	27.61	671.70
	7	Unscheduled maintenance Cost	(unit cost)	0.00	10.03	20.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.22	70.08
	8	Ordering Cost	(unit cost)	1.00	0.00	1.00	1.01	0.00	1.01	1.01	0.00	1.02	0.00	1.02	0.00	13.98
	9	Component Price	(unit cost)	21.02	0.00	22.10	23.15	0.00	20.21	22.28	0.00	20.33	0.00	21.43	0.00	296.52
	10	Purchasing Cost	(unit cost)	22.02	0.00	23.11	24.16	0.00	21.22	23.29	0.00	21.35	0.00	22.45	0.00	310.50
	11	Stoppage Loss	(unit cost)	0.00	30.08	60.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30.67	210.23
		Annual Present Value :	(unit cost)	46.03	73.20	139.65	54.36	24.21	54.57	53.66	36.52	45.74	24.44	46.94	68.50	1262.50

Table 6-30 Average annual cost calculation for run#1 all replications

			Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Sub-total	1a	Scheduled maintenance Cost	(unit cost)	25.70	27.01	27.10	28.26	28.91	28.78	28.96	29.86	29.43	34.41	32.21	36.69	35.75
	2b	Unscheduled maintenance Cost	(unit cost)	2.67	2.74	4.22	3.25	2.59	4.95	3.91	7.63	8.66	5.50	4.35	8.48	6.42
	3c	Ordering Cost	(unit cost)	1.00	0.21	0.77	0.40	0.89	0.72	0.51	0.72	0.54	0.80	0.65	0.80	0.73
	4d	Component Price	(unit cost)	20.20	4.52	17.96	8.45	19.50	16.03	11.34	16.42	12.08	17.86	14.65	18.52	16.27
	3c+4d	Purchasing Cost	(unit cost)	21.20	4.72	18.74	8.84	20.39	16.75	11.84	17.14	12.61	18.67	15.30	19.33	17.01
	5e	Stoppage Loss	(unit cost)	8.00	8.22	12.65	9.75	7.78	14.85	11.73	22.88	26.38	16.51	12.61	25.44	19.25
		Annual Cost :	(unit cost)	57.57	42.68	62.71	50.10	59.68	65.32	56.44	77.51	77.08	75.09	64.46	89.94	78.43

Table 6-30 Average annual cost calculation for run#1 all replications (continued)

			Year	14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
Sub-total	1a	Scheduled maintenance Cost	(unit cost)	39.12	38.86	41.69	37.92	42.40	40.64	46.70	44.04	44.53	48.59	47.14	47.46	912.18
	2b	Unscheduled maintenance Cost	(unit cost)	5.18	6.28	7.45	7.14	3.66	9.68	8.28	7.37	5.24	7.17	9.82	10.08	152.70
	3c	Ordering Cost	(unit cost)	0.71	0.92	0.74	0.87	0.68	0.97	0.83	1.08	0.81	1.02	0.80	1.13	19.30
	4d	Component Price	(unit cost)	15.49	20.98	17.42	20.03	15.76	20.96	18.99	23.75	19.03	23.61	17.43	25.15	432.39
	3c+4d	Purchasing Cost	(unit cost)	16.19	21.90	18.17	20.90	16.44	21.93	19.82	24.83	19.85	24.63	18.23	26.28	451.69
	5e	Stoppage Loss	(unit cost)	15.53	18.85	22.34	21.41	10.47	29.03	25.39	22.67	16.30	20.32	30.08	30.25	458.68
		Annual Cost :	(unit cost)	76.02	85.89	89.64	87.37	72.97	101.27	100.18	98.91	85.91	100.72	105.27	114.09	2426.93

Table 6-31 Average annual cost after present value projection for run#1 all replications

		Year		1	2	3	4	5	6	7	8	9	10	11	12	13
PV Projection	6	Scheduled maintenance Cost	(unit cost)	25.08	25.71	25.17	25.62	25.57	24.83	24.38	24.53	23.59	26.91	24.57	27.31	25.97
	7	Unscheduled maintenance Cost	(unit cost)	2.60	2.61	3.92	2.94	2.29	4.27	3.29	6.26	6.94	4.30	3.32	6.31	4.66
	8	Ordering Cost	(unit cost)	0.98	0.20	0.72	0.36	0.79	0.62	0.43	0.59	0.43	0.63	0.50	0.60	0.53
	9	Component Price	(unit cost)	19.71	4.30	16.68	7.66	17.24	13.83	9.54	13.48	9.68	13.97	11.18	13.79	11.82
	10	Purchasing Cost	(unit cost)	20.68	4.50	17.40	8.01	18.03	14.45	9.97	14.08	10.11	14.60	11.67	14.39	12.35
	11	Stoppage Loss	(unit cost)	7.81	7.82	11.75	8.83	6.88	12.81	9.87	18.79	21.14	12.91	9.62	18.94	13.98
		Annual Present Value :	(unit cost)	56.17	40.64	58.25	45.41	52.77	56.36	47.52	63.67	61.77	58.72	49.18	66.96	56.96

Table 6-31 Average annual cost after present value projection for run#1 all replications (continued)

		Year		14	15	16	17	18	19	20	21	22	23	24	25	Aggregate
PV Projection	6	Scheduled maintenance Cost	(unit cost)	3.67	4.35	5.02	4.70	2.35	6.06	5.06	4.40	3.05	4.07	5.44	5.45	107.35
	7	Unscheduled maintenance Cost	(unit cost)	0.50	0.64	0.50	0.57	0.44	0.61	0.51	0.64	0.47	0.58	0.44	0.61	13.88
	8	Ordering Cost	(unit cost)	10.97	14.51	11.75	13.19	10.12	13.14	11.61	14.17	11.08	13.41	9.66	13.60	310.08
	9	Component Price	(unit cost)	11.48	15.14	12.26	13.76	10.56	13.74	12.12	14.81	11.55	13.99	10.10	14.21	323.96
	10	Purchasing Cost	(unit cost)	11.01	13.04	15.07	14.09	6.72	18.19	15.53	13.53	9.49	11.54	16.67	16.36	322.39
	11	Stoppage Loss	(unit cost)	3.67	4.35	5.02	4.70	2.35	6.06	5.06	4.40	3.05	4.07	5.44	5.45	107.35
		Annual Present Value :	(unit cost)	53.87	59.39	60.48	57.51	46.87	63.46	61.26	59.01	50.01	57.20	58.34	61.69	1403.46

Table 6-32 LCC result of scenario 5 for all runs

SM Period	RUN#	SM Cost	UM Cost	Ordering Cost	Component Price	Purchasing Cost	Stoppage Loss	Total
180 days	1	649.76	107.35	13.88	310.08	323.96	322.39	1403.46
	2	649.76	107.35	41.63	310.08	351.71	322.39	1431.21
	3	649.76	107.35	13.88	310.08	323.96	483.59	1564.65
	4	649.76	107.35	41.63	310.08	351.71	483.59	1592.41
	5	649.76	214.70	13.88	310.08	323.96	322.39	1510.81
	6	649.76	214.70	41.63	310.08	351.71	322.39	1538.56
	7	649.76	214.70	13.88	310.08	323.96	483.59	1672.00
	8	649.76	214.70	41.63	310.08	351.71	483.59	1699.76
	9	1082.93	107.35	13.88	310.08	323.96	322.39	1836.63
	10	1082.93	107.35	41.63	310.08	351.71	322.39	1864.38
	11	1082.93	107.35	13.88	310.08	323.96	483.59	1997.83
	12	1082.93	107.35	41.63	310.08	351.71	483.59	2025.58
	13	1082.93	214.70	13.88	310.08	323.96	322.39	1943.98
	14	1082.93	214.70	41.63	310.08	351.71	322.39	1971.73
	15	1082.93	214.70	13.88	310.08	323.96	483.59	2105.18
	16	1082.93	214.70	41.63	310.08	351.71	483.59	2132.93

Table 6-33 LCC result of scenario 3 for all runs

SM period	RUN#	SM Cost	UM Cost	Ordering Cost	Component Price	Purchasing Cost	Stoppage Loss	Total
365 days	1	450.09	279.63	5.99	318.32	324.30	832.20	1886.22
	2	450.09	279.63	17.96	318.32	336.28	832.20	1898.20
	3	450.09	279.63	5.99	318.32	324.30	1248.30	2302.32
	4	450.09	279.63	17.96	318.32	336.28	1248.30	2314.29
	5	450.09	559.26	5.99	318.32	324.30	832.20	2165.85
	6	450.09	559.26	17.96	318.32	336.28	832.20	2177.83
	7	450.09	559.26	5.99	318.32	324.30	1248.30	2581.95
	8	450.09	559.26	17.96	318.32	336.28	1248.30	2593.93
	9	750.15	279.63	5.99	318.32	324.30	832.20	2186.28
	10	750.15	279.63	17.96	318.32	336.28	832.20	2198.25
	11	750.15	279.63	5.99	318.32	324.30	1248.30	2602.38
	12	750.15	279.63	17.96	318.32	336.28	1248.30	2614.35
	13	750.15	559.26	5.99	318.32	324.30	832.20	2465.91
	14	750.15	559.26	17.96	318.32	336.28	832.20	2477.89
	15	750.15	559.26	5.99	318.32	324.30	1248.30	2882.01
	16	750.15	559.26	17.96	318.32	336.28	1248.30	2893.98

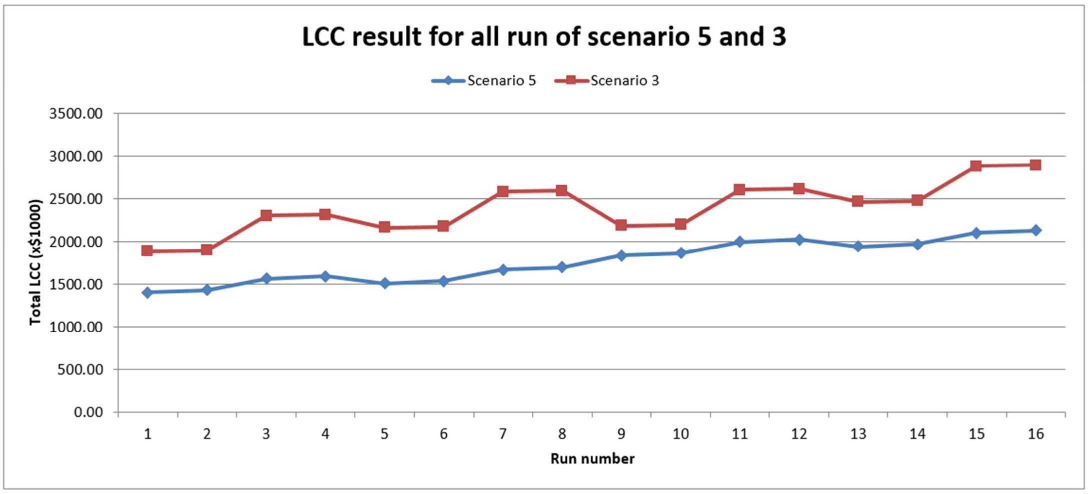


Figure 6-27 LCC result of all runs for scenario 5 and scenario 3

6.4.6 Sensitivity analysis

In general, this process is to analyse how different ranges of cost ratio values affect the LCC. To start the process, all associated cost elements in the LCC in Table 6-30 and 6-31 are charted in Figure 6-28 and Figure 6-29 respectively. In scenario 5, the policy to perform the six-monthly scheduled maintenance causes maintenance cost to contribute most to the LCC. Conversely in scenario 3, annual scheduled maintenance policy generates a high number of turbines days loss, which impacts more on unscheduled maintenance cost and stoppage loss compared to scenario 5. The cost that contributes most to the LCC of scenario 3 is stoppage loss, as shown in Figure 6-29.

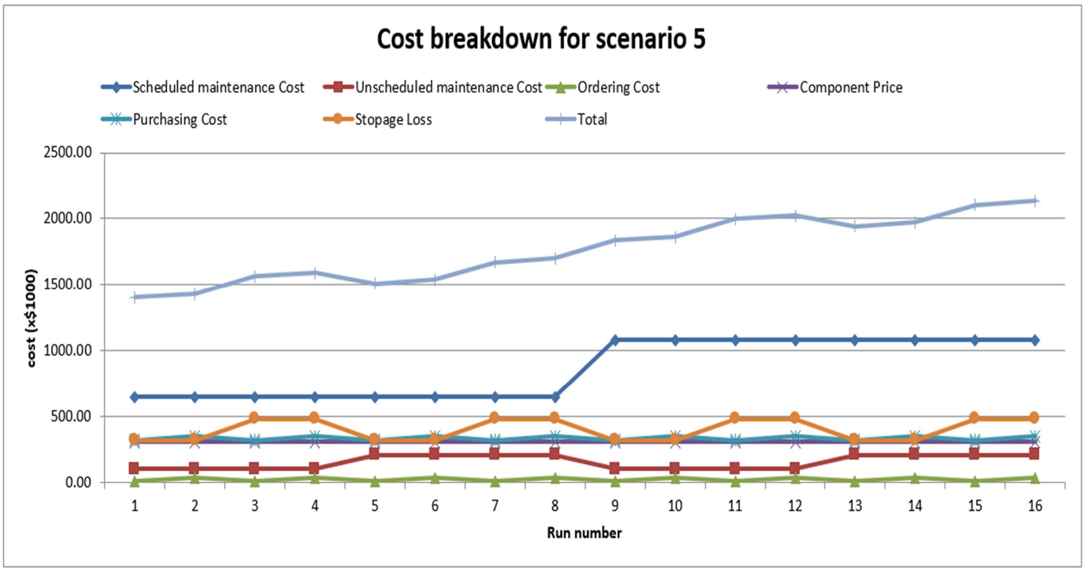


Figure 6-28 Scenario 5 cost breakdown

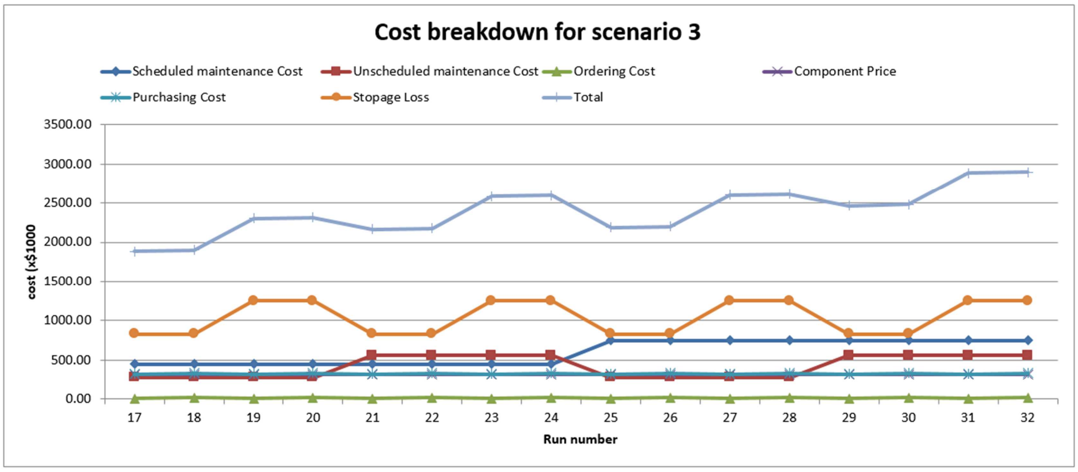


Figure 6-29 Scenario 3 cost breakdown

Both Figures 6-28 and 6-29 indicate that the LCC is composed mostly of 2 dominant cost elements: scheduled maintenance cost and stoppage loss. Because a scheduled maintenance job is required to maintain the asset, it does not make sense to remove the scheduled maintenance cost from the LCC for this sensitivity analysis. Conversely, in some cases where the stoppage loss can be ignored, an interesting result of the LCC after removing the stoppage loss is discovered and shown in Figure 6-30.

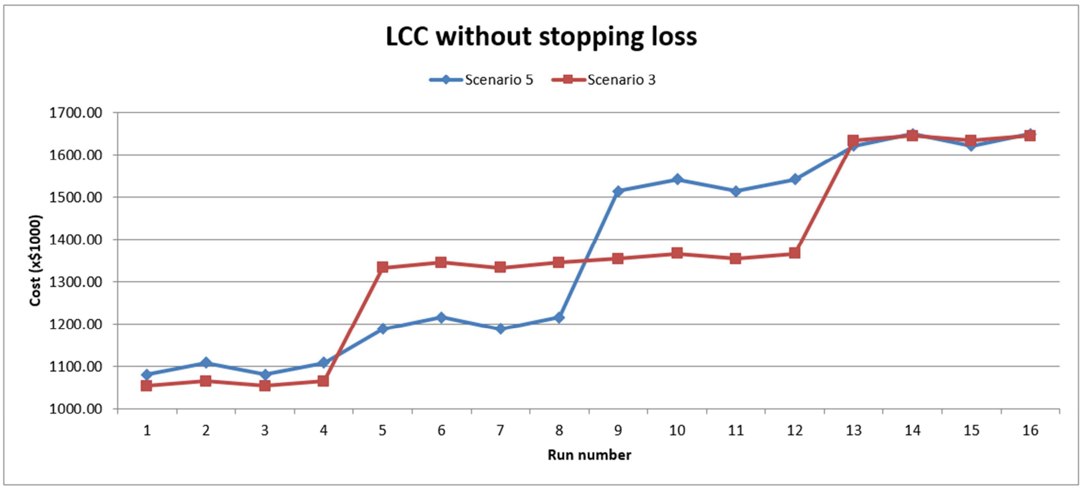


Figure 6-30 LCC plotting after removing stoppage loss

In Figure 6-27 scenario 5 generates lower LCC in all runs than scenario 3 but it is not dominant. The figure shows that different combinations of cost ratio values generate different LCC, which in turn leads to different optimum scenarios. To support the decision making in Figure 6-30, we should refer to Table 6-34. For instance, at axis numbers 1 to 4 in Figure 6-30, scenario 3 is better than scenario 5, because they have smaller total cost. Then, at axis numbers 5 to 8, scenario 5 is better. We concludes that for SMC/C=3, UMC/C= 10, and DC/C = 1 or 3, scenario 3 is preferred. But when the ratio's value UMC/C turns to 20, scenario 5 is more feasible. Details can be found in Table 6-34.

Table 6-34 LCC cost after removing stoppage loss

Axis No	Run#		OQ		SMI		SMC/C	UMC/C	SL/C	DC/C	LCC PV	
			SC5	SC3	SC5	SC3					SC05	SC03
1	1	17	20	50	180	365	3	10	0	1	1081.07	1054.02
2	2	18	20	50	180	365	3	10	0	3	1108.82	1066.00
3	3	19	20	50	180	365	3	10	0	1	1081.07	1054.02
4	4	20	20	50	180	365	3	10	0	3	1108.82	1066.00
5	5	21	20	50	180	365	3	20	0	1	1188.42	1333.65
6	6	22	20	50	180	365	3	20	0	3	1216.17	1345.63
7	7	23	20	50	180	365	3	20	0	1	1188.42	1333.65
8	8	24	20	50	180	365	3	20	0	3	1216.17	1345.63
9	9	25	20	50	180	365	5	10	0	1	1514.24	1354.08
10	10	26	20	50	180	365	5	10	0	3	1541.99	1366.06
11	11	27	20	50	180	365	5	10	0	1	1514.24	1354.08
12	12	28	20	50	180	365	5	10	0	3	1541.99	1366.06
13	13	29	20	50	180	365	5	20	0	1	1621.59	1633.71
14	14	30	20	50	180	365	5	20	0	3	1649.34	1645.69
15	15	31	20	50	180	365	5	20	0	1	1621.59	1633.71
16	16	32	20	50	180	365	5	20	0	3	1649.34	1645.69

In Table 6-34, some axis numbers have the same value in all cells, for instance axis number: 1 and 3, 2 and 4. In the original runs, those axes have different stoppage loss. Those runs are kept in the table although the values are similar.

6.4.7 Case Results and Findings

In this case study, the developed integrated model: system dynamics simulation and the life cycle model is applied and results are verified for a maintenance resource-provisioning policy setting for wind turbine converters in a wind farm. Eight scenarios are generated and run by system dynamic simulation and the optimum scenario is selected based on minimum life cycle cost through the developed LCC model

In contrast to the previous case studies, cost ratio values rather than actual cost values were used to calculate costs in the LCC model due to the unavailability of cost details. This calculation process is repeated on all 30 replications in the simulation. The average of the annual cost and annual present value projection for 30 replications are presented. The result of the LCC indicates that scenario 5 has the minimum LCC.

For the decision making purposes, the result shows that SMC/C; UMC/C; DC/C are external uncontrolled variables, and maximum order quantity and scheduled maintenance interval are controlled variables. Based on the simulation result, a decision can be made with reference to the uncontrolled variables. The decision contains the interval of scheduled maintenance and maximum order quantity variables. For instance, when SMC/C=3; UMC/C=10; and DC/C=1, the suggested scenario is the policy; in terms of annual scheduled maintenance interval with a maximum Order Quantity of 50 units. When the delivery cost ratio increased to 3 or the cost ratio of the scheduled maintenance increases to 5, the decision remains as scenario 3. If the unscheduled maintenance increases to 20, the cost ratio becomes uninfluential, and the suggested decision turns to scenario 5.

6.5 Linking the simulation result with the CLD

The results of the simulation for three case studies were obtained. A brief analysis should be presented to gain a better understanding as to why one scenario provides better results compare to the others. This can be done by linking the result of the simulation with the feedback structure in CLD. In the three case studies, different ranges of four input variables are incorporated into the system dynamics model. Those variables are: (1) Maintenance interval, (2) desired inventory level, (3) provided man-hours, and (4) Threshold.

The different values of input variables have different impacts on asset performance, but this impact can be significant or insignificant. However, the result of the statistical analysis of the simulation result indicates that only different scheduled maintenance interval variables have a significant impact on asset availability. From the CLD in Figure 5.2, the lower asset availability comes from a higher value of asset failure and repair time. To increase the asset availability, asset failure and repair time should be reduced. Reducing asset failure can be done by performing more frequent scheduled maintenance, but this will increase repair time, and vice versa. This circumstance required optimisation of the scheduled maintenance interval to achieve optimum asset availability.

In the first case study, 5 year and 7 year scheduled maintenance intervals are assessed. The result shows that a 7 year scheduled maintenance interval provides higher asset availability. The reason for this is that a 5 year scheduled maintenance

interval requires more accumulated repair time, and hence reduces asset availability. It may reduce asset failure and leads to lower number unscheduled maintenance, but in general it could not significantly reduce the total number of days loss. It should be noted that higher loss of days means lower asset availability. Conversely, a 7 year scheduled maintenance interval may lead to more unscheduled maintenance intervals, but it can reduce the accumulated repair time for scheduled maintenance. The accumulation of the number of days loss caused by asset failure, unscheduled maintenance and scheduled maintenance in a 7 year scheduled maintenance interval is significantly lower compared to a 5 year scheduled maintenance interval, and provides higher asset availability.

In case study two, 7 year and 10 year scheduled maintenance intervals are assessed. The result shows that a 7 year scheduled maintenance interval generates a lower number of loss of days compared to a 10 year scheduled maintenance interval. In a 10 year scheduled maintenance interval, the accumulated repair time is significantly reduced; however it also generates more frequent asset failure and unscheduled maintenance.

The different values of other input variables do not have a significant impact on asset availability. This means that by providing a minimum value in the case study may not affect asset availability. However, the main objective of this research is not just maximising asset availability, but also in minimising the total LCC. Hence, all values of the output variables should be integrated into the LCC equation to find the combined policies with minimum LCC.

7 CONCLUSION AND RECOMMENDATION

7.1 Introduction

A new modelling method has been established as an integrated decision support model for maintenance resources provisioning management to support decision making to achieve optimum performance of engineered assets in complex technical systems.

The integration of system dynamic simulation with a life cycle cost model is capable of overcoming the modelling complexity associated with interrelated maintenance programs of engineered assets in a complex technical system, and is a suitable modelling approach for providing an integrated decision support model for maintenance resource-provisioning management. It has been verified through case studies that system dynamics simulation when integrated with a life cycle cost model provides a suitable integrated model that is capable of generating alternatives for a maintenance resource-provisioning policy, and capable of determining alternatives associated with optimum performance for engineered asset maintenance programs in a complex technical system.

A model for complex asset maintenance and a maintenance resource-provisioning management policy has been developed. The model is a combination of the system dynamics simulation model and the Life-Cycle Cost analytical model. The developed system dynamics simulation model successfully served its purpose to model the cause-effect relationships between the resource provisioning variables and maintenance programs variables involved in managing engineered assets in a complex technical system and its related supporting functions. In each case study, several scenarios are generated and applied into the system dynamics simulation model. Utilising the output of the simulation, the developed LCC model was employed and proved to be capable of assisting in the selection of the optimum scenario.

7.2 Case Study Findings Related to the New Application

The purpose of the case studies was to verify that the newly developed model can be tailored to different situations depending on the nature of an engineered asset

and its units functioning within a technical system. Having the model successfully tailored for these case studies was then verified by the research, it was found to be capable of generating alternatives for the maintenance resource-provisioning policies, and in determining alternatives that provide optimum performance of the overall set of assets in the technical system. As an overall finding, the newly developed models were easily tailored for application in three case studies selected; however in each case the model required different adjustments to be fully suitable for each case study. In each of the case studies a set of alternative scenarios was successfully generated by the newly developed models to represent the alternative maintenance resource-provisioning policies, and then the alternative policy associated with optimum performance was determined.

The ranges of values in terms of the input and output variables in the generated scenarios provide the basis for identifying those variables that have the most significant impact on the selection of resource provisioning or maintenance policy for achieving optimum asset performance. Identifying these significant variables indicates the impact of variables and the alignment between maintenance and other support functions.

The newly developed model is capable of handling large fleets of similar assets. Simplification of the simulation logic, including the introduction of a temporary intermediate buffer to store temporary information, makes this an efficient modelling process.

7.3 Implication of Research Findings

The capability of system dynamics simulation has been extended by incorporating life cycle cost models. This has been shown to allow the modelling of resource provisioning policy implications given their interrelationship with the maintenance program. Such an enhancement is required particularly when considering complex technical systems which have been found to be inadequately modelled by other techniques, including analytical modelling, genetic algorithms, or the discrete event simulation method. The newly developed model provides a means of analysis to identify variables that have the most significant impact on asset performance and achieving optimisation. It can model, in a general format, the interrelationships and interdependences between many functions within an

organisation which makes it easily exploited for further research purposes and tailored for application to assets with different attributes or for different industries while accounting for changes or adjustment for adaptation to each case.

7.4 Practical Implication of Research Finding

The newly developed models can be adapted as a tool to generate different resource provisioning and maintenance policies and selecting the optimum policy for any set of assets in a complex technical system. It can also be useful as a basis for sensitivity analysis to determine significant factors which impact an asset performance.

The developed model is also capable of adequately representing the interdepartmental interaction in an organisation, and therefore can assist in managing the interface between these departments. In this respect, the developed model can be used to support decision making processes in asset management. The model provides a representation of integrating the maintenance department and other functions in an organisation, and can provide a basis for information management to manipulate management plans and to determine the strategy and required resources that lead to an appropriate decision based on efficiency, effectiveness and optimum cost.

7.5 Research Limitations

Although the newly developed models are able to serve the purpose of the research there are some limitations:

1. The system dynamics simulation has not covered all maintenance resources. For the purpose of developing a simulation approach that can be followed for any number of resources, only the interrelationships with the main functions of maintenance resources have been studied: purchasing, inventory and human resources. In purchasing and inventory, only one type of component is presented. In human resource provisioning, only general man-hours is presented, regardless of the type of skill that should be provided. The more types of maintenance resources involved in the model, the bigger the research task becomes in terms of time, and software capacity, due to the need for more buffer variable to be provided in the model. The impact of this limitation on the value

of the results of this research are significant because the newly developed models are developed and verified based on those selected resources, while it provides a basis for further research on covering other resources that are not covered by this research. The research covered only one type of resource from purchasing, inventory and human resource department. Confirming the model results with actual practice supported the validity of the model and provides confidence for adapting it for further research or application to modify and extend the model to include more resources that may exist in a more complex asset maintenance resource-provisioning program.

2. The model has not included the combination of different sources and/or policies for human resources such as recruiting, sub-contracting, or outsourcing. These constitute data related to input variables and do not impact on the output of the model, but has limited the human resource scenarios that are initially generated from the input variables. These input variables: recruitment, sub-contracting, outsourcing or combination were not included in the case studies but can be easily included in the model if those mentioned constraints are removed.
3. It is possible to include the algorithm of the newly developed LCC model directly into the system dynamics model, but this will increase the computational burden. In order to reduce the computational burden, the LCC calculation is performed separately outside the system dynamics model. This can only affect the accuracy of the result but has no impact on the validity of the model or its result.

7.6 Directions for Future Research

The direction for future research is mostly related to further development of the newly developed models to handle the various complexities that may exist in managing more resources or relationships. A number of recommendations for future research can be based on some of the limitations as identified for potential continuation of this research in the previous section.

The developed model has the potential to explore interrelationships between various life cycle and support functions or management systems in terms of identifying the variables that have significant impact and potential for interface

management. The model also can be used to study alignment of requirements with objectives, and requirement at the low levels with those at higher levels.

More detail of future research that might be initiated based on the research limitations are:

1. To develop a new integrated model with more maintenance resources (different skills of human resources and different types of inventory). As stated in Section 7.5 that at this stage, the newly developed model provides general interaction among maintenance, purchasing & inventory, and human resource provisioning systems with one type of maintenance resource from each supporting department. There is a good opportunity to develop a model with extended types of maintenance resources. However, this model should also to adjust or develop a new algorithm to be included in the model, to cater for the higher computational burden and higher model complexity.
2. The newly developed model in this research has not included combinations of different sources or combined provisioning policies. In the purchasing & inventory department, different sources of spare parts may come from different suppliers and different policies of purchasing & inventory can create different levels of safety stock or different inventory levels. In human resources provisioning, a combined policy such as sub-contracting, outsourcing, can be elaborated upon.
3. This research was initiated from the result of a literature review that showed the combination of system dynamics and LCC model is suitable for optimizing or improving performance of a complex system of engineered assets. It is based on an analysis that the nature of the system dynamics model fits to represent the system and the LCC model is capable of supporting the cost calculation of each policy. However, the comparison of this modelling approach with other methods in the literature review was not thoroughly discussed. Further research to compare the capabilities and benefits of those methods is recommended.

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