Computationally Optimised Manpower Rosters for Airline Short-Term Layover Maintenance

A research report submitted by

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Abstract

Introduction: Short-term layover maintenance activities at an airline base generally involve the execution of significant numbers of high-frequency, short-duration routine inspections in between flights on aircraft that are deployed to ongoing flight operations. The problem of scheduling labour supplies for this type of maintenance activity requires an operations manager to consider issues such as the number of scheduled flights each day, the timing constraints for the tasks that must be implemented on aircraft that are departing from or arriving at the base of operations, the employee skills and certifications that are needed to implement the required maintenance actions, as well as the potential for the planned flight schedule and associated maintenance schedule to be disrupted by unforeseen events such as flight delays. Published literature in the operations research subject area of 'personnel scheduling' covers a range of computational and mathematical techniques that can be adapted to solve or optimise this type of scheduling problem. This study has explored whether there is a significant knowledge gap between state-of-the-art developments in published research in this subject area and practical application at aircraft maintenance organisations on the African continent. Furthermore, the study has sought to establish whether computational models for the optimisation of an airline's short-term layover maintenance labour resources that are based on a fixed flight schedule and thus a fixed task demand profile are sufficiently robust to the effects of flight schedule disruptions (e.g. delays) that occur routinely in real-life operations to support their practical application.

Methods: A case study method has been employed in this study. In this regard, a case airline company based in Johannesburg, South Africa (with an in-house maintenance division) has been used for data collection purposes and for the implementation and testing of an experimental labour scheduling model for the short-term layover maintenance staffing problem. This labour scheduling model has been developed by adapting modelling concepts and techniques from contemporary operations research literature to the case setting. Initially, the experimental model has been used to generate an optimised staff roster for short-term layover maintenance activities under the ideal condition of 100% on-time performance of the case airline's flight schedule. This optimised roster has then been compared to the existing staff roster and associated labour planning model that are in use at the case organisation for the given category of maintenance activity. Performance criteria such as total direct labour costs and the stability of each staff roster have been considered in this comparison. Following on from the initial computational modelling exercise, the optimised staff roster has then been subjected to sensitivity testing in a simulation environment in order to assess its robustness in scenarios where the input flight schedule and associated task demand profile for short-term layover maintenance activities is disrupted from the original plan. To ensure high levels of realism, schedule disruption profiles based on actual flight operations records in the case setting have been used in this testing process.

Results: The initial study results show that the experimental model for the short-term layover maintenance labour scheduling problem uses 33% fewer AMEs and 48% fewer rostered manhours to meet the service demands of the case airline under fixed flight schedule conditions than the equivalent labour force specified by the organisation's existing labour planning model. However, it has been noted that a significant portion of this resource saving relates to conservative demand modelling by the case organisation, particularly with regards to the quantities and standard time inputs that have been imposed for after-flight checks in the organisation's existing planning model. Adjusting for these conservative inputs, it has been shown that the experimental model provides a 22.0% reduction in rostered manhours and associated labour costs in comparison to a modified version of the case organisation's existing model, but with no reduction in the number of AMEs employed. Although not as substantial as the original finding, this more realistic outcome remains positive from the perspective of the operations manager and it has been estimated that associated savings in direct labour cost savings could amount to almost 1.3 million rand per annum. The robustness testing of the output labour roster from the experimental labour scheduling model has also yielded satisfactory results. In this regard, the output roster has been shown to require only 3.75 manhours of unplanned AME overtime in order to manage the modified demand profiles for short-term layover maintenance tasks relating to simulated flight schedule disruptions over a 20 day testing period in the case setting. This level of unplanned overtime adds only 0.41% in supplementary charges to the case organisation's labour bill at an overtime rate of 1.5 times the normal AME labour rate. Furthermore, no requirements for AME callouts and no conflicts in terms of induced flight delays due to missed maintenance tasks have been identified over the robustness testing period. These findings suggest that the impacts of unplanned flight schedule disruptions on the experimental labour planning model are largely insignificant.

Conclusions: The outcomes of the study support the assertion that a significant knowledge gap exists between state-of-the-art research in the subject area of personnel scheduling and practical application at African-based aircraft maintenance organisations. In addition, preliminary evidence has been obtained to suggest that computational models for the optimisation of short-term layover maintenance labour resources at an airline under fixed flight schedule conditions are sufficiently robust to the effects of schedule disruptions to support their practical application. However, these conclusions must be considered within the context of the case-based research methodology that has been employed. In this regard, it is recommended that further research be conducted in order to examine the transferability of research findings at the case organisation to a broader population of aircraft maintenance organisations on the African continent. Furthermore, it is acknowledged that only a limited scale of robustness testing has been implemented in this study. As a result, additional robustness testing over an expanded set of test days is recommended as an extension to the study.

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List of Abbreviations and Acronyms Used

Abbreviation or Acronym	Full Description
2-D	2-Dimensional
a/c	Aircraft
AF	After-Flight
AME	Aircraft Maintenance Engineer
AMO	Approved Maintenance Organisation
ATA	Actual Time of Arrival
ATC	Air Traffic Control
ATD	Actual Time of Departure
CP	Constraint Programming
e.g.	For Example
FLM	First Line Maintenance
IPO	Input-Process-Output
JNB	OR Tambo International Airport (International Air Transport Association Airport Code)
LAME	Licensed Aircraft Maintenance Engineer
LSM	Least Squares Method
MME	Missed Maintenance Event
MS	Microsoft
NZD	New Zealand Dollar(s)
OCC	Operations Control Centre
ORTIA	OR Tambo International Airport
PC	Personal Computer
PF	Pre-Flight
SACAA	South African Civil Aviation Authority
STA	Scheduled Time of Arrival
STD	Scheduled Time of Departure
STLM	Short-Term Layover Maintenance
SVM	Short Visit Maintenance
TC	Transit Check
US	United States
USA	United States of America
USD	United States Dollar(s)
ZAR	South African Rand(s)

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1 Introduction

1.1 Purpose of the Study

The purpose of this study is to critically assess the current processes being applied by aircraft maintenance organisations within the airline industry in Africa to schedule labour supplies to meet the short-term layover maintenance (STLM) demands of airlines. In this regard, the study has focused on identifying whether there are significant gaps between current organisational practices and the best practices identified in contemporary literature on personnel planning and scheduling. A significant focus area of this study has been to investigate whether recent advancements in computational modelling techniques relating to personnel scheduling can be applied to optimise STLM labour supplies at such organisations. This optimisation focuses on minimising associated labour costs and staffing levels while still ensuring adequate coverage in terms of the availability of sufficient manpower with appropriate skill levels to meet the prevailing demand.

Despite their intended benefits in terms of labour force optimisation, it has been noted that there is a potential limitation with the computational labour planning models that are described in recent literature dealing specifically with the STLM problem at airlines. In this regard, these models have been developed based on a fixed flight schedule input with no associated uncertainty. There is a concern regarding the robustness of these models in real-life airline applications where aircraft operating schedules may be significantly disrupted by unplanned events such as aircraft breakdowns and adverse weather that lead to flight delays, flight cancellations or the deployment of standby aircraft. As a result, this study has also sought to expand on existing research by investigating the impact of flight schedule uncertainty on STLM labour planning in detail.

1.2 Context of the Study

1.2.1 Overview of the Operational Environment Considered in this Study

This subsection provides an overview of the operating environment within which this study has been conducted, i.e. aircraft maintenance services with respect to airline operations. In this regard, the reader is given a basic description of the structuring of airline maintenance programs. This includes an explanation of what STLM activities are, how they are scheduled and how they fit within the broader hierarchical structure of planned airliner maintenance tasks. This is followed by a discussion of the legal requirements in terms of the qualification levels of technicians that are required when performing and certifying maintenance on an aircraft. These requirements play a significant role in determining the skill levels that must be allocated to work groups when building rosters for airline maintenance activities. In addition, some basic statistical information regarding the prevalence of flight delays as a form of schedule disruption in airline operations is presented. This information alerts the reader to the observation that flight delays are an everyday occurrence in the operations of airline carriers. As such, any labour scheduling methodology for operational staff at an airline that does not consider the impact of flight delays (and other schedule disruptions) is overlooking an everyday decision factor in operational processes at the affected organisation.

1.2.1.1 Classification of Airline Planned Maintenance Activities

Planned maintenance programs for the support of commercial airliners involve a progressive hierarchy of checks, inspections and tasks focusing on the various structural components and systems of the aircraft. As a typical example, aircraft maintenance organisation Lufthansa Technik differentiates the maintenance of aircraft into two main categories, namely (1) 'line maintenance' and (2) 'heavy maintenance' or 'overhaul' (Lufthansa Technik 2011). As per Lufthansa Technik, 'line maintenance' is described as short-term aircraft maintenance work that is carried out while an affected aircraft keeps to its usual operating schedule. Under this classification, a progressive system of daily checks, weekly service checks and 'A' checks is implemented in between flights or overnight, with the aircraft remaining in revenue service throughout. According to Lufthansa Technik, A-checks are carried out every 350 to 750 flying hours depending on the aircraft type. Looking beyond 'A' checks, Lufthansa Technik describes 'overhaul' events as high level aircraft checks that can take anywhere from two to six weeks to complete, thereby necessitating the removal of an affected aircraft from revenue service for the duration of the check. This organisation indicates that overhaul-level maintenance checks are carried out at intervals of between three and ten years depending on the equipment type under consideration.

Summarising from the descriptions of Hessburg (2000), Yang, Yan and Chen (2003) and Lufthansa Technik (2011), the following classification system for planned airliner maintenance activities has been established and used in this study:

- **Line maintenance activities:**
  Line maintenance activities encompass aircraft daily checks, defect rectifications and other short-term planned maintenance tasks up to 'A' check level:
  - <u>Daily checks</u> – these checks are short in duration (one to two hours maximum) and can be carried out at the aircraft gate or parking bay with minimal requirements for aircraft disassembly and special tooling or equipment. Daily checks are referred to by certain authors as 'short-term layover maintenance' checks and this is the description that has been used throughout this study. Yang *et al*. (2003) include aircraft pre-flight checks, transit checks and daily (or after-flight) checks within the scope of 'short-term layover maintenance'. A pre-flight check is carried out before the first flight of the day for a

given aircraft. A transit check is carried out in between any two flights in a continuous sequence of flights for an aircraft (if applicable). An after-flight check is carried out after an aircraft completes its planned set of flights for the operational day. By implication, short-term layover maintenance (STLM) checks are frequent in nature and are demanded in direct correlation to the published flight schedule being operated by an affected aircraft.

  - 'A' checks – these checks are more comprehensive in scope, technical complexity and disassembly requirements than short-term layover maintenance checks and are generally carried out at flying hour intervals of between 350 and 750 hours. This corresponds to time intervals of anywhere from approximately six weeks to six months depending on the frequency of flights at a given operator. 'A' checks can be completed at the aircraft parking ramp, or in an aircraft hangar environment if available, generally on an overnight basis. 'A' check task packages may include some limited requirements for the use of specialised tooling, manpower or equipment.

- **Heavy maintenance checks:**
  Heavy maintenance checks encompass aircraft 'C' checks and structural or 'D' checks. These checks are comprehensive in scope and generally include significant disassembly requirements for an affected aircraft. Heavy checks are triggered at intervals of as high as three to ten years, so are infrequent in nature. However, when triggered, they require considerable downtime on an affected aircraft, necessitating its removal from revenue service for up to six weeks. Detailed inspection requirements and specifications for the use of specialised tooling, manpower or equipment are typical for this level of maintenance.

Note:
A more detailed summary of the basic hierarchy of airliner maintenance checks is provided in Appendix A. Table A1 in this appendix summarises from the writings of Hessburg (2000) on this hierarchical structure and the associated scope of maintenance tasks.

It is evident from this subsection that STLM tasks are the lowest level of planned maintenance events on airliners with the highest frequency of execution. As the primary subject area of this study, these tasks are called out on every day-of-operations at an airline company. Furthermore, the timing, scope and quantity of STLM tasks called out relates directly to the sequences of flights that are allocated to each aircraft by an affected operator. As such, the operator's published flight schedule for the day plays a major role in determining STLM service levels. In this regard, a more intensive schedule of arriving and departing flights at a given airport location will generally produce a higher quantity of STLM events that must be attended to at that location than a less intensive flight schedule will.

1.2.1.2 Qualification Requirements of Airline Maintenance Personnel

Repair and maintenance tasks that are implemented in order to keep aircraft in a safe and reliable flying condition are carried out by tradesman called 'aircraft maintenance engineers', or AMEs for short (Karakonam 2010). In researching the training and qualification requirements for AMEs in support of this study, it has been found that there is a high degree of commonality in the standards implemented by aviation regulatory authorities across the globe. As a typical example, the Civil Aviation Authority of New Zealand (2000) classifies AMEs into two categories, namely those who are accredited as licensed aircraft maintenance engineers (LAMEs) and those who are unlicensed. This regulatory organisation indicates that both LAMEs and unlicensed AMEs are approved to inspect, repair and service aircraft. However, only a LAME can certify that an aircraft that has been subjected to maintenance is safe to operate and can sign off the necessary paperwork to release the aircraft back to operations. In this regard, unlicensed maintenance engineers must have all their work supervised and approved by a LAME.

In general, the LAME qualification is broken down into various sub-categories that depend on the particular area(s) of specialisation and possibly also the years of experience of a LAME. These sub-categories are usually dictated by national regulatory requirements. For example, the South African Civil Aviation Authority (1997) has defined a Category II license for LAMEs that incorporates the following rating sub-categories:

- Category A ratings provide for the certification of airframe maintenance tasks for aircraft or rotorcraft registered in the Republic of South Africa.

- Category C ratings provide for the certification of engine maintenance tasks for engines installed in aircraft or rotorcraft registered in the Republic of South Africa.

- Category W ratings provide for the certification of maintenance tasks on the avionic, electrical or instrument equipment, or any combination of such equipment, installed on aircraft or rotorcraft registered in the Republic of South Africa. The holder of a Category W rating is able to perform a more comprehensive scope of maintenance on electrical, avionic or instrument systems than the privileges granted to a Category A and / or C LAME.

Note:
A 'rotorcraft' is a machine such as a helicopter that uses rotor blades to generate aerodynamic lift.

The information provided in this subsection indicates that an aircraft maintenance organisation that is engaged in airline STLM activities requires appropriate numbers of AMEs on its labour force in order to perform the aircraft maintenance tasks that are demanded of it. Furthermore, in order to enable the release of each maintenance task that has been performed, this complement of AMEs must collectively hold an appropriate level of license approvals. These licence approvals must be relevant to the category of aircraft and the types or models being worked on, as well as to the scope of tasks that are being performed. AME license holding is therefore a critical decision factor in the staff rostering processes within such an organisation.

1.2.1.3 Flight Schedule Delays and Other Schedule Disruptions at Airlines

Although commercial airlines operate flights according to a published flight schedule, there are a range of occurrences that contribute to disruptions to these planned schedules and their associated resource allocations. This assertion is supported by Kohl, Larsen, Larsen, Ross and Tiourine (2004) who have stated that flight schedules at airlines often have to be revised during operations due to disruptions caused by issues such as severe weather, technical problems and crew sickness. Levin (2007) expands on this statement by highlighting that sources of disruption to flight schedules include external factors such as adverse weather and air traffic congestion that are largely beyond the control of airlines, as well as internal factors over which airlines can exercise a considerable level of control such as crew rostering errors, refuelling delays and aircraft technical faults. The research of Darlay, Kronek, Schrenk and Zaourar (2010) stipulates that schedule disruptions occur either in the form of flight delays or flight cancellations. In addition, Kohl *et al.* (2004) identify changes in aircraft registration number (or tail number) allocations that do not manifest in delays or cancellations as a form of schedule disruption.

The prevalence of flight delays as a form of disruption to airline schedules is highlighted in a number of published literature sources. Niehues, Belin, Hansson, Hauser, Mostajo and Richter (2001) have reported that 25.5% of intra-European flights in the year 2000 were subject to arrival or departure delays exceeding 15 minutes from the times scheduled. In the same document, corresponding figures from the US airline industry have been presented showing that 27.4% of flights by major US airlines were delayed in that year. These authors have suggested that a ratio of one delay for every four scheduled flights is a reasonable norm for the airline industry. This ratio is supported by Stellin (2009), who expressed concern with the sampling method that was applied within the US airline industry by which an overall on-time performance statistic of 79% was determined for the month of April 2009. In this regard, Stellin identifies a value of 75% as being a more typical on-time performance rate for the industry (i.e. 25% of flights delayed).

The Department of Infrastructure and Transport of the Australian Government (2011) has declared significantly lower levels of flight delays for the Australian domestic airline industry, applying the same 15 minute allowance as described in the preceding paragraph. This source claims long-term on-time performance averages for all domestic Australian routes from November 2003 to March

2011 of 84.5% for departures and 83.2% for arrivals. This data places flight delay levels at 15.5% for departing flights and 16.8% for arriving flights within the Australian domestic market over this measurement period.

Looking at the African continent, Tippel (2011) has reported an announcement by the Airports Company South Africa (ACSA) that it was to commence publishing on-time performance data for all South African domestic airlines in the public domain from June 2011. In this respect, ACSA data for the operating period from January to September 2011 indicated the following on-time performance statistics for all domestic scheduled airline services in the country (Airports Company South Africa 2011):

- 86.5% at OR Tambo International Airport in Johannesburg
  (i.e. 13.5% of flights subject to delays)

- 87.3% at Cape Town International Airport
  (i.e. 12.7% of flights subject to delays)

- 86.9% at King Shaka International Airport in Durban
  (i.e. 13.1% of flights subject to delays)

Note:
A delay exclusion buffer of 15 minutes from the published departure or arrival times of flights has been applied by ACSA in capturing the above performance data.

The implication of the information and discussion in this subsection is that the planned operating schedules of airlines are regularly disrupted by various classes of occurrences that result in flight delays, flight cancellations or changes in aircraft registration allocations during operations. Where an airline flight schedule is subjected to such disruptions, it is a logical inference that associated STLM events will also be subject to changes in timing, quantity or scope. If flight delays alone are considered as the driver of schedule disruptions, published statistics indicate that these events can occur as often as one in every four flights on average in the airspace of Europe and the USA. For African operations, a more realistic level for flight delays based on data relating to South African airline companies is one delay for every seven to eight flights flown on average. Despite exhibiting comparatively lower occurrence levels in relation to those measured for Europe and the USA, the averages presented for the African environment support the viewpoint that flight delays are an everyday occurrence within medium to large size airlines that operate 20 flights or more on any particular day-of-operations. As a result, recovery processes for such disruptions are likely to be a critical issue in the day-to-day operational control of these airlines.

1.2.2 Description of the Business Problem Addressed in this Study

This study has addressed the business problem faced by aircraft maintenance organisations to efficiently schedule skilled labour resources in the form of aircraft maintenance engineers to meet the short-term layover maintenance needs of one or more airline operators. There are a number of operating factors that complicate this scheduling process and present opportunities for resource optimisation. A summary of the key issues in relation to this business problem are summarised in this subsection.

The concept of short-term layover maintenance in commercial airline operations encompasses three types of aircraft checks, namely pre-flight checks, transit checks and daily (or after-flight) checks (Yang *et al.* 2003). These checks are implemented as follows for each aircraft that is deployed into service on any given day-of-operations (see Subsection 1.2.1.1):

- A pre-flight check is accomplished prior to the first flight of the day.

- A transit check is accomplished in between any two consecutive flights during the course of the day.

- An after-flight check is accomplished after the last flight of the day.

As per Yang *et al*. (2003) and Ip, Chung and Ho (2010), the planning of STLM events is frequently separated from the planning of higher level and more detailed aircraft maintenance events such as 'A' checks and 'C' checks. This separation is attributed to the unique scheduling requirements of STLM checks when compared to other categories of aircraft maintenance. In this regard, STLM checks are usually performed at the aircraft gates or parking bays at a given airport and take only one to two hours to complete on average (Yang *et al.* 2003; Ip *et al.* 2010). Furthermore, because STLM checks are performed before the departure or after the arrival of flights, when affected aircraft are positioned at the airport gates, these checks have to fit within the time constraints of the airline operating schedule (Yang *et al.* 2003). On this point, Yang *et al*. (2003) highlight that a failure to adequately meet these scheduling requirements will lead to airline punctuality being affected and extra operating costs being incurred.

It can be deduced from the preceding paragraph that demand levels for STLM activities at a given airport location will be subject to peaks and troughs in activity depending on the schedule of flight arrivals and departures at the airport that must be serviced. Yang *et al*. (2003) have observed that differences in STLM activity levels between peak and off-peak periods can be substantial and it is thus challenging for affected airlines or aircraft maintenance organisations to efficiently deploy their maintenance crews against these fluctuating demand levels. A further issue has been highlighted by Belien, Demeulemeester and Cardoen (2010) that the timing of STLM events is not necessarily fixed, even when considering a fixed airline flight schedule that operates exactly on time. In this regard, these authors point out that the main requirement for the timing of STLM events is that the maintenance must take place within the time interval between the scheduled time of arrival (STA) of an affected aircraft and its next scheduled time of departure (STD) at a given airport location. For example, in a scenario where an aircraft arrives at 11:00 at a given airport and is planned to depart again at 12:00, a 20 minute workload on that aircraft can be scheduled to commence at any time between 11:00 and 11:40 without impacting the underlying flight schedule. The implication of this observation is that improved operational efficiencies can be sought in the scheduling of STLM tasks by exploiting the timing flexibilities between the STA and the STD of each successive flight in the associated airline flight schedule.

The work of Belien *et al.* (2010) also identifies the possibility of using workload division as a source of flexibility in the deployment of STLM labour resources. As per these authors, workload division entails the use of flexible numbers of workers for any given task depending on the current occupancy levels of the on-duty workforce. An example highlighted by these authors is that an event with a workload equal to four manhours can potentially be performed by four workers each working for one hour, by two workers each working for two hours, or by two workers where one works for one hour and the other works for three hours. It is clear from this example that a huge range of possible resource allocations and thus opportunities for optimisation can be explored through the application of workload division. However, despite its significant potential in enabling workforce optimisation, some practical limitations should be considered when implementing this technique. For example, it may be advisable to prohibit maintenance tasks from being subdivided over multiple non-consecutive time periods. It may also be practical to restrict the hand-over of maintenance events between workers on a common shift or between consecutive shifts.

As per Ip *et al.* (2010), human factors issues add further complexity to the problem of maintenance crew scheduling for STLM operations. These authors highlight two key issues under this subject area. Firstly, the qualifications and license holdings of AMEs and LAMEs in a given scheduling scenario must be sufficient to enable the completion and release of the maintenance events that are called out (see Subsection 1.2.1.2). Secondly, crew rostering decisions relating to equitable time off allocations are of significant importance in ensuring the general well-being and satisfaction of maintenance personnel. These decisions encompass various issues such as the allocation of weekends off (or fixed days off on particular weekdays), time off allocations on public holidays, as well as the authorisation of annual leave days.

Based on the wide range of decision factors and variables that are at play, Ip *et al*. (2010) have concluded that the scheduling of maintenance crews for STLM activities is an extremely complex problem. Furthermore, these authors have suggested that the methods currently being applied to address this problem at airlines and their partnering aircraft maintenance organisations tend to be based too heavily on the experience of maintenance management personnel and cumbersome and labour-intensive manual processes. For these reasons, Ip *et al.* (2010) have proposed the use of mathematical modelling and computational optimisation techniques for multi-criteria decisions as a logical development area for this type of scheduling problem. In fact, a number of authors have already conducted research into the application of computational modelling to solve airline STLM labour scheduling problems, including Yang *et al.* (2003), Belien *et al.* (2010) and Ip *et al.* (2010). It is noteworthy that all three of these referenced author groups have claimed favourable results in terms of the workforce optimisation outcomes that have been achieved using their respective computational models in case testing scenarios. However, despite these successes, the work of Belien *et al.* (2010) has highlighted the issue that current computational models need to be made more robust to the uncertainties that affect the execution of real-life airline flight schedules. These authors highlight three primary sources of uncertainty in this regard, as follows:

- Uncertainty in the labour supply
  (i.e. employee illness and other sources of absenteeism)

- Uncertainty in the task demand
  (i.e. unscheduled aircraft defects and breakdowns that lead to supplementary unplanned workloads)

- Uncertainty in the timing of workloads
  (i.e. airline flight delays)

A review of the computational models of Yang *et al.* (2003), Belien *et al.* (2010) and Ip *et al.* (2010) has shown that these models all assume a fixed airline operating schedule as a modelling input. These models therefore exclude any unforeseen flight schedule disruptions that may modify the associated demand profiles for STLM tasks, both in terms of the timing and scope of workloads. This is an obvious development area for these computational models in order to improve their accuracy in replicating the uncertainties of real-life airline operations. However, the incorporation of flight schedule disruptions as an input to these models is also likely to significantly increase their complexity. The result is that the models may become far more cumbersome to solve if modified to incorporate such factors.

From the various issues detailed in this subsection, two business problems have been identified and explored in this study. These problems are summarised as follows:

- Firstly, it has been sought to determine if the business practice of scheduling personnel for airline STLM activities at African-based aircraft maintenance organisations can be notably improved through the application of state-of-the-art labour scheduling concepts extracted from contemporary operations research literature. In this regard, a particular area of focus has been to adapt computational modelling methods described in this research literature to a real-life business setting to optimise relevant performance measures such as labour efficiency and associated manpower costs.

- Secondly, the study has sought to extend the work of Belien *et al.* (2010) by investigating the extent to which an optimised labour roster for airline STLM operations, developed using contemporary computational modelling methods, is robust to the sources of uncertainty that may impact the execution of airline flight schedules. In this regard, the study has focused primarily on investigating the impact of uncertainties in the timing of STLM workloads that are brought about by airline flight delay events. In addition, task demand changes relating to other airline schedule disruptions such as flight cancellations and aircraft registration number changes during operations have also been considered.

  Note:
  For clarity, a typical example of an aircraft registration number change during operations at an airline is the deployment into service of a standby aircraft to eliminate a departure delay on an outbound flight at a given airport location. In this example, the registration change is implemented by the airline because the aircraft originally allocated to operate the outbound flight is significantly delayed on its preceding inbound flight to the affected airport. A typical outcome in such a scenario is that the standby aircraft being deployed into service will require a pre-flight check as opposed to the transit check that would have been performed on the aircraft originally allocated to the flight had it arrived on time from its preceding inbound flight. Furthermore, the delayed aircraft will typically also require either a transit check or an after-flight check upon its eventual arrival to the airport base depending on the exact nature of the operational changes that the airline has chosen to implement. Aircraft registration changes such as this may increase the overall number of STLM checks that must be performed in the support of a given flight schedule.

Referring to Subsection 1.5 of this study, it should be noted that additional workloads to investigate and rectify unplanned aircraft technical faults have not been considered under the scope of STLM services in this study. Furthermore, uncertainty in the case organisation’s labour supply through factors such as employee absenteeism has been excluded from consideration.

1.3 Problem Statement

1.3.1 Main Problem

The main problem that has been addressed in this study is the optimisation of labour scheduling processes that are employed by aircraft maintenance organisations in delivering STLM services to airline operators. In this regard, the study has focused its investigations on aircraft maintenance operations based on the African continent. Two relevant sub-problem areas have been explored with respect to this main problem. Firstly, the study has sought to benchmark existing STLM crew scheduling practices in real-life airline maintenance environments against state-of-the-art labour scheduling concepts extracted from contemporary operations research literature. In this regard, particular focus has been given to evaluating the potential adaptation of suitable computational models described in this literature to real-life STLM business settings to optimise labour scheduling outputs such as workforce efficiency and associated manpower costs. Secondly, the study has sought to ascertain, through sensitivity analysis, whether these computational crew scheduling models are sufficiently robust when applied to real-life STLM operations due to the unplanned task demand variations that affect such operations in reality. These task demand variations are the result of unforeseen disruptions to airline flight schedules that occur due to source events such as aircraft breakdowns, air traffic control delays and inclement weather.

1.3.2 Sub-Problem 1

The first sub-problem that has been addressed in this study is to benchmark existing STLM crew scheduling practices in real-life airline maintenance environments against state-of-the-art labour scheduling concepts extracted from contemporary operations research literature. In this regard, particular focus has been given to evaluating the potential adaptation of suitable computational models described in this literature to real-life STLM business settings to optimise labour scheduling outputs such as workforce efficiency and associated manpower costs.

1.3.3 Sub-Problem 2

The second sub-problem that has been addressed in this study is to ascertain, through sensitivity analysis, whether computational crew scheduling models adapted from contemporary operations research literature are sufficiently robust when applied to real-life STLM operations due to the unplanned task demand variations that affect such operations in reality. These task demand variations are the result of unforeseen disruptions to airline flight schedules that occur due to source events such as aircraft breakdowns, air traffic control delays and inclement weather.

1.4 Significance of the Study

A number of reasons have been identified why this study is significant in terms of its chosen subject area, i.e. the development of optimised personnel schedules for airline STLM operations. Some of these reasons relate to the business management advantages that the study provides. Others relate to the study's contribution to the development of existing literature on the STLM labour scheduling problem. Reasons for the study's significance are as follows:

- The study has developed data in a real-life case setting to quantify the labour scheduling benefits that can be achieved in STLM operations through the application of advanced staff scheduling concepts extracted from contemporary operations research literature.

- Expanding on the preceding point, the case data that has been generated in the study provides a measure of the gap that exists between the personnel scheduling practices detailed in contemporary literature sources and the practices being applied in reality within the STLM operations of African-based aircraft maintenance organisations.

- In addition, the study has extended existing research in its subject area by analysing the impact of flight schedule disruptions on the demand planning processes and subsequent shift scheduling activities applicable to STLM operations in the case setting.

- Closely linked to the preceding point, the study has also analysed historical data on flight delay occurrences in the case setting in order to ascertain whether probabilistic modelling of these flight delays can be applied to forecast uncertainties in the timing of upcoming STLM workloads.

- Summarising from the preceding two points, the study has provided quantitative data to ascertain whether existing computational models for STLM crew scheduling are sufficiently robust in their current form. The study has also contributed to the ongoing refinement of these models to better replicate the uncertain environment of real-life airline operations. These outcomes are of importance in facilitating the practical implementation of these models within airline operators, or their associated aircraft maintenance organisations, to improve real-life personnel scheduling processes.

- In conclusion, the outcomes of the study provide information and guidance specifically to operational personnel who are responsible for developing STLM labour schedules within airline maintenance operations. However, these outcomes may be adapted more broadly for use in any operational environment in which multiple-criteria decisions must be made in the scheduling of jobs, tasks or resources as part of ongoing operations.

1.5 Delimitations of the Study

The delimitations that have been applied in this study are as follows:

- The study addresses manpower scheduling requirements for airline short-term layover maintenance (STLM) operations only. The study does not address the scheduling of labour supplies for higher level aircraft maintenance activities such as 'A' checks and heavy maintenance checks.

- In support of the preceding delimitation, all maintenance workloads that exceed the routine requirements of the given daily check work scope that is being implemented are considered to be beyond the scope of work of the technicians that are rostered for STLM activities. As such, it is understood that all maintenance actions that are required to correct non-routine defects or technical faults that are identified during aircraft daily checks, or alternatively to respond to aircraft in-service breakdowns, shall be handed over to a higher level work team within the broader line maintenance function.

- While the study does consider the impacts on the STLM labour planning problem of flight schedule disruptions such as aircraft equipment breakdowns and weather-related delays, labour supply issues such as absenteeism and sick leave are excluded from consideration as a modelling input.

- The study assumes a full-time workforce as a modelling input. In this regard, the study does not consider the possibility of applying flexible management strategies in relation to part-time work, such as the use of part-time or temporary workers, rate-per-hour contractors or short-time shift arrangements.

- The study applies the licensing and qualification requirements for AME work authorisations that are applicable at the case organisation. In generalising the research outcomes in the case setting to other aircraft maintenance organisations on the African continent, the study does not consider the implications of differences that may exist in these requirements between the affected organisations. However, it is firmly acknowledged that differences in these requirements may exist due to variations in national regulatory requirements, or due to organisation-specific procedures.

- The study only considers STLM operations at a single airport or maintenance base. It does not consider the optimal integration of multiple sites. In this regard, the case organisation's main maintenance base at OR Tambo International Airport in Johannesburg has been used as the case setting for the study (see Subsection 3.3.1).

- In optimising personnel schedules for the STLM operations under consideration, the study does not consider the sociological and psychological impacts of different patterns of work (e.g. day shift versus night shift allocations) on the performance capabilities of affected aircraft maintenance technicians.

1.6 Definition of Terms

The following definitions are applicable in this study:

- *Aircraft Maintenance Engineer (AME)*
  A tradesperson qualified to undertake the maintenance, repair, overhaul, modification, assembly and / or testing of aircraft, aircraft systems, aircraft components, aircraft engines and / or associated equipment (Fair Work Australia 1999).

- *Aircraft Registration Number (or Aircraft Tail Number)*
  A unique alphanumerical identification code similar to a motor car registration that is issued to each aircraft within a particular country (Federal Aviation Administration 2009). This code includes a prefix that designates the country where the affected aircraft is registered, while the remainder of the code is the aircraft's individual registration code within the country of registry. For example, all type certified aircraft in South Africa carry the registration prefix 'ZS' and an individual aircraft may be registered using any available code from 'ZS-AAA' to 'ZS-ZZZ'.

- *Avionics*
  Electronic equipment such as instrumentation, flight guidance computers and cockpit display screens that are designed for use in aircraft and other aerospace vehicles (Merriam-Webster Dictionary 2011).

- *Cancellation (or Flight Cancellation)*
  Within the airline industry, an event where a carrier removes a scheduled flight from service within seven days of its planned departure date and time (Australian Government 2011). This classification of event is considered to be a flight schedule disruption in the context of this study.

- *Delay (or Flight Delay)*
  Within the airline industry, an event in which either the departure time or the arrival time of a flight fails to meet the specifications for an 'on-time arrival / departure'. This classification of event is considered to be a flight schedule disruption in the context of this study. For further information, refer to the definition of an 'on-time arrival / departure' that is also provided in this subsection.

- *Hard Constraint*
  With reference to the computational modelling that has been applied in this study, a hard constraint is a constraint that cannot be violated without compromising the integrity of the affected model.

- *Heavy Maintenance*
  High level maintenance activities in which the associated aircraft checks, or packages thereof, require considerable downtime on an affected aircraft, necessitating its removal from revenue service (Hessburg 2000; Lufthansa Technik 2011). Detailed inspection requirements and specifications for the use of specialised tooling, manpower or equipment are typical of this category of maintenance work.

- *Heuristics*
  A heuristic is a generic rule or method, such as 'Think of a Similar Problem', 'Draw a Diagram', 'Make a Graph or Table', 'Guess and Check' or 'Trial and Error', that can be used as an aid in solving different types of problems, although there is no guarantee that it will be successful (Wong 2008).

- *Licensed Aircraft Maintenance Engineer (LAME)*
  An AME that is approved to certify and release the maintenance, repair, overhaul, modification, assembly and / or testing of aircraft, aircraft systems, aircraft components, aircraft engines and / or associated equipment within the scope of his / her given license categories (Fair Work Australia 1999; Civil Aviation Authority of New Zealand 2000).

- *Line Maintenance*
  Maintenance activities that are carried out on an aircraft during which the aircraft keeps to its usual operating schedule (Lufthansa Technik 2011). Examples of line maintenance activities are daily checks, weekly service checks and 'A' checks that are generally carried out overnight or between flights on operational aircraft. On completion of such a check, an affected aircraft can be deployed immediately back into scheduled service.

- *Metaheuristics*

  A metaheuristic is a high-level iterative generation process that guides and modifies subordinate heuristics by intelligently combining different search concepts and using adaptive learning strategies to structure memory information for the purpose of finding high quality (i.e. near-optimal) solutions in an efficient fashion (Osman 2004).

- *On-Time Arrival / Departure*
  - According to standard practice in the airline industry, a flight arrival is measured as being 'on-time' if the affected aircraft docks at its allocated arrival gate at the destination airport within 15 minutes of the scheduled arrival time as shown in the associated carriers' flight schedule (Australian Government 2011). Note that neither diverted nor cancelled flights count as on-time arrivals as per this definition.
  - Similarly, the airline industry measures a flight departure as being 'on-time' if the affected aircraft vacates its allocated departure gate at the origin airport within 15 minutes of the scheduled departure time as shown in the associated carriers' flight schedule (Australian Government 2011).

- *Personnel Scheduling*

  Personnel scheduling, or rostering, is the process by which an organisation generates work or shift timetables for its staff in order to cover a planned operating timetable or satisfy the demand for its goods or services (Caprara, Fischetti, Toth, Vigo and Guida 1997; Ernst, Jiang, Krishnamoorthy and Sier 2004). In this study, the terms 'personnel scheduling', 'personnel rostering' or other equivalent terms such as 'labour scheduling' may be used interchangeably with the same meaning.

- *Short-Term Layover Maintenance (STLM)*

  Within the airline industry, short-term layover maintenance activities encompass the routine aircraft checks that occur on a daily basis and which can be carried out at the aircraft gate or parking bay on an airport, generally in under two hours, with minimal needs for special tooling or equipment (Yang *et al*. 2003). Such routine checks include pre-flight checks prior to the first flight of the day, transit checks between flights and after-flight checks after the final flight of the day.

- *Soft Constraint*

  With reference to the computational modelling that has been applied in this study, a soft constraint is a constraint that should not be violated wherever possible, but which does not compromise the integrity of the affected model if violated.

1.7 Assumptions

The following assumptions have been applied from the outset with regards to the study:

- It is assumed that Category W LAMEs (i.e. electrical or avionic system specialists) are not required for the performance or certification of any aspect of the daily checks on any aircraft type. While these LAMEs are needed to certify maintenance and troubleshooting tasks on aircraft that require the use of external avionic test equipment or where electrical wiring and components must be disturbed, these types of tasks are beyond the scope of the routine checks that are implemented during normal aircraft line operations. As such, only Category A and C LAMEs are needed to certify daily check maintenance tasks.

- Daily checks typically include tasks relating to both the airframe and engines of an affected aircraft. As such, a LAME that is restricted to only Category A or Category C work will not be able to fully certify the completion of such a check on an aircraft for which he / she is type-rated without assistance from a fellow LAME who is qualified in the outstanding category and appropriately type-rated. All LAMEs deployed by the case organisation to its STLM function are thus assumed to be qualified as both Category A and Category C license holders. Read together with the assumption relating to Category W LAMEs, this assumption ensures that each individual LAME meets all the functional requirements to fully certify any daily check on the aircraft and associated engine types for which he / she is rated. This in turn means that only one LAME is required to attend to each daily check that is called out.

  Note:
  A failure of either or both of the preceding assumptions will have a detrimental effect on the study's results as more than one LAME may then be required to attend to each daily check event and labour resource levels are likely to be affected negatively. The validity of these assumptions has been specifically checked in the case setting through formal interviews (see Appendices D to F). These interviews have verified that dual licensing in the A and C Categories is a typical practice amongst AMEs in the airline maintenance environment.

- Both AMEs and LAMEs can <u>perform</u> daily check work on any aircraft type provided that a type-rated LAME <u>inspects and releases</u> this work. It is further assumed that a LAME can <u>perform and release</u> daily check work on an aircraft for which he / she is type-rated without the need for this work to be inspected by another type-rated LAME. A requirement for an additional inspection in such a case will mean that at least two LAMEs are required to attend to each daily check event. This, in turn, may impact labour resource levels negatively and to the detriment of the study's results.

- It is assumed that workloads for aircraft daily checks in the case setting are consistently completed within the estimated standard time in manhours (or manminutes) for each event type, irrespective of the time of day at which the work is carried out, or the experience and motivation levels of the crew member(s) performing the check. A failure for maintenance technicians to adhere to the standard time requirements for daily check workloads in reality will reduce the reliability of the study's results.

- Physical proximity factors at the case organisation's base of operations are considered to be minor for all successive maintenance events. In this respect, the time that is taken for maintenance personnel to transit between different working locations for successive jobs is assumed to be limited to not more than five minutes in all cases. Physical proximity factors that prevent maintenance personnel from meeting this transit time assumption in reality will reduce the reliability of the study's result.

- Based on an observation made by Belien *et al.* (2010), it is assumed for the purposes of this study that the maintenance division of the case organisation (refer to Subsection 3.3.1) operates as if it is a completely independent contractor to the parent airline. In this regard, it is understood that this maintenance division will not attempt to modify demand profiles for STLM tasks by influencing or adapting the airline's flight scheduling decisions.

2 Literature Review

2.1 Overview and Key Themes

This section contains a literature review on the key themes of relevance to the study and which lead into the research questions that have been posed.

The first theme reviewed is that of the optimal scheduling of labour resources as a component of operations management. This includes a background investigation into the general characteristics and classes of labour schedules that have been identified in the diverse operating environments of business entities and other relevant organisations. In addition, the methodologies and algorithmic modelling techniques that have been applied in the optimisation of organisational labour schedules are reviewed, as well as the software platforms or other tools used for calculation and iteration purposes. The literature review also considers published research relating to the application of advanced labour scheduling techniques within the airline maintenance services industry and, more specifically, for the provision of short-term layover maintenance services.

The second theme reviewed is that of airline schedule disruptions and the associated impacts on flight operations, as well as ground handling and maintenance services. Airline recovery processes and resource management techniques in response to unplanned schedule disruptions are covered under this theme. An examination of existing research into the statistical profiling of schedule disruption events such as flight delays is also included.

This chapter concludes with a summary of the significant observations and findings relating to the literature reviewed.

2.2 Optimisation of Labour Schedules as an Operations Management Problem

2.2.1 General Description and Characteristics of the Labour Scheduling Process

The topic of labour scheduling is addressed in a wide range of literature sources in the field of operations management. In this regard, labour scheduling is frequently referred to using equivalent terminology such as ‘crew rostering’ or ‘workforce scheduling’. Ernst *et al.* (2004) describe personnel scheduling (or rostering) as the process by which an organisation constructs work timetables for its staff so that it can satisfy the demand for its goods or services. Musliu, Gartner and Slany (2002) describe workforce scheduling as the means of assigning employees to shifts or days-off for a given period of time. Caprara *et al.* (1997) refer to crew management as a process by which the work schedules of crews are built as needed to cover a planned timetable.

All three of these descriptions refer to the supply management aspect of the labour scheduling process whereby available personnel are assigned to timetables that specify sequences of on-duty shifts as well as off-duty rest days for each allocated job post. However, the description referenced from Ernst *et al.* (2004) is preferred as it also identifies the important issue that labour supplies should be appropriately quantified in the scheduling process based on an assessment of the prevailing demand levels for the goods or services under consideration.

The main purpose of labour scheduling as per Ernst *et al.* (2004) is to develop good or optimal solutions in modelling environments that present vast numbers of feasible solutions in order to achieve one or more of the following: to minimise or reduce labour costs, to meet employee preferences, to distribute shifts equitably amongst employees and to satisfy workplace constraints for the given situation. Alfares (1999) lists a similar set of objectives in a study relating to staffing in a maintenance environment, namely minimum cost, maximum availability, maximum reliability, or a combination of these measures.

It can be inferred from the preceding paragraphs that the generic labour scheduling process can be separated into at least two distinct components or modules. Firstly, required staffing levels are determined based on the demand for the goods or services in question. Thereafter, the available staff members are assigned to timetables that specify their allocated duty shifts to meet these demand levels. In support of this observation, there are various practical examples of modular or phased approaches to labour resource scheduling problems in published literature sources:

- Kohl and Karisch (2004) have observed that the crew planning problem at airlines is usually divided into two distinct phases. In this regard, these authors have identified an initial crew pairing phase whereby anonymous pairings are formed out of the scheduled flight legs such that the crew needs on each flight are covered. This is followed by a crew rostering or assignment phase in which these pairings are sequenced to rosters and assigned to individual crew members, together with other work activities that may be required such as ground or office duties, reserve (i.e. standby) duties and off-duty blocks. These findings are similar to those of Tam (2004), whose research work relating to aircrew scheduling at airlines has identified two distinct sub-problems, namely the tour-of-duty planning problem and the rostering problem respectively.

- Aickelin, Burke and Li (2007) indicate that the problem of rostering nurses for the wards at a major UK hospital can be decomposed into three independent stages. As per these authors, the first stage uses a knapsack model to check if there are enough nurses to meet the demand for services. If not, additional nurses are allocated to the affected ward, so that the second stage will always permit a feasible solution. The second stage is deemed to be the most difficult stage by these authors and is concerned with determining the actual allocations of day shifts or night shifts to be worked by each nurse. The third stage then uses a network flow model to assign the nurses on day shift allocations to either early day shifts or late day shifts.

- With regards to the scheduling of personnel for the short-term layover maintenance of airliners, Yang *et al*. (2003) prescribe a three-step process. In the first step described by these authors, the maintenance department must estimate the STLM manpower demand in manhours based on the available ground time slots, the various aircraft types being serviced and the tasks that are required to be carried out. A manpower supply plan must then be generated in the second step according to the manpower demand profile obtained from step 1. In the third step, maintenance personnel must be assigned to meet the supply plan in a way that satisfies applicable certification requirements and any other relevant regulatory requirements, as well as employee vacation schedules.

In a generic examination of the personnel scheduling problem, Ernst *et al*. (2004) have identified up to six distinct modules that make up the rostering process, starting with the determination of staffing requirements and ending with the specification of the work to be performed, over a given time period, by each individual in an affected workforce. These authors describe the six modules as ‘demand modelling’, ‘days off scheduling’, ‘shift scheduling’, ‘line of work construction’, ‘task assignment’ and ‘staff assignment’ respectively. A description of each of these modules is given in Table B1 in Appendix B. Ernst *et al*. (2004) do acknowledge that the development of a particular roster in a given industry or organisational application may require only some of the modules to be considered. Furthermore, these authors specify that several of the listed modules may be combined into one procedure in practical modelling applications.

Ip *et al.* (2010) claim that the separation of the labour scheduling process into a number of component phases offers an advantage in that it allows for different mathematical or computational techniques to be applied to each of the phases as required to cater for and optimise the individual problem characteristics of each. This thinking is supported by Ernst *et al.* (2004) who have stated that it is usually not computationally practical to deal with all the modules required to generate a labour roster simultaneously. These authors further indicate that the decomposition of the problem into several separate modules makes it more manageable to deal with and often makes sense in terms of an organisation’s business practices. In this regard, the authors highlight the example that task assignment in a given organisational setting could be carried out at any time before a given shift starts without causing significant disruption to the staff provided that the predetermined shift assignments remain fixed. So, if applicable, the authors indicate that it may be more sensible to generate shift assignments ahead of time, but to delay any task assignments until one or two days before the actual day-of-operations when the set of jobs to be performed is better known.

The work of De Causmaecker, Demeester, Vanden Berghe and Verbeke (2004) also discusses the usefulness of a modular approach to personnel scheduling based on the observation that every company has its own needs and desires concerning staffing. These authors indicate that the diversity of different staffing scenarios in combination with the need to be generic in terms of modelling techniques and best practices is most conveniently met by a framework of independent components. This thinking links back directly to the writings of Ernst *et al.* (2004) in that some or all of the components of their generic modular framework may require consideration depending on the particular application area in which a roster is being built.

Many literature sources discuss the issue that personnel scheduling problems are challenging from a modelling and optimisation perspective. For instance, Yang *et al.* (2003) indicate that the problems of manpower planning and crew assignment are large and complex in terms of the number of variables and constraints that must be considered. These authors indicate that the numbers of such modelling factors can run into tens or even hundreds of thousands for a given application, making scheduling problems difficult and time-consuming to solve as integer linear programs. Yang *et al.* (2003) thus advocate the use of sophisticated algorithms to efficiently solve such problems. These assertions are congruent with the finding of Musliu *et al.* (2002) that it is almost impossible to generate a personnel schedule in a short time without the help of a computer, even for simple instances of a given problem type. This finding is based on the observation that workforce schedules are complex problems that require a relatively high number of constraints to be satisfied and possibly also soft constraints to be optimised. Musliu *et al.* (2002) also discuss the issue that prohibitively large search spaces and conflicting constraints are usually encountered in the development of workforce schedules. For these reasons, these authors stress that the generation of good feasible schedules in a reasonable amount of time is generally more relevant than trying to find an optimal schedule, unless this is absolutely required. The research of Ernst *et al.* (2004) makes further reference to the difficulty of finding even just good solutions to personnel scheduling problems due to their highly constrained and complex nature. These authors indicate that it is even more difficult to determine an optimal solution that minimises costs, meets employee preferences, distributes shifts equitably amongst employees and satisfies all the workplace constraints in effect for a given organisational setting.

Looking more deeply at the complexity of labour scheduling problems, Ernst *et al.* (2004) indicate that the level of complexity of a given scheduling problem is influenced by the degree to which days off scheduling, line of work construction and task assignment are integrated. These authors point out that an appropriate strategy for the decomposition of a given scheduling problem into its constituent modules can be applied to reduce modelling complexity. However, these authors also point out that integration of the modules required to generate a roster, whilst not usually practical from the perspective of computational complexity, is desirable in terms of creating the best overall rosters. On this point, certain literature sources contain evidence of attempts to integrate multiple modules of the labour scheduling process in a single computational model. A good example of this is the study of Belien *et al.* (2010) that has produced results indicating that an integrated approach to staffing (i.e. determining the workforce size needed) and scheduling (i.e. producing duty rosters for the available workforce) is possible from a computational point of view, albeit with greater modelling complexity than a segregated set of successive modelling steps.

2.2.2 Classification and Properties of Labour Scheduling Problems by Application Area

De Causmaecker *et al.* (2004) have presented a framework that classifies companies according to the nature of their personnel scheduling problems, which in turn gives rise to different modelling approaches. This framework includes four distinct classification categories that the authors have named as follows: permanence centred planning, fluctuation centred planning, mobility centred planning and project centred planning. Each of these categories corresponds to a group of organisations with similar labour planning characteristics. For example, De Causmaecker *et al.* (2004) identify fluctuation centred planning as the labour scheduling classification that is applicable to organisations such as call centres and fast food restaurants whose labour planning is based on fluctuating and indefinite demand levels. Ernst *et al.* (2004) have also developed a classification of organisational application areas relating to personnel scheduling. In this regard, these authors have proposed a set of ten basic organisation types or industry sectors that each exhibit distinct labour scheduling characteristics. An example of an industry sector that is identified by Ernst *et al.* (2004) under this classification is the hospitality and tourism sector. In this regard, these authors identify the following generic characteristics relating to labour scheduling at hotels:

- Hotels normally employ staff members with a variety of different skills such as catering, housekeeping, reception, reservations and maintenance.

- Hotel staff members in certain functions need to be rostered on a continual basis, i.e. 24 hours a day and 7 days a week.

- Demand for services at hotels is not generally known with certainty in advance of services being requested or reserved and management often relies on a combination of intuition, software systems and local knowledge in forecasting demand.

- Some hotel staff may be multi-skilled and others will have training needs written into applicable workplace agreements.

Table B2 in Appendix B lists the ten distinct organisational application areas for labour scheduling problems as proposed by Ernst *et al.* (2004). This table also includes a proposed cross-reference to the classification system of De Causmaecker *et al.* (2004) along with supporting notes. For the problem of labour scheduling for the short-term layover maintenance needs of an airline at a given airport base, it is inferred from Subsection 1.2.1 that STLM tasks are generally called out on every day-of-operations at such a base and the timing and quantity of events called out is linked directly to the published flight schedule. Looking at the contents of Table B2, this problem corresponds to the application area of venue management, albeit within a broader transportation system that exhibits mobility centred demand planning characteristics.

2.2.3 Techniques, Models and Algorithms for the Solution or Optimisation of Labour Scheduling Problems

It has already been highlighted in Subsection 2.2.1 that most labour scheduling problems are complex in nature and that computational methods are generally required to find good or optimal solutions to these problems in an efficient manner. On this issue, Ernst *et al.* (2004) indicate that the development of computational models and algorithms has already been covered extensively in literature pertaining to application areas such as crew scheduling and rostering in transportation systems, as well as nurse scheduling in health care systems. For illustrative purposes, three examples of relevant literature sources that investigate the application or development of modelling approaches and algorithms for labour scheduling problems are as follows:

- Beasley and Cao (1996) have presented a generic crew scheduling model that formulates the scheduling problem as a zero-one integer linear program with associated constraints. This model can then be optimised through the application of numerical methods such as langrangean relaxation, subgradient optimisation and a tree search procedure.

- Tam (2004) has also applied a zero-one integer linear programming method in addressing a tour-of-duty planning problem in relation to airline aircrew scheduling. In this instance, the problem is solved through the application of a ‘branch and price’ algorithm that uses constraint branching.

- Aickelin, Burke and Li (2007) have proposed a methodology for solving rule-based nurse rostering problems that is based on contemporary developments in the fields of artificial intelligence and heuristics at the time of their study. In this methodology, use is made of an ‘estimation of distribution’ algorithm in which an intelligent search feature improves the individual solutions produced in each progressive algorithmic cycle.

In their generic analysis of labour scheduling problems, Ernst *et al.* (2004) have segregated the various methods and techniques that they have identified in related literature sources for solving such problems into five principal categories. The five categories presented by these authors are: demand modelling, artificial intelligence approaches, constraint programming, metaheuristics and mathematical programming approaches. A detailed description of each of these categories is presented in Table B3 in Appendix B.

It has been noted while reviewing case-specific modelling studies in the labour scheduling field that a number of researchers have applied linear programming methods to solve personnel planning problems. This observation is supported by the writings of Glover and McMillan (1986) who identified that most efforts to automate scheduling over the 12 years preceding their study had relied chiefly on one or another variant of linear programming. Much more recently, Brucker, Qu and Burke (2011) have also indicated that personnel scheduling problems can generally be formulated as integer linear programs. In addition, Ernst *et al.* (2004) make reference to the frequent application of linear programming to solve labour planning problems. These authors note that the related literature is heavily skewed towards mathematical programming and metaheuristic approaches for rostering problems as opposed to CP and other techniques arising out of artificial intelligence research. Where mathematical programming approaches are applied, Ernst *et al.* (2004) assert that scheduling and rostering problems are often formulated as linear programs or linear integer programs.

An important drawback that is discussed in a number of literature sources is that the use of linear programming to address labour scheduling problems can result in large model formulations that are difficult and time-consuming to solve. As per Butchers, Day, Goldie, Miller, Meyer, Ryan *et al.* (2001), most early attempts to optimise linear programming formulations in airline crew scheduling problems failed because of inadequate solution methods and a lack of computing power. A similar issue is noted in the study of Glover and McMillan (1986) relating to the general employee scheduling problem. These authors make mention of the fact that, at the time of their study, solving a scheduling problem with even just a few thousand integer variables to optimality was difficult in terms of the computer equipment and associated processing times needed to generate optimal solutions. Butchers *et al.* (2001) do indicate that, since the mid-1980s, improvements in optimisation techniques and increases in computing power have resulted in the development of successful optimisation-based solution methods for aircrew scheduling problems. However, even with the availability of far greater computer processing power in the early 2000s, Ernst *et al.* (2004) still claim that large integer linear programming models with millions or even billions of variables are challenging if not impossible to solve efficiently to optimality. These authors mention in this regard that the availability of increasingly greater computing power has been followed closely by exponential growth in the number of variables being considered in linear programming problems.

To deal with very large linear programming formulations, Ernst *et al.* (2004) have discussed two potential solution methods that may be implemented by researchers or practitioners. The first of the methods discussed by these authors is to limit the number of feasible solution columns that are generated and to thus settle on a reasonably-sized problem formulation that is adequately representative of the comprehensive set of feasible solution columns. This smaller problem formulation can then be searched for the best available solution in terms of appropriate performance measures. In this regard, Ernst et al. (2004) indicate that the solution columns can be generated using techniques such as random number generation, the application of intuitive criteria or by iterative means. The second method discussed by these authors is to partially generate all possible solution columns using column generation approaches.

An additional factor that should be considered with regards to the computational optimisation of labour schedules is the programming skills that are needed to develop computational models that adequately encompass real-world problems (Kohl and Karisch 2004). On this issue, Kohl and Karisch (2004) have asserted that the transformation of a complex rule set and objective function relating to a real-world scheduling problem into resource variables is non-trivial and can only be done by experts. These authors have further stated that they are not aware of the existence of a rule language and compiler for this purpose.

Despite the multitude of research papers that have been published dealing with the computational modelling of personnel scheduling problems, Ernst *et al.* (2004) point out that there are many application areas where manual rostering practices persist. These authors assert that this is partly due to a perception that existing rostering software is not sufficiently flexible to cater for the specific practices that are applied at individual workplaces. In this regard, these authors indicate that suitable models and algorithms often require significant modifications in order to be transferred to a different application area, or alternatively to accommodate changes within an organisation. Ernst *et al.* (2004) thus advocate the formulation of new models that provide greater flexibility to accommodate individual workplace practices. These authors also propose that efforts be made to integrate existing rostering algorithms and software with industry-standard Enterprise Resource Planning and Human Resources systems in order to expand accessibility to a larger number of users. These observations and assertions are supported by the work of De Causmaecker *et al.* (2004) who found that personnel scheduling remained a manual process in 11 out of 11 different companies that were investigated in their study. Although some evidence was found of the use of software tools in support of staff scheduling activities (e.g. Microsoft Excel in a hospital staff planning application), these authors did not find any evidence to suggest that these software tools supported automated planning processes. Instead, it was found that the software tools were employed more simply as a means by which to present rosters to affected staff members, while the underlying staff scheduling processes remained manual in nature.

2.2.4 Computational Solver Platforms Applicable to Labour Scheduling Problems

A number of software programs have been developed that can be used to implement the methods described in Table B3 in Appendix B for optimising or solving personnel scheduling problems. These programs include both commercial and open source offerings. As was discussed by Glover and McMillan (1986) in their study during the 1980s, it is noteworthy that such programs can generally be implemented successfully on microcomputers. This is an important issue because microcomputer devices such as desktop and laptop personal computers are highly accessible to managers and supervisors in most modern workplaces. Examples of such software programs and their areas of application are as follows:

- A highly accessible software platform for performing computational solving is the Microsoft Excel Solver that has been provided with every copy of the Microsoft Excel program and the Microsoft Office program package shipped to market since the early 1990s (Fylstra, Lasdon, Watson and Waren 1998). These authors claim that this solver product has been successfully applied by numerous spreadsheet users with little or no formal training to solve problems up to the scope of medium-sized industrial linear programs. Excel Solver was the platform used by Ip *et al.* (2010) for optimisation purposes in their study on the airline STLM personnel scheduling problem. In this regard, Excel Solver was used to optimally solve a mixed integer linear program that assigns tasks to maintenance groups as per a given flight schedule and constraint set relating to the certification levels of the rostered technicians.

- Talbi (2009) has highlighted a range of software frameworks, e.g. MOEA-Matlab, TEA and PISA, that have been developed specifically for the implementation of multiple-objective metaheuristics approaches. This author makes mention of the fact that these frameworks are all open source offerings with the exception of MOEA, although this is based on the popular Matlab environment.

- In addition to its capabilities as highlighted by Talbi (2009) in implementing metaheuristics approaches, MathWorks (2011) states that the Matlab environment is also tailored with built-in toolboxes and capabilities for building and solving linear programming models. In this regard, Matlab can be used to construct both binary integer (i.e. zero-one) and mixed integer linear programs. Furthermore, MathWorks indicates that the Matlab program can be applied to implement artificial intelligence approaches such as the structuring of computational neural networks.

- The CPLEX package developed by IBM is another example of commercially available software that can be applied to solve personnel scheduling problems. IBM indicates that its

CPLEX Optimisation Studio can be employed to speed the development and deployment of optimisation models in areas such as mixed integer linear programming and constraint programming (IBM 2011). Yang *et al.* (2003) have made use of the CPLEX package in developing a mixed integer model for optimising airline STLM manpower planning through the use of flexible labour strategies. The CPLEX package has also been used by Belien *et al.* (2010) to solve a mixed integer linear programming model for airline STLM labour planning that combines staffing and rostering decisions in a single integrated model.

- Linear programming problems do not necessarily require proprietary tools to solve. In this respect, the GNU Linear Programming Kit is an example of a powerful, proven and freely accessible open source software tool that applies well-known operations research algorithms (e.g. 'branch and bound') to solve numerical problems with multiple constraints (Ceron 2006).

2.2.5 Organisational Benefits of Optimised Labour Scheduling Processes

Warner (1976) has proposed a concise checklist that can be used to compare staff scheduling approaches or formulations in terms of the benefits achieved. Although formulated for use in health care applications, this checklist can be generalised to most personnel scheduling problems. The factors that are covered by this checklist are as follows:

- *Coverage*: Are the tasks adequately covered by the schedule provided? Otherwise, the organisation must call out additional personnel.

- *Quality*: How good are the working conditions of the staff based on union rules, organisation rules and individual preferences?

- *Stability*: Are individual schedules fairly homogeneous? More homogeneous schedules enable staff members to more easily organise their social and family lives.

- *Flexibility*: How elegantly does the approach deal with changes from one scheduling horizon to the next (e.g. personnel turnover, changes of preference, etc.)?

- *Fairness*: Are the tasks equally shared among the staff while taking into account varying status levels such as seniority?

- *Cost*: What levels of resources (human, time, computing power) are required to build a given personnel schedule?

Warner's checklist is reasonably congruent with the observations made by Ernst *et al.* (2004) as have already been highlighted in Subsection 2.2.1, i.e. that the primary objectives of applying sophisticated personnel scheduling techniques are to ensure adequate coverage of the task demand, to minimise associated costs and to maximise employee satisfaction. Another potential benefit of partly or fully automated computational approaches to staff scheduling problems is highlighted in the work of Kohl and Karisch (2004). These authors suggest that there is a major cost saving potential where automated labour scheduling models can be applied in a timely fashion to adapt to environmental changes. Using the airline industry as an example, these authors claim that a system or model that is capable of doing simulations easily and efficiently to allow for ready adaptation to new rules, regulations and operating factors adds significant value to an affected organisation. At an airline, such changes could include regular flight schedule changes and the evolution of flight crew union agreements.

Some quantitative measures of the benefits that have been achieved through the implementation of advanced computational modelling processes for staff scheduling are specified in published literature on the topic. Two examples of quantified benefits in terms of cost savings are as follows:

- As per Butchers *et al.* (2001), between 1986 and 1999 staff and consultants from Air New Zealand worked in collaboration with academics from the University of Auckland to develop computer-based solutions to labour scheduling problems at the airline. According to these authors, this collaboration facilitated the development of eight application-specific and optimisation-based computer systems that have been employed to solve all aspects of the tours-of-duty planning and rostering processes for national and international operations at Air New Zealand. It is claimed that these computer systems have saved the airline 15,655,000 NZD per year whilst providing crew rosters that better respect the preferences of individual crew members.

- Alfares (1999) reports that a study of aircraft maintenance worker schedules was carried out during the summer of 1997 at the aviation department of Saudi Aramco in Dhahran, Saudi Arabia. As per this author, Saudi Aramco is the largest oil company in the world and its aviation department transports company workers and equipment by air to remote areas such as oil fields and exploration sites. At the time of the study, the aviation department at Saudi Aramco had requested assistance in reviewing the existing work schedules and manpower distribution of its aircraft maintenance personnel in order to reduce overtime and to better cover the maintenance demands associated with a seven-days-a-week flying schedule. By using an integer programming formulation, Alfares has claimed that a revised labour schedule was formulated for these maintenance workers that completely eliminated the need for weekend overtime to be worked and yielded an estimated cost saving of

98,000 USD per year. This author also highlights that no increase in worker numbers was required as a result of this proposed new personnel schedule.

2.2.6 Examples of the Application of Computational Methods to the Airline STLM Labour Scheduling Problem

As discussed in Subsection 1.2.2 of this study, a number of research papers have been published wherein computational models that are specific to the problem of scheduling personnel for STLM activities at airlines are described. Noteworthy examples of such research works are:

- Yang *et al.* (2003) have presented a model that includes various flexible strategies to enable an airline to effectively manage its maintenance manpower supply for STLM tasks. These authors have formulated this model as a mixed integer program that is solved using the IBM CPLEX commercial software package. In support of their study, Yang *et al.* (2003) claim that a variety of flexible labour management strategies have been widely applied in other industries. However, at the time of this particular study, these authors assert that little research had focused on the application of flexible management strategies as a means for optimising airline crew scheduling problems. In order to evaluate the model's performance, Yang *et al.* (2003) have tested its implementation using operating data from an airline based in Taiwan. The test results that were obtained by these authors for this experimental case show that such flexible strategies can deliver favourable efficiencies in terms of output factors such as the total manhours supplied to meet the prevailing task demand and the associated labour cost. It is noteworthy that the issue of maintenance certifications has been addressed in this model through a simplifying assumption in which the workforce is composed of squads, each of which holds a common set of maintenance certificates.

- The research of Belien *et al.* (2010) presents a methodology for constructing the workforce schedules of an aircraft maintenance company where the staffing and scheduling decisions are integrated in a single problem formulation. In this regard, these authors have focused on the line maintenance operations at a case company that are represented by regular short inspections of aircraft between their arrival and next departure at a specific airport. In essence, this scenario is a short-term layover maintenance planning problem. The case company that has been employed in this study is a major airline maintenance company that is active at Brussels Airport in Belgium. At the time of the study, this company maintained about 300 flights weekly. Belien *et al.* (2010) have formulated the optimisation problem using a mixed integer linear programming approach. This linear program is then solved heuristically using a 'branch and bound' enumeration framework where each node of the tree represents a combination of work teams and team sizes. A detailed computational experiment has been performed by these authors in order to demonstrate the algorithmic performance of their integer programming model. In this regard, use has been made of the IBM CPLEX software package to perform the necessary calculations. The computational results that have been produced by these authors indicate that it is possible to achieve labour occupancy levels of as high as 85% for realistic problem instances using this approach. In similar fashion to Yang *et al.* (2003), the model of Belien *et al.* (2010) deals with the issue of maintenance certifications by applying the simplifying assumption that each team within the workforce is composed in such a way that all important skills are present. On this point, Belien *et al.* (2010) have noted that the extension of their model to cater for variations in skills between work teams is an area for future development.

- As per Ip *et al.* (2010), the reliability and safety of aircraft in flight is extremely necessary and this depends to a significant degree on the implementation of a suitable maintenance system at each airline operator. On this point, these authors hold the view that efficient labour scheduling is an essential function in enabling the effective implementation of such a system. As such, Ip *et al.* (2010) have presented a research paper that describes an integer programming model by which to determine optimal solutions to aircraft maintenance planning and workforce scheduling problems. This model has been designed for use at airline operators or their associated maintenance service providers. The model applies a sequential 3-stage methodology for labour scheduling, encompassing initial maintenance demand scheduling, maintenance pairing and maintenance group assignment respectively. Ip *et al.* (2010) have developed their integer programming model in the Microsoft Excel environment, using the Microsoft Excel Solver function to find the optimal solution to each given rostering scenario. In addition, Microsoft Excel VBA has been used in the development of the scheduling model in order to reduce the manual process and to provide a user-friendly interface. These authors have tested the application of their model in a case setting whereby sets of workforce task schedules have been developed for a maintenance operation that performs airline STLM activities. In this regard, an airline maintenance services company in China has been used as the case organisation. Using their model in this experimental setting, Ip *et al.* (2010) have succeeded in finding optimal solutions to various test scenarios that have been developed. The computation times for generating these solutions have been deemed to be acceptable and the solutions have been shown to balance the workloads of the affected maintenance groups whilst fulfilling all of the modelling constraints that have been established. The integer programming formulation has also been successful in combining the crew scheduling and task assignment stages in the roster development process, which the authors claim as being a major contribution to the body of literature on aircraft maintenance crew scheduling. Furthermore, the authors have highlighted that the results presented are easy and clear for practitioners to read and understand. It is of additional note that the model of Ip *et al.* (2010) is an extension of the work of Yang *et al.* (2003) and Belien *et al.* (2010) in that the licence holding of each individual maintenance group within the affected workforce has been incorporated as a variable in the construction of the integer programming model.

It is noteworthy that integer linear programming formulations have been employed in all three of the studies discussed in this subsection. It is also of note that these studies have all made use of a single experimental case organisation to test the implementation of the affected model, each with favourable results in terms of the workforce optimisation outcomes that have been achieved.

2.2.7 Research Question 1

Considering the airline short-term layover maintenance labour scheduling problem, is there a significant knowledge gap between state-of-the-art developments in published research and practical application at aircraft maintenance organisations on the African continent?

2.3 Schedule Disruptions in the Airline Industry

2.3.1 General Description and Sources of Airline Schedule Disruptions

Kohl *et al.* (2004) indicate that there are a number of external events in real-world operations that can disrupt the smooth execution of airline schedules. These authors identify that the most common sources of schedule disruptions are aircraft mechanical problems, inclement weather, airport congestion and industrial action. As a result of such disruption events, airlines have to adjust their schedules and corresponding resource allocations by implementing changes such as flight cancellations, retiming of flights (i.e. delays) and aircraft fleet type changes (Kohl *et al.* 2004).

Referring to Subsection 1.2.1.3, Levin (2007) presents an expanded description of airline schedule disruptions by highlighting that sources of disruptions include both internal and external factors in a given operational setting. In this regard, disruption sources include external factors such as adverse weather and air traffic congestion that are largely beyond the control of airlines, as well as internal factors over which airlines can exercise a considerable level of control such as crew rostering errors, refuelling delays and aircraft technical faults or breakdowns (Levin 2007).

Bierlaire, Eggenberg and Salani (2007) offer a comparable view to the above authors by describing an airline schedule disruption as any unforeseen event that makes the execution of the planned flight schedule unfeasible. Due to the fact that disruptions are inherently unforeseen events, these authors indicate that the occurrence of a disruption event requires the operations control function of an affected airline to institute reactive recovery plans. Furthermore, these authors claim that it is very unlikely that the flight schedule published by an airline's scheduling function will actually be carried out as planned on any given day-of-operations. Bierlaire *et al.* (2007) highlight three examples of disruption sources that can cause a planned flight schedule to collapse, namely bad weather, propagated delays and unforeseen technical or maintenance inputs.

In order to understand the prevalence of disruption events in the day-to-day operations of airlines, this study has probed published statistical data on airline operations for information relating to levels of flight delays, flight cancellations and aircraft type changes on flights. Referring to Subsection 1.2.1.3 of the study, statistical data reported by the Department of Infrastructure and Transport of the Australian Government claims that levels of flight delays on Australian domestic flight routes for the period from November 2003 to March 2011 were as follows: 15.5% for departing flights and 16.8% for arriving flights (Australian Government 2011). This report claims that, on average, 1.2% of all scheduled domestic flights over this reporting period were cancelled. Similarly, Niehues *et al.* (2001) have reported that levels of flight delays on intra-European flights and domestic flights within the USA in the year 2000 were 25.5% and 27.4% respectively. These authors assert that it is a reasonable norm in the airline industry for one in every four scheduled flights to be delayed. As per Mosley (2012), flight cancellation rates in the US airline industry for December 2011 and January 2012 were 0.8% and 1.5% respectively. This statistical data lends support to the view that flight delays are a significantly more common manifestation of schedule disruptions than flight cancellations. It should be noted that published data relating to occurrences of aircraft tail number or type changes in response to airline schedule disruptions has not been found for use in this study. As such, the prevalence of this category of schedule disruption in the day-to-day operations of airlines cannot be estimated with confidence based on the literature that has been reviewed.

2.3.2 Disruption Management at Airlines

Expanding on the observations of Bierlaire *et al.* (2007) that have been presented in the preceding subsection, Vaze (2009) notes that an airline flight schedule often deviates significantly from the original plan on a given day-of-operations due to delays and disruptions. According to this author, such operational irregularities compel the affected airline operator to implement reactive measures through a decision-making process that is referred to as the 'airline recovery process'. Vaze notes that there are significant additional costs associated to such irregularities in addition to planned airline operating costs. In this regard, the United States Air Transport Association has estimated that supplementary aircraft operating costs of around 8.1 billion US dollars were attributable to flight delays in the year 2007. Furthermore, the work of Bierlaire *et al.* (2007) quotes an estimated cost per minute of delay time of around 72 Euros for European airline operations.

Kohl *et al.* (2004) indicate that it is challenging for airlines to manage changes to their operating schedules because each cancellation, retiming of a flight or aircraft fleet type change must be feasible in terms of both crew and aircraft availability and should preferably minimise passenger inconvenience. These authors describe the process of monitoring and scheduling an airline's crew and aircraft resources close to or on a given day-of-operations as 'disruption management', or alternatively as 'operations control'. Bierlaire *et al.* (2007) refer to the same process as the 'day of operations problem'. These authors indicate that each scheduled flight has to either be served by an aircraft or cancelled where disruptions are encountered. In this regard, the cost of a schedule recovery plan is determined by considering the costs relating to cancellations, delays, aircraft swap-outs and supplementary maintenance actions. The work of Bierlaire *et al.* (2007) supports the notion of resource feasibility with respect to aircraft. In this regard, these authors indicate that the recovery plan for a disrupted flight schedule should adhere to a given set of constraints such that maintenance requirements and aircraft type allocations post recovery are compatible with the original flight schedule. As per Bierlaire *et al.* (2007), an airline's schedule recovery decisions are taken at the Operations Control Centre (OCC) with the aim of finding a set of feasible operations that recover the planned schedule in the shortest time and in the most cost-effective manner.

2.3.3 Schedule Disruption Impacts on STLM Operations at Airlines and Associated Aircraft Maintenance Organisations

The issue has been raised in Subsection 1.4 of the study that previous research into the computational optimisation of personnel scheduling for airline STLM tasks has not quantified the impact of flight schedule disruptions on the viability of such optimised solutions. This assertion is supported by Bierlaire *et al.* (2007) who have commented that the literature specific to resource and crew scheduling problems at airlines is generally lacking in contributions in which aircraft maintenance operations are considered to be variable in nature (i.e. subject to disruptions from a pre-planned maintenance schedule). Belien *et al.* (2010) have addressed the same issue by recommending future research to improve the robustness of their line maintenance staffing and scheduling model to sources of uncertainty. These sources of uncertainty include unexpected aircraft technical faults that add to the planned maintenance work demand and aircraft flight delays that change the timing of maintenance tasks in comparison to the planned schedule. These authors have questioned whether it is possible to incorporate such uncertainty into their labour scheduling model by adding 'robust constraints' or by developing a stochastic programming model. The alternative option presented by these authors is to assess the impact of these sources of uncertainty through simulation approaches.

Higle and Johnson (2005) have undertaken research to investigate the problem of flight schedule planning that takes the requirements for aircraft maintenance into account. Although these authors assume a single type of aircraft maintenance in their investigation, they recognise the problem that different types of maintenance must be performed at different intervals and possibly in different locations. Higle and Johnson also note the issue of random times that may be registered for short inspections (i.e. short-term layover maintenance) on aircraft due to the identification of defects during such inspections that must then be remedied. In such instances, repair times can easily exceed the predicted time for an affected task. These authors have thus proposed the use of stochastic linear programming with associated randomness factors to model repair times for short inspections. Referring to the delimitations detailed in Subsection 1.5 of this study, it is noteworthy that this particular source of task demand variability has not been considered in this study and is therefore a point for discussion and future investigation.

The research of Higle and Johnson (2005) complements the work of Belien *et al.* (2010) in that it has identified the need for further research into the uncertainty relating to unscheduled aircraft maintenance events. In this regard, Higle and Johnson (2005) describe unscheduled maintenance events as a class of flight schedule disruption that occurs where an aircraft sustains some type of breakdown during a flight that requires immediate attention to enable the aircraft to remain in service after landing. These authors have identified that such maintenance requirements can vary considerably in scope, ranging anywhere from simple light bulb replacements to engine damage relating to a birdstrike event. They also note that unscheduled maintenance events may require technicians or spare parts to be transported to non-maintenance stations in order to carry out aircraft repairs, which takes time and exacerbates the associated schedule disruption. In addition, Higle and Johnson assert that, whereas scheduled maintenance events are largely predictable in nature, unscheduled maintenance events occur randomly.

2.3.4 Statistical Profiling of Airline Flight Delays

Mueller and Chatterji (2002) have produced a study that is devoted to the analysis of departure, en-route and arrival delays of aircraft operating out of one of ten major US hub airports with the objective of improving delay prediction. These authors have attempted the stochastic modelling of flight delays by creating probability density functions of real-life flight delay data over a three week measurement period. In this regard, Mueller and Chatterji have modelled the density functions of delay event durations using Normal and Poisson distributions based on the mean and standard deviations derived from the raw data, but which have then been improved by adjusting the mean and standard deviation values via a least squares method. The work of Mueller and Chatterji has shown that departure delay durations are modelled better using a Poisson distribution, whereas en-route and arrival delay durations are modelled better using Normal distributions. These authors state that such modelling methods can be used to improve the accuracy of probabilistic sector departure time or sector arrival time forecasts.

In a similar study, Kondo (2009) has analysed delay propagation sequences for flight data in the USA for the year 2007. Kondo has tested the hypothesis that the durations of propagated delays are exponentially distributed by fitting the Weibull or Gamma probability density function to the recorded delay data and then examining to see how close the estimates of the shape parameter are to a value of one. This author has found that propagated delays closely follow the Exponential distribution in the chosen research setting. It should be noted in respect of Kondo's study that 'propagated delays' (also called 'reactive delays') are the flight delays that manifest indirectly on the second or later flight in a sequence of flights on a given day-of-operations after an initial delay event has affected the timing of an earlier flight in the sequence.

In a detailed study of aircraft arrival delays and airport on-time performance, Bai (2006) has compared theoretical Lognormal and Gamma distributions to the measured distribution of the daily average arrival flight delay duration at a case US airport. The measurements in Bai's study spanned the period from 01 January 2002 to 31 December 2003. According to this author, a Lognormal distribution profile has been found to give a better fit than a Gamma distribution profile to the operational data collected at the case airport.

2.3.5 Research Question 2

Where based on a fixed flight schedule and thus a fixed task demand profile, are computational models for the optimisation of an airline's short-term layover maintenance labour resources sufficiently robust to the effects of flight schedule disruptions (e.g. flight delays) that occur routinely in real-life operations to support their practical application?

2.4 Conclusions of Literature Review and Restatement of Research Questions

Based on the literature that has been reviewed for this study, a number of important conclusions can be drawn. These conclusions are summarised by their associated research question in this subsection, together with a restatement of the two research questions that have been posed.

2.4.1 Conclusions of Literature Review Relating to Research Question 1

The generation of good or optimal personnel schedules in a given organisational setting is generally a complex and highly constrained problem (Musliu *et al.* 2002; Yang *et al.* 2003). As a result, a significant number of research papers have been produced that are focused on the development and implementation of computational models to replace or support manual staff scheduling processes (Ernst *et al.* 2004). In fact, in many problem settings it is practically impossible to find good or optimal solutions to staff scheduling problems in an efficient manner without the use of a computer (Musliu *et al.* 2002). Despite the research findings that support the use of computational methods in optimising labour schedules, there are many application areas where manual rostering practices persist (Ernst *et al.* 2004). Possible reasons for this are:

- The perception that existing rostering software is not sufficiently flexible to cater for the scheduling practices that are applied in specific workplaces (Ernst *et al.* 2004).

- The need to employ expert assistance to enable the transformation of a complex rule set and objective function in relation to a real-world scheduling problem into resource variables (Kohl and Karisch 2004).

As a result of these observations, the study has taken steps to assess the level of sophistication of the modelling methods that are employed by the case organisation in its existing labour scheduling approach for STLM activities. The implementation of computer-based optimisation has been set as a benchmark factor in assessing whether the incumbent scheduling approach is comparable to modern best practices as described in associated operations research literature.

It is evident from the associated literature that labour scheduling is commonly implemented by breaking the problem up into a number of sequential components or phases appropriate to a given organisational setting (De Causmaecker *et al.* 2004; Ernst *et al.* 2004; Ip *et al.* 2010). This practice is logical in that it is usually not computationally practical to deal with all the modules required to generate a labour roster simultaneously (Ernst *et al.* 2004). A decomposition approach allows for different mathematical or computational techniques to be applied to each phase in order to optimise the individual problem characteristics of each (Ip *et al.* 2010). Furthermore, such an approach generally makes a given rostering problem more manageable to deal with and often makes sense in terms of an organisation's business practices (Ernst *et al.* 2004). The generic personnel scheduling process is composed of up to six distinct modules as follows: 'demand modelling', 'days off scheduling', 'shift scheduling', 'line of work construction', 'task assignment' and 'staff assignment' respectively (Ernst *et al.* 2004). The development of a particular roster in a given industry or organisational application may only require some of these modules to be applied and it is possible that several of the modules may be combined into one procedure in practical implementations (Ernst *et al.* 2004). For example, in a study relating to personnel scheduling for STLM tasks at a Chinese airline maintenance services company, Ip *et al.* (2010) have applied a sequential 3-stage methodology for workforce scheduling, namely initial maintenance demand scheduling, maintenance pairing and maintenance group assignment respectively.

It should be noted from the preceding paragraph that demand modelling is the starting point of any given personnel scheduling problem. Demand modelling is the process by which a demand profile for labour resources is derived from a predicted pattern of incidents (Ernst *et al.* 2004). Three categories of incidents can be identified on which demand levels for personnel are based, namely task-based demand, flexible demand and shift-based demand (Ernst *et al.* 2004). For the case of task-based demand, demand levels are obtained from lists of individual tasks that are to be performed based on predetermined starting times and durations, or a time window within which each task must be completed (Ernst *et al.* 2004). In a flexible demand scenario, the occurrence of upcoming incidents is not explicitly known and must be modelled using appropriate forecasting methods (Ernst *et al.* 2004). In this regard, requests for service may have random arrival rates and possibly also random service times. For shift-based demand, demand levels are obtained directly from a specification of the number of staff members that are needed on duty during different shifts (Ernst *et al.* 2004). Shift-based demand profiling may be applied as a simplification to the more complex problems of rostering to either task-based or flexible demand profiles (Ernst *et al.* 2004).

It has thus been investigated in this study whether the existing labour scheduling approach for STLM activities at the case organisation can be described as a modular process that is consistent with the generic process detailed by Ernst *et al.* (2004). A particular area of focus in this regard has been to confirm that the organisation's current process commences with a demand modelling component that adequately describes the profile of workloads that are required to be met over the relevant planning horizon. In an airline STLM environment, the timing and quantity of workloads called out can be forecast directly from the published flight schedule that is being supported on any given day-of-operations. On this basis, this is a case of task-based demand. Thus, it has been expected to find that STLM labour planning activities at the case organisation are initiated by an analysis of the planned flight schedule as received from the airline's flight operations planning function. It has also been noted that flight schedule disruptions at airlines may introduce aspects of flexible demand into the STLM labour planning problem, although this component has yet to be explored in detail in literature relating specific to STLM rostering. Thus, this study has considered whether flexible demand levels are considered in any way as part of the STLM demand modelling process at the case organisation. In addition, the study has considered the possible application of shift-based demand modelling at the case organisation as a simplification to task-based or flexible demand modelling practices.

Personnel scheduling problems can be classified according to generic characteristics such as the nature of demand planning for a given problem or the business application under consideration (De Causmaecker *et al.* 2004; Ernst *et al.* 2004). In this regard, Ernst *et al.* (2004) have classified the scheduling of ground staff at an airport, including aircraft maintenance personnel, under the business application of 'venue management'. Most airport-based personnel scheduling problems are characterised by demand levels for services that are relatively well known as they are driven by regular airline flight timetables (Ernst *et al.* 2004). In addition, the scheduling of aircraft maintenance personnel for STLM activities incorporates the added complexity of allocating a range of small tasks to shifts in the presence of skill constraints (Ernst *et al.* 2004). It has been noted that skill constraints relating to the licenses and qualifications of AMEs and LAMEs needed to perform and release aircraft maintenance tasks (including STLM tasks) have been incorporated by Ip *et al.* (2010) in an integer programming model for this type of crew rostering. In this study, it has thus been explored how the existing labour scheduling approach for STLM activities at the case organisation addresses the problem of skill constraints in the assignment of AMEs and LAMEs to shift teams (or work groups) and in the subsequent allocation of tasks to these teams or groups.

Algorithmic modelling techniques for the solution or optimisation of personnel scheduling problems can be classified according to five principal categories (Ernst *et al.* 2004). These categories are described as follows: ‘demand modelling’ (generally in scenarios of flexible demand planning), ‘artificial intelligence’ techniques, ‘constraint programming’, ‘metaheuristics’ and ‘mathematical programming’. Existing research into the optimisation of personnel schedules for airline STLM activities, including work by Yang *et al.* (2003), Ip *et al.* (2010) and Belien *et al.* (2010), has made use of integer linear programming as an optimisation method. The use of this method has been tested in an experimental case setting in each of these three literature sources, producing favourable outcomes in each instance. As per Ernst *et al.* (2004), integer linear programming is a sub-category of mathematical programming. It is noteworthy that the highly accessible MS Excel environment has been used successfully by Ip *et al.* (2010) to construct their integer programming model for STLM crew optimisation, whereas Yang *et al.* (2003) and Belien *et al.* (2010) have used more specialised commercial software for their numerical optimisation needs (i.e. IBM CPLEX). By adapting from existing research work on the topic, this study has implemented an experimental computer-based integer programming model for the development of STLM labour schedules at the case organisation. An attempt has also been made to classify the technique(s) currently used by the case organisation for labour scheduling against the framework presented by Ernst *et al.* (2004). Furthermore, the software platforms used for computational optimisation purposes in the existing labour scheduling process, if applicable, and in the experimental model have been reviewed in terms of accessibility and specialisation.

The main purpose of optimising labour scheduling processes is to achieve one or more of the following results: to minimise or reduce labour costs, to maximise the availability or reliability of services, to meet employee preferences, to distribute shifts equitably amongst employees and to satisfy workplace constraints for the given situation (Alfares 1999; Ernst *et al.* 2004). A key outcome of this study has therefore been to critically assess the outputs of the existing labour scheduling approach for STLM activities at the case organisation and to compare its performance against the outputs of the experimental computational method adapted from existing literature on the optimisation of STLM crew schedules. In order to perform this assessment in a structured and consistent manner, the staff scheduling checklist developed by Warner (1976) has been applied. Although this checklist was originally developed to assess the relative benefits of competing staff schedules in healthcare applications, it is sufficiently generic in construction to enable its broader application to most personnel scheduling problems. The factors that are covered by this checklist are summarised in Table 1 that follows this paragraph.

Table 1 – Checklist for Assessing the Benefits of a Given Labour Schedule (Warner 1976)

Performance Factor	Assessment Criteria
Coverage	Are the tasks adequately covered by the schedule provided? Otherwise, the organisation must call out additional personnel.
Quality	How good are the working conditions of the staff based on union rules, organisation rules and individual preferences?
Stability	Are individual schedules fairly homogeneous? More homogeneous schedules enable staff members to more easily organise their social and family lives.
Flexibility	How elegantly does the approach deal with changes from one scheduling horizon to the next (e.g. personnel turnover, changes of preference, etc.)?
Fairness	Are the tasks equally shared among the staff while taking into account varying status levels such as seniority?
Cost	What level of resources (human, time, computing power) is required to build a given personnel schedule?

2.4.2 Restatement of Research Question 1

Considering the airline short-term layover maintenance labour scheduling problem, is there a significant knowledge gap between state-of-the-art developments in published research and practical application at aircraft maintenance organisations on the African continent?

2.4.3 Conclusions of Literature Review Relating to Research Question 2

There are a number of events in real-world airline operations that can disrupt the smooth execution of flight schedules. Such events include external factors such as adverse weather and air traffic congestion that are largely beyond the control of airlines, as well as internal factors over which airlines can exercise a considerable level of control such as crew rostering errors, refuelling delays and aircraft technical faults or breakdowns (Kohl *et al.* 2004; Bierlaire *et al.* 2007; Levin 2007). The result of schedule disruption events is that airlines have to reactively adjust their schedules and corresponding resource allocations through recovery plans that implement changes such as flight cancellations, retiming of flights (i.e. delays) and aircraft fleet type changes (Kohl *et al.* 2004; Bierlaire *et al.* 2007; Vaze 2009).

Schedule disruption events are frequent occurrences, to the extent that it is unlikely that the flight schedule published by an airline will be implemented exactly as it was planned on any given day (Bierlaire *et al.* 2007). In this regard, Niehues *et al.* (2001) have asserted that disruption events that result in flight delays occur as frequently as one in every four scheduled flights on average at airlines. Flight cancellations are far less common manifestations of schedule disruption events, with average levels ranging from 0.8% up to 3.9% of flights as per two literature sources that have been reviewed (Australian Government 2011; Mosley 2012). Published statistical data on the prevalence of aircraft fleet type changes within airlines in response to schedule disruptions has not been found for use in this study. Nevertheless, the statistical data that has been reviewed implies that schedule disruptions can impact up to 30% or more of airline flights on average.

As a result of these conclusions, selected day-of-operations records from the case organisation have been scrutinised in this study in order to investigate the incidence rates and properties of flight delays, flight cancellations and aircraft tail number or type changes that have occurred historically in the case setting. This data has then been compared against the literature review findings in order to determine if the observations in an African setting are consistent with the statistical information and research findings referenced from a broader global industry perspective. The incidence rates of aircraft swap-out events (i.e. aircraft tail number or type changes) have been compared to the incidence rates of flight delays and cancellations at the case organisation in order to provide new insight into the relative prevalence of these changes in relation to more commonly referred-to delay and cancellation rates.

Schedule disruptions add significantly to the planned operating costs of airlines (Vaze 2009). Where disruptions occur, each scheduled flight has to either be served by an aircraft or cancelled (Bierlaire *et al.* 2007). The cost of a schedule recovery plan in response to a schedule disruption is determined by considering the costs relating to cancellations, delays, aircraft swap-outs and supplementary maintenance actions (Bierlaire *et al.* 2007). Furthermore, it is challenging for an airline to manage unplanned changes to its flight schedule because each cancellation, retiming of a flight or aircraft swap-out must be feasible in terms of both crew and aircraft availability and should preferably minimise passenger inconvenience (Kohl *et al.* 2004).

It has been noted that literature specific to resource and crew scheduling at airlines is generally lacking in contributions in which aircraft maintenance operations, including those relating to STLM activities, are subject to variability from a pre-planned maintenance schedule (Bierlaire *et al.* 2007; Belien *et al.* 2010). Such variability may include changes to the timing or scope of STLM tasks due to flight delays and aircraft swap-outs that result from airline schedule disruptions, or unforeseen additions to the line maintenance workload that arise due to in-service aircraft breakdowns or defects that are identified during routine checks (Higle and Johnson 2005; Belien *et al.* 2010). It has therefore been questioned in this study whether existing line maintenance staffing models are sufficiently robust to these sources of unplanned variability (or uncertainty) to enable their practical implementation in real-world airline operations (Belien *et al.* 2010).

Whereas a fixed flight schedule input has been used to develop an optimised STLM labour plan in response to Research Question 1, the focus of Research Question 2 has been to test this labour plan under disrupted flight schedule conditions. In this regard, the study has used disrupted flight schedule profiles (including delays, cancellations and aircraft swap-outs) that have been recorded at the case organisation to modify the fixed flight schedule input in the experimental model prior to the processes of task and staff assignment. In doing so, it has been assessed to what extent this optimised labour plan is robust to variations in the quantity, timing and scope of STLM tasks that are brought about by real-life schedule disruption events using its predetermined crew resources (i.e. without applying overtime hours or calling out additional labour resources). Any instances of overtime or callout support have been assessed in terms of their practical feasibility and their associated supplementary maintenance costs. The findings of these assessments have been used to determine if current computational models for optimising an airline's STLM labour resources that apply a fixed flight schedule input are sufficiently robust to the effects of flight schedule disruptions to support their application within real-life airline operations. These findings have also influenced recommendations for further research into airline recovery planning for schedule disruptions, where it may be necessary to consider maintenance crew availability in addition to the flight crew and aircraft resources that are available.

A number of research studies have already been published that are dedicated to the stochastic modelling of flight delays at airlines (Mueller and Chatterji 2002; Bai 2006; Kondo 2009). These studies compare real-life measurements of airport or airline delay characteristics against selected theoretical probability distributions, e.g. Normal and Poisson distributions, in order to determine whether such theoretical distributions can reasonably replicate the measured delay profiles. The use of such modelling methods is intended to enable the accurate prediction of flight delay incidence rates and durations through probabilistic forecasting of the departure times or arrival times of airline flight sectors (Mueller and Chatterji 2002). This study has supplemented existing research by comparing a selection of theoretical probability distributions to records of the incidence rates and durations of flight delays at the case organisation over a six month period. In this regard, the study has assessed the 'goodness of fit' of each theoretical profile in order to determine which profile best matches the measured data for these two delay characteristics. It has also been assessed if this matching is sufficiently accurate to enable the simulation of realistic incidence patterns and durations of airline flight delays in a computational environment.

Belien *et al.* (2010) have raised the question as to whether existing STLM labour scheduling models can be improved through the incorporation of stochastic modelling with respect to sources of uncertainty such as flight delays and aircraft breakdowns. The outcomes of the study in relation to Research Question 2 have been used to discuss the modelling of these uncertainties, chiefly those introduced by flight delays. Although stochastic modelling of uncertainties in the timing of STLM workloads as a result of flight delays is well supported in existing research literature, it has been noted in certain literature sources that real-life airline recovery plans include the possibility for aircraft swap-outs to be implemented in response to delay events, or potential delay events. Such changes in respect of aircraft resource allocations may affect the scope of STLM tasks in addition to any associated timing changes (refer to Subsection 1.2.2 of the study), thereby complicating the mechanism by which flight delay events are translated into corresponding STLM demand changes. In an environment of regular aircraft swap-outs in response to flight delay events, it may thus be an over-simplification to only consider timing changes for STLM tasks in response to flight delays.

2.4.4 Restatement of Research Question 2

Where based on a fixed flight schedule and thus a fixed task demand profile, are computational models for the optimisation of an airline's short-term layover maintenance labour resources sufficiently robust to the effects of flight schedule disruptions (e.g. flight delays) that occur routinely in real-life operations to support their practical application?

3 Research Methodology

This section describes the quantitative research methodology that has been applied in the conduct of this study. In this regard, the section commences with a brief review of supporting literature on the methodological topics of relevance to the study. These topics are quantitative modelling and simulation, sensitivity analysis and robustness testing, as well as case research. This review is followed by a description of the actual research design that has been implemented. A number of supplementary topics in relation to the chosen research design are also presented. These topics include a description of the case site and a discussion of the case selection decision, as well as an overview of the research instruments that have been used. Information is also presented on the data collection and analysis processes that have been implemented in respect of the chosen research design and the associated research instruments. The section concludes with a concise evaluation of the validity and reliability of the study.

3.1 Literature Review on Research Methodology Issues

3.1.1 Quantitative Modelling and Simulation

As per Creswell (2003), a quantitative research approach can be defined as one in which the investigator develops knowledge primarily through the testing of propositions that are believed to be true on the basis of not yet having been disproven. The following common attributes of quantitative research methods are highlighted by this author:

- The application of cause and effect thinking.
- The use of measurement and observation.
- The testing of theories.
- The reduction of problems to specific variables, hypotheses and questions.

Quantitative research methods typically employ experiments and surveys as strategies of inquiry and, in addition, collect observations as well as information on predetermined instruments that give rise to statistical data (Creswell 2003). Expanding on Creswell’s observations in a more focused area of application, Bertrand and Fransoo (2002) describe model-based research as a specific form of quantitative research where models of causal relationships between control variables and performance variables are developed, analysed and tested. These authors identify computer simulation and mathematical programming as examples of model-based approaches that can be applied in quantitative research studies. Looking at the application of simulation approaches in the research environment, Dooley (2002) describes 'discrete event simulation' as one of three main schools of simulation practice. Dooley goes on to describe discreet event simulation as a methodology in which an organisational system is modelled as a set of entities that evolves over time according to resource availability and the triggering of particular events. Expanding on the above description, Dooley highlights the following characteristics in respect of discrete systems:

- A discrete system is one in which the state variables only change a finite number of times and at specific points in time.

- By plotting the quantitative values associated with the state of the system, one would find these values to be piecewise continuous in that they would make discrete jumps at points in time whilst remaining constant for periods of time in between these points.

Axelrod (1997) outlines seven primary applications of simulation in the social sciences as follows: (1) prediction, (2) performance, (3) training, (4) entertainment, (5) education, (6) proof, and (7) theory discovery. Axelrod highlights that the value of simulation as a scientific methodology lies principally in prediction, proof and discovery. As per Dooley (2002), prediction simulation takes a model, composed of a structure and rules governing that structure, and produces an output. By comparing different outputs obtained using different scenarios of structures and governing rules, Dooley indicates that researchers can infer what might happen in a real situation if such scenarios were to occur. This author further indicates that the vast majority of models used in the operations research and operations management fields fall into this category, where predictions are made as to how certain input, process and rule changes (e.g. in inventory control, material handling, quality, productivity, etc.) will impact operational outputs. Axelrod (1997) asserts that the use of simulation for prediction can help to validate or improve the model upon which a given simulation is based. Axelrod further indicates that, while prediction is the most common use that people assign to simulation as a scientific technique, the use of simulation for the discovery of new relationships and principles is at least as important as its use for proof or prediction purposes.

3.1.2 Sensitivity Analysis and Robustness Testing

Kleijnen (2001) interprets the concept of 'sensitivity analysis' to be a systematic investigation of how the outputs of a simulation react to extreme values of the associated modelling input(s), or alternatively to drastic changes in the modelling structure. This author does not include marginal changes or perturbations in input values in his interpretation of sensitivity analysis. Pannell (1997) offers a broader interpretation by indicating that the parameter values and assumptions of any model are subject to change and error. As per Pannell, sensitivity analysis can be broadly defined as the investigation of how potential changes and errors impact on the conclusions to be drawn from a particular model. Unlike Kleijnen, Pannell does not differentiate extreme input values from marginal input changes in his definition of sensitivity analysis.

As per Pannell (1997), sensitivity analysis can be applied to a wide range of uses. In this regard, Pannell separates these usage areas into four main categories as shown in Table 2 below. It should be noted that the highlighted bold text entries in Table 2 refer to uses of sensitivity analysis that are deemed to have significance in the context of this study, or for future research relevant to the research topic. Pannell asserts that parameters in all models are uncertain to at least some degree and that the modeller is likely to be unsure of their current values while being even more uncertain about their future values. It is this uncertainty, according to Pannell, that is a primary reason why sensitivity analysis is helpful in making decisions or recommendations. This author indicates that, if an optimal strategy or solution determined through a modelling process is shown to be robust (i.e. insensitive to changes in modelling parameters), then this strategy or solution can be implemented or recommended with confidence. On the other hand, Pannell indicates that, if a strategy or solution is not robust, sensitivity analysis can be used to demonstrate how important it is to make modelling changes or to build in flexibility in response to the changing optimal solution.

Table 2 – Uses of Sensitivity Analysis as Proposed by Pannell (1997)

Category Number	Category Description and Sub-Categories
1	Decision Making or Development of Recommendations for Decision Makers: **a) Testing the robustness of an optimal solution.** **b) Identifying critical values, thresholds or break-even values where the optimal strategy changes.** c) Identifying sensitive or important variables. d) Investigating sub-optimal solutions. **e) Developing flexible recommendations which depend on circumstances.** **f) Comparing the values of simple and complex decision strategies.** **g) Assessing the 'riskiness' of a strategy or scenario.**
2	Communication: **a) Making recommendations more credible, understandable, compelling or persuasive.** b) Allowing decision makers to select assumptions. c) Conveying lack of commitment to any single strategy.
3	Increased Understanding or Quantification of the System: **a) Estimating relationships between input and output variables.** **b) Understanding relationships between input and output variables.** **c) Developing hypotheses for testing.**
4	Model Development: **a) Testing the model for validity or accuracy.** b) Searching for errors in the model. c) Simplifying the model. d) Calibrating the model. **e) Coping with poor or missing data.** **f) Prioritising acquisition of information.**

3.1.3 Case Research

According to Zainal (2007), a case study is an empirical inquiry that investigates a contemporary phenomenon, specifically one involving a limited number of events (or conditions) and associated relationships, in its real-life contextual setting. This author highlights that case study research, or case research, can be robustly applied as a research methodology most particularly where it is necessary to conduct a holistic and in-depth investigation of a complex issue (or set of issues). Leonard-Barton (1990) expands on this description by including both past and current phenomena as relevant subjects for case research. A case study can collect data by multiple means and from a variety of sources (Benbasat, Goldstein and Mead 1987; Leonard-Barton 1990). In this regard, direct observation and systematic interviewing are typical means of data collection in case studies. Sources of case study data can include documentation (e.g. formal reports or newspaper articles), physical artefacts, as well as public or private archival records.

Case study research offers a number of advantages to researchers. These advantages include the following factors:

- Case research is well suited to processes of theory building, theory testing and theory extension or refinement (Benbasat *et al.* 1987; Voss, Tsikriktsis and Frohlich 2002).

- The examination of data in case research is generally conducted within the situation in which an event or activity takes place (Benbasat *et al.* 1987; Zainal 2007).

- Case studies have been shown to have high levels of validity as viewed by practitioners in the field of operations management, who are the ultimate end-users of operations research (Voss *et al.* 2002).

- Case research increases the chance of establishing a linkage between cause and effect, which can be difficult in survey-based research (Voss *et al.* 2002).

Despite the various advantages that have been listed in this subsection, the use of case research does also present certain challenges to researchers. The work of Voss *et al.* (2002) highlights two such potential challenges, namely that case studies can be time consuming and, more importantly, limiting in terms of the generalisability of conclusions that are drawn in a given research setting. It is therefore recommended that careful consideration be given to potential challenges before using case study methods, particularly with regards to the issue of the generalisability of findings to other settings or contexts within the affected research area.

3.2 Research Design

3.2.1 Overview of the Research Design

This research study has been based primarily on the application of an experimental computational model in a case setting to simulate a personnel scheduling process relating to airline maintenance. Due to its use of a model-based experiment as a strategy of inquiry, the study is categorised as being quantitative in nature (Bertrand and Fransoo 2002; Creswell 2003). To offer a more detailed description, the study has adapted computer simulation and mathematical programming processes from relevant literature sources and tested them in an experimental case setting for the purpose of optimising control variables relating to personnel scheduling for airline STLM activities. Control variables in this scenario include factors such as the length of shifts and the number of shift teams within the workforce roster. The intention of this research has been to collect objective evidence to ascertain whether sophisticated modelling concepts adapted from relevant contemporary literature sources can be applied robustly in a real-life airline STLM operation to optimise labour scheduling performance factors. These performance factors include the number of staff employed, the total weekly manhours supplied by the workforce roster and the associated labour costs.

This subsection of the study gives a detailed description of the research design that has been implemented in respect of the two research questions that have been posed. It also considers some of the noteworthy characteristics of the research design as they relate to the review of methodological issues presented in Subsection 3.1. The relative advantages and disadvantages of the research design are also examined in this subsection.

3.2.2 Description of the Research Design as it Relates to Research Question 1

The main focus in responding to Research Question 1 has been to adapt existing research on the computational modelling and optimisation of STLM labour scheduling problems in order to produce an optimised personnel plan using an experimental simulation model in the chosen case setting. This has been carried out under the ideal assumption of a fixed (i.e. undisrupted) flight schedule in responding to Research Question 1. This optimised personnel plan has then been assessed to determine if it offers any significant improvement over the case organisation’s current STLM labour schedule in terms of the performance factors of ‘coverage’ and ‘cost’ that are described in Table 1 in Subsection 2.4.1. In this regard, the assessment has focused primarily on comparing the cost of direct labour associated with the two contrasting personnel schedules. It should be noted that the human factor issues described in Table 1, namely the ‘quality’, ‘stability’, ‘flexibility’ and ‘fairness’ of a given personnel schedule, have not been considered in this study as part of the performance assessment of the two applicable labour schedules. However, reasonable consideration of these issues has been provided for in establishing an appropriate set of constraints for the experimental simulation model. For a detailed description of the case setting (also referred to as the case site), refer to Subsection 3.3.1.

In addition to comparing the two applicable STLM labour schedules in terms of their associated direct labour costs, the study has also considered whether the development of an optimised labour plan in the case setting using computational methods was possible to accomplish in a reasonable time frame and in a practical fashion. In this regard, the study has made a determination on the practicality of performing the required computational modelling using desktop or laptop personal computers in conjunction with existing commercial or open source software packages that are, in general, readily-available to the modern operations or human resources manager. The outcomes of this determination relate back to the factor of 'cost' that is described in Table 1.

Multiple research instruments have been employed in addressing Research Question 1. These instruments include the computational model that has been developed in the case setting, as well as various instruments that have been used to collect case data relevant to the study. Examples of the instruments that have been used for data collection purposes at the case site include formal interviewing, measurement, physical artefacts and archival records. A detailed description of each of these instruments is given in Subsection 3.4.

3.2.3 Description of the Research Design as it Relates to Research Question 2

In addressing Research Question 2, the optimised labour schedule for the case organisation that was produced in response to Research Question 1 has been subjected to tests to determine its sensitivity to uncertainty in the timing and scope of STLM workloads. In this regard, it should be remembered that the computational model that was used to develop this labour schedule applied the ideal assumption of a fixed flight schedule. In real-life airline operations, flight schedules are inherently uncertain due to the frequent occurrence of flight schedule disruptions such as flight delays, flight cancellations and aircraft swaps. As a result, there are usually differences between the predetermined flight schedule and the actual sequences of flights that are flown by an airline on any given day-of-operations. This, in turn, affects the demand profile for STLM tasks on the associated aircraft fleet.

In order to better understand the implications of the uncertainty described in the preceding paragraph on STLM labour scheduling, day-of-operations records from the case organisation have been analysed in order to map a set of daily STLM task demand profiles that are based on actual airline operations, including associated schedule disruption events. Changes in both the timing and scope of STLM tasks due to flight schedule disruptions have been considered in this regard. These variable task demand profiles that are based on fluctuating levels of schedule disruptions from day to day have been loaded against the predetermined personnel roster for STLM activities that was optimised in response to Research Question 1. Task allocation processes have then been performed in order to determine the extent to which the variable task demand profiles relating to real-life operations can be feasibly covered by this predetermined labour force without the need to call out additional labour resources.

Note:
With reference to the observations of Higle and Johnson (2005) and Belien *et al.* (2010) that are presented in Subsection 2.3.3 of the study, it should be remembered that unplanned maintenance workloads to repair in-service aircraft breakdowns and non-routine defects identified during STLM checks are considered to be beyond the scope of the workforce allocated to STLM duties. It is assumed that these unplanned workloads are redirected to a higher level line maintenance team at the point of identification.

The response to Research Question 2 has also considered the feasibility of applying probabilistic methods to model the variations that occur in STLM demand profiles due to schedule disruptions such as flight delays. In this regard, incidence rates and durations of flight delays as recorded by the case airline have been aggregated and profiled over a six month period. This data has been used to produce histograms of real-life flight delay characteristics, namely the duration in delay minutes per delay event and the percentage of delayed flights per day-of-operations. Using these histograms, actual delay characteristics at the case organisation have been compared against a selection of theoretical probability distributions with appropriately matched modelling parameters. The selection of these distributions has been made according to the supporting literature sources detailed in Subsection 2.3.4 of this study. These comparisons have been assessed to determine if any of the theoretical distributions can be applied to accurately replicate the measured flight delay characteristics. Thereafter, it has been contemplated whether it is possible to model the causal relationship between an originating flight delay event and the resulting variations in the associated task demand profile for STLM tasks without accessing day-of-operations records that detail the disruption management decisions that have been implemented by an affected airline.

Similarly to the research design that has been implemented in respect of Research Question 1, multiple research instruments have been employed in responding to Research Question 2. In this regard, further use has been made of the computational model that has been developed in the case setting, this time as an instrument in the sensitivity testing process that has been carried out. In addition, various archival records at the case site have been accessed for the purpose of collecting data on the characteristics of airline flight delays and other schedule disruptions, as well as their impact on operational planning and management at the airline. Each of these instruments is described in greater detail in Subsection 3.4.

3.2.4 Characteristics of the Research Design

From Subsections 3.2.2 and 3.2.3 it is clear that data collection in this study has not been limited to a single source and means of collection. This is a typical characteristic of a case-based research design (Benbasat *et al.* 1987; Leonard-Barton 1990). In this respect, the study includes primary data that has been obtained through both observation and interviewing, as well as from physical artefacts and archival records. Subsection 3.4 provides further information on the various data collection instruments that have been employed.

Furthermore, the simulation approaches that have been implemented in this study conform to the specifications laid out by Dooley (2002) in relation to discrete event simulation. In this regard, the STLM operation at the case organisation's main base has been modelled as an organisational system that evolves over time based on particular event 'triggers'. These triggers are:

- The start and finish times of individual shifts – at shift change times, step changes occur in the quantity of on-duty skilled workers (AMEs).

- The start and finish times of STLM tasks – the commencement and completion of each aircraft check introduces a step change to the quantity of active workers that is demanded from the pool of available AMEs. The activity levels of STLM tasks are, in turn, constrained by the sequences and timing of company aircraft movements (i.e. arrivals and departures) at the affected airport location.

With reference to the application areas specified by Axelrod (1997), the study has made use of simulation for the purpose of prediction. In responding to Research Question 1, computer-based simulation has been applied to a staff scheduling problem in order to predict how the output of the scheduling process (i.e. the staff duty roster) is impacted by changes in labour supply variables within a framework of rostering rules. In this way, it has been possible to predict an optimal labour supply configuration that provides sufficient coverage to meet the demand for STLM services and which satisfies the rostering rules that have been imposed. In responding to Research Question 2, the optimised workforce roster that was developed in addressing Research Question 1 has been subjected to robustness tests to assess its ability to provide sufficient coverage where the task demand input is inherently uncertain and subject to variation. In this regard, simulation has been employed to predict how sensitive the coverage characteristics of the optimised labour schedule are to becoming unfeasible where unplanned task demand variations are in effect. It should be remembered that unplanned task demand variations are a typical characteristic of airline STLM operations due to the frequent occurrence of flight schedule disruptions during day-to-day flight operations at airlines. As such, any operational model that uses a fixed flight schedule as an input factor should be shown to be robust to flight schedule disruptions in order to demonstrate its feasibility for practical implementation.

3.2.5 Advantages and Disadvantages of the Research Design

Looking at the advantages of the research design that has been applied in this study, a number of important issues can be identified. These issues are as follows:

- Firstly, it has been noted that case research lends itself to a process of theory testing and, if applicable, subsequent theory extension or refinement (Voss *et al.* 2002). This is a very relevant issue as this study is based around the testing of a theoretical model in a real-life setting in order to measure the performance capabilities of the model and to determine its robustness to uncertainties that exist in real-life. The empirical data generated through this testing has then been used to provide recommendations for the ongoing refinement of the theoretical model to more accurately describe the real-life operational process that has been modelled. The work of Bertrand and Fransoo (2002) gives support to the assertions of Voss *et al.* (2002) by highlighting that there is a major opportunity for theory-building to be achieved in real-life operational processes through the empirical validation of axiomatic models adapted from existing operations research. In addition, Axelrod (1997) asserts that the use of simulation for prediction can help to validate or improve the model upon which a given simulation is based.

- Secondly, case research has been shown to have high levels of validity as viewed by practitioners in the field of operations management (Voss *et al.* 2002). These practitioners are the ultimate end-users of operations research and are the target audience for this particular study. In addition, quantitative modelling in the arena of operations management has had a successful history in terms of improving real operational processes, which is the main outcome that is intended for this study (Bertrand and Fransoo 2002).

- Thirdly, by exploring a given operations management problem in a single case setting, it is generally possible to achieve a greater depth of insight into the problem characteristics that are at play than in a scenario where multiple cases are evaluated (Voss *et al.* 2002).

Although a number of advantages have been identified relating to the design of this study, there are also some disadvantages that need to be borne in mind. Factors that have been identified in this regard are as follows:

- Firstly, case research is generally time consuming (Voss *et al.* 2002).

- Secondly, the use of a single case setting to facilitate the testing of the quantitative model on which much of this study is based limits the 'generalisability' of the conclusions that have been drawn (Voss *et al.* 2002; Zainal 2007).

- Thirdly, the field of operations management research is lacking in a clearly defined and objective framework by which to identify and measure the applicable characteristics of a real-life operational process (Bertrand and Fransoo 2002). As a result, this construct problem has to be dealt with in a subjective and situation-dependent way when applying this type of research in a real-life setting (as is applicable in this study), which in turn makes it more difficult to judge the scientific value of the associated research outcomes (Bertrand and Fransoo 2002).

- Finally, the case study method has received criticism in terms of its lack of robustness as a research tool (Zainal 2007). This assertion is well supported by the generalisability and subjectivity problems described in the preceding two bullet points.

3.3 Population and Sample

The results of this study are intended to be of interest to the broader pool of line maintenance service providers to airlines based on the African continent. This pool of service providers includes in-house maintenance departments within such airlines as well as third party aircraft maintenance organisations that service the line maintenance needs of one or more customer airlines. However, due to the application of a single-case design, it is not relevant to define a research population and sampling method for this study. Instead, this subsection describes the case site and discusses the reasons for its selection in relation to the research problem that has been investigated.

3.3.1 Case Site

The case site that has been used in this study is the main base of the airline company, Airlink, and its associated aircraft maintenance services provider. More specifically, the study has focused on the line maintenance and flight scheduling functions that operate in this setting. It should be noted that the terms 'case setting' and 'case site' are used interchangeably within the study. According to its company website, Airlink is a privately-owned regional airline company based in South Africa that operates scheduled commercial flights across a wide network of routes within the Southern African region. This route network includes flights to other southern African states like Botswana, Mozambique, Zambia and Zimbabwe. Airlink carries out the majority of its day-to-day aircraft maintenance activities through its own internal maintenance division. This maintenance division is an approved Aircraft Maintenance Organisation (AMO) under the oversight of the South African Civil Aviation Authority (SACAA).

The main base of Airlink's maintenance division is an aircraft hangar facility located at OR Tambo International Airport (ORTIA) in Johannesburg. Over the time period of data collection relating to this study (i.e. January 2011 to September 2011), this division carried out a combination of line maintenance and heavy maintenance activities on a fleet of up to 33 regional airliners. These maintenance activities related predominantly to the Airlink aircraft fleet, although some third party work was also contracted in from other operators. The fleet of aircraft operated and maintained by Airlink over this period consisted of a mix of three distinct aircraft types. These aircraft types are as follows:

- The British Aerospace Jetstream 41 (or J41 for short) – this aircraft is a 29 seat regional airliner that is equipped with twin turbopropeller engines.

- The Embraer ERJ135LR (or ERJ135 for short) – this aircraft is a 37 seat regional airliner that is equipped with twin turbofan engines.

- The British Aerospace RJ85 (or RJ85 for short) – this aircraft is a 78+ seat regional airliner that is equipped with four turbofan engines.

Short-term layover maintenance is a key activity that is carried out by the Airlink maintenance division through its Line Maintenance Department. The majority of this layover maintenance is carried out at the ORTIA base station, although the division also manages a number of smaller 'outstation' line maintenance facilities. These facilities perform STLM checks and carry out defect rectifications at a number of other airport locations within South Africa, such as at Cape Town International Airport for example. Airlink has made both its flight operations and maintenance divisions available for the purpose of data collection in support of this study.

3.3.2 Case Selection

The process of sampling in a case-based study is understood to be the means by which one or more chosen case sites are selected. In this regard, Voss *et al.* (2002) indicate that case selection or sampling is of vital importance where multiple case studies are to be used in a research work. However, only a single case organisation is considered in this study. As such, the case selection process has been deemed to be of comparatively lesser importance as a methodological issue than would have been the case for a study involving multiple case sites. Nevertheless, a number of relevant decision factors can be identified in the selection of Airlink as the case organisation.

These decision factors can be related to the research work of Miles and Huberman (1994) as cited in Curtis, Gesler, Smith and Washburn (2000) that presents criteria for the evaluation of sampling strategies. These criteria include the following two points:

- The sampling plan should be feasible with regards to accessibility and the investment of money and time that it requires.

- The sample should provide for a high likelihood of generating rich information on the research topic under investigation.

Looking at the case selection decision factors in relation to the two points highlighted above, a number of linkages can be made. On the first point, Airlink is an African airline operator with its principal base of operations at OR Tambo International Airport (ORTIA) in Johannesburg, South Africa. Johannesburg is the city within which the author of this study resides. Airlink also has its own internal maintenance division that performs a wide scope of both line maintenance and heavy maintenance activities on behalf of the parent airline. As such, it has been possible to investigate the interrelationships between flight operations and maintenance as they pertain to the research problem at hand within a single organisational setting. This would not have been possible in an environment of maintenance outsourcing by the airline company. Additionally, the author of this study has a close working relationship with Airlink and is known to its operations managers within the flight operations and line maintenance areas. This combination of factors has ensured a high degree of accessibility to the case organisation and has minimised the time and cost of data collection in relation to this study.

On the second point, the website of the Airports Company South Africa (2012) states that ORTIA is the largest and busiest airport on the African continent. In this regard, flight statistics published on this website indicate that a total of 17,980 aircraft movements (i.e. flight arrivals and departures) occurred at this airport during the month of September 2011. To understand the contribution of Airlink to these aircraft movements, a company flight statistics report compiled internally at Airlink for September 2011 has been examined. This report indicates that 2,067 of these 17,980 aircraft movements corresponded to Airlink flights, or a percentage level of 11.5%. Equivalent data for the month of October 2012 shows that Airlink flights covered 2,354 out of the total of 17,831 aircraft movements that took place at ORTIA for the month, or 13.2%. Based on this data, Airlink is responsible for approximately 11 to 13 percent of all aircraft movements at the largest and busiest airport in Africa. As a result, it has been deemed that Airlink's main base of operations at ORTIA is a rich data source for investigating the problem of personnel scheduling problem for airline STLM activities in an African setting.

3.4 Research Instruments

According to Voss *et al.* (2002), the research design that is used to explore an operations management problem should consider the processes and systems at play, the methods that shall be applied to study them and the operating data that needs to be collected from them. The business process of concern in this study is the scheduling of labour supplies for airline STLM activities. The research instruments in this instance are the devices that have been used to investigate this process in the chosen case setting, as well as the methods that have been used to gather relevant operating data in support of these investigations. A concise overview of each of these research instruments is given in this subsection. Firstly, the personnel scheduling model on which much of this study is based is described in detail. This is followed by a description of each data gathering instrument that has been employed. In this regard, it should be remembered that multiple instruments for data collection have been used during the course of this study, including formal interviewing, physical artefacts, observation and archival records.

3.4.1 The Personnel Scheduling Model

The experimental staff scheduling model that has been adapted and tested in this study applies a computer-based formulation to execute a business operations process. As a result, this model can be represented in the form of an input-process-output model (Zwikael and Smyrk 2011). This representation is illustrated in Figure 1. It is clear from this figure that the process of computing an optimised output labour plan from the various modelling inputs has been performed in two steps in this study. In the first step, a STLM task demand profile is generated from the planned airline flight schedule and the standard time inputs for the applicable STLM tasks. Computations are then performed to determine an optimal shift roster that satisfies the shift constraints that have been specified, while supplying adequate numbers of workers at appropriate times of duty and with appropriate levels of certification to ensure that the task demand is adequately covered at all times. In the second step, task assignment processes are performed to ensure that each STLM task that is demanded is assigned to one or more members of the on-duty workforce. This process must ensure that tasks are assigned in a manner that prevents the occurrence of multiple occupancy conflicts for individual staff members and which ensures that the required skills or certification levels are made available as appropriate for each task. The assignment process should also support an equitable queuing policy for tasks such that the total workload that is assigned to each member of the workforce across the duration of each shift is kept as uniform as possible.

With reference to Figure 1, the main objective of the computational model that has been developed is to optimise the supply of labour whilst satisfying the shift coverage requirements that are called out by the associated demand profile for STLM tasks. Although Warner (1976) lists coverage as a performance factor for a given labour schedule, it has been viewed as a simple yes or no factor in this study. As such, coverage has been incorporated in the experimental simulation model as a modelling constraint. The key objective of the experimental model can therefore be reduced to minimising one or more of the following:

- The cost of labour (in the form of AMEs) that is employed and rostered to meet the STLM requirements of the airline.
- The total quantity of manhours that is allocated to the work roster that is implemented for the STLM workforce.
- The total quantity of AMEs that is allocated to the work roster that is implemented for the STLM workforce.

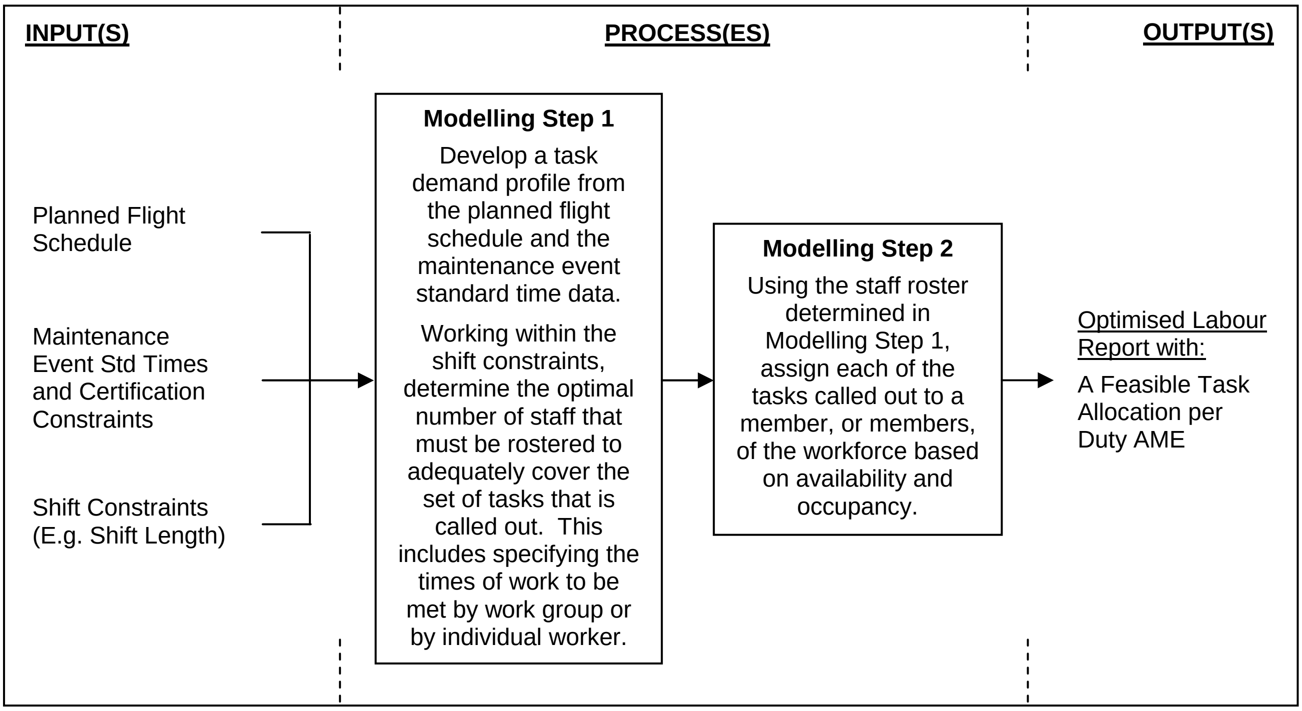


Figure 1 – Input-Process-Output (IPO) Model Representation of the Experimental Personnel Scheduling Model

Adapting from the work of Belien *et al.* (2010), the cost of AME labour that is employed in a STLM operation can be expressed mathematically as shown in Equation 1. This equation is described in greater detail in Section 4 of the study where it has been populated according to the modelling constraints that have been developed within the case setting. It should be noted that the use of this equation requires a basic understanding of the terminology and illustrative devices that have been used in this study to describe shift rosters. An overview of these shift roster descriptors is provided in Appendix C.

$$TC = \sum_{c \in C} \sum_{s \in S} \sum_{d \in D} M_{sc} \times W_{scd} \times z_{scd} \qquad (1)$$

The indices and sets used in Equation 1 are:

$c \in C$: cycles (i.e. shift teams) in the personnel schedule

$s \in S$: work groups (or 'shifts') per cycle

$d \in D$: days per cycle

Note:

Sets *S* and *C* contain all combinations of feasible work group start times and shift durations per operational day in the case setting.

The data parameters used in Equation 1 are:

TC : total AME labour cost across one cycle length of the roster

M_{sc} : number of full-time AME slots per work group *s* in cycle *c*

W_{scd} : average labour cost per AME per work group *s* in cycle *c* on day *d*

z_{scd} : binary decision variable –

>> 1 if work group *s* in cycle *c* is scheduled to work on day *d*

>> 0 if otherwise

Where AMEs are paid based on an hourly wage and a record of hours worked, parameter W_{scd} in Equation 1 can be replaced by the product of parameters H_{scd} and D_{scd} as follows:

H_{scd} : average hourly labour cost per AME in work group *s* in cycle *c* on day *d*

D_{scd} : duration of working shift in hours for work group *s* in cycle *c* on day *d*

Figure 2 depicts an extension to the IPO model detailed in Figure 1. This extension provides for the implementation of the sensitivity testing that has been performed in response to Research Question 2. In this regard, profiles of flight schedule disruptions are introduced between the first and second modelling steps. In this way, the staffing and rostering decisions that are made in the first modelling step based on the planned flight schedule are retained, as would generally occur in an actual airline operation. However, the eventual allocation of tasks to the available members of the workforce can be varied in an attempt to cater for the subsequent effects of task demand variations that are associated to unplanned flight schedule disruptions. The effects of schedule disruptions on labour planning for STLM activities has been measured in this study according to occurrences of 'missed maintenance events', or 'MMEs' for short (see Figure 2). MMEs generate requirements to call out additional labour resources, or alternatively to allocate unplanned overtime to members of the on-duty workforce, in order to avoid flight cancellations and to control the impact of resulting flight delays. Both of these outcomes have an influence on the cost of labour and may also influence labour resource levels that are maintained for the affected function. Subsection 3.6

of the study, which focuses on the issues of data analysis and interpretation that are relevant to the research questions at hand, provides further information on MMEs and their potential impacts on STLM labour scheduling processes.

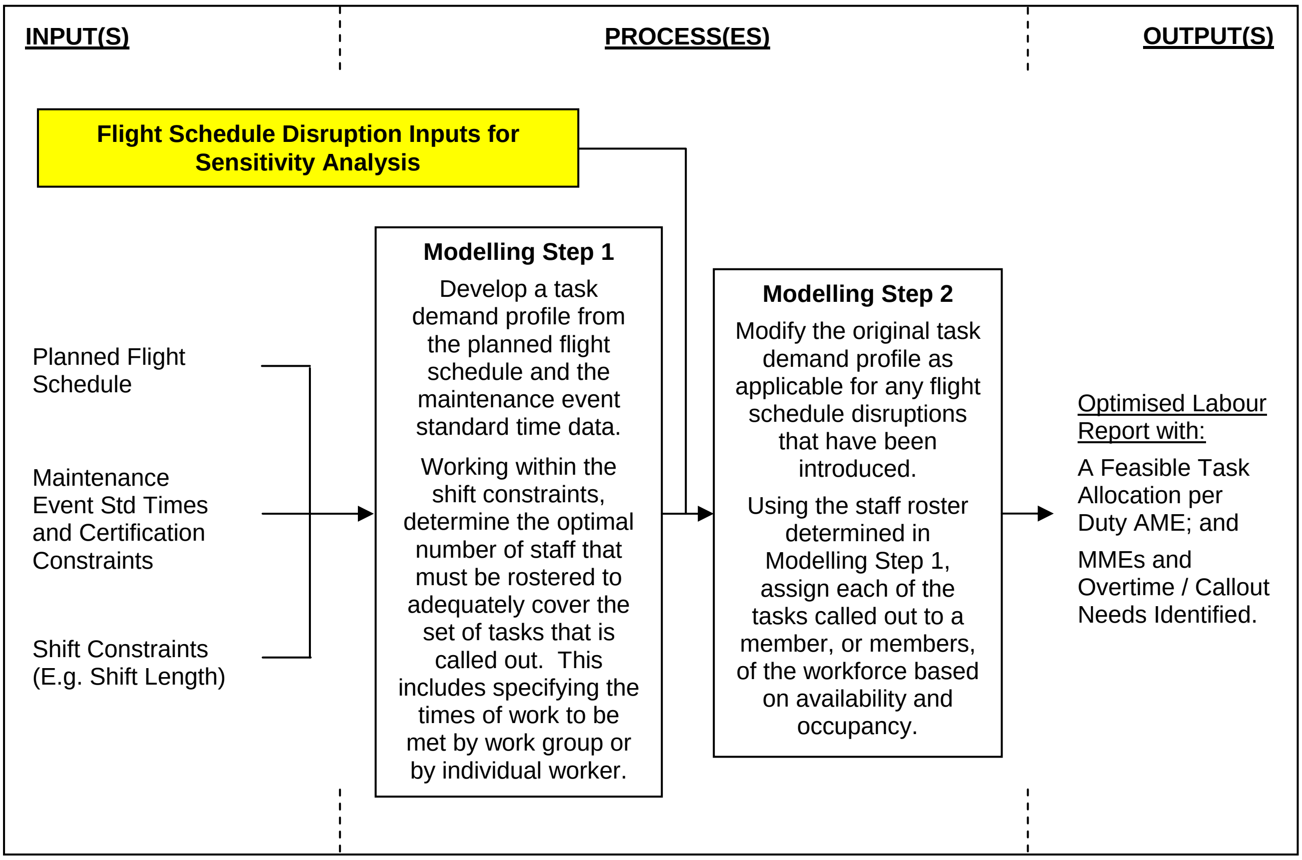


Figure 2 – Input-Process-Output (IPO) Model Representation of the Experimental Personnel Scheduling Model, Including Unplanned Schedule Disruption Inputs for Sensitivity Testing

3.4.2 Instruments for Data Collection

It has been mentioned already that multiple instruments have been used in this study for collecting data in the case setting. This has been necessary due to the diverse requirements for case data in relation to the two research questions that have been posed. An overview of each of these instruments is given in this subsection. Each affected instrument has been described according to the research question to which it applies.

On the topic of data gathering, the views expressed by Voss *et al.* (2002) with respect to structured interviews have been carefully considered in developing this study. These authors assert that structured interviews, which are often supported by unstructured interviews and interactions, are typically the prime sources of data in case research. Structured interviews have played a key role in relation to various aspects of this study, although the information that follows clearly shows that these interviews have been supported by a number of other means of data collection.

3.4.2.1 Data Collection Instruments Relating to Research Question 1

As an initial area of focus, this study has assessed how the case organisation currently schedules AMEs within its labour force to perform STLM activities. This assessment has included a review of the technology, models and decision-support tools that are used in implementing this scheduling process. The data gathering instruments that have been applied in this area of the study are structured interviews and a physical artefact. Firstly, structured interviewing has been conducted with two key management personnel within Airlink's maintenance division to explore the existing processes and techniques for STLM labour scheduling at the organisation, including supporting tools. The interview respondents that have been selected in this regard are the AMO Accountable Manager who is the head of the Airlink maintenance division and the Chief Inspector who oversees its line maintenance function. The interview format that has been developed is based on the funnel model whereby each interview starts with broad and open-ended questions which become more specific and detailed as the interview progresses (Voss *et al.* 2002). A copy of this structured interview format is provided in Appendix D. Secondly, the study has scrutinised the existing forecasting model that has been developed and implemented within the case organisation for the planning of line maintenance labour supplies, including those allocated to the STLM function. The assessment of this model has focused on extracting relevant performance characteristics such as the number of staff members and manhours supplied to the STLM function. This performance data has been used as the benchmarking standard against which to consider the potential benefits to the case organisation of implementing the alternative model for STLM labour scheduling (based on adaptations from contemporary operations research) that has been tested in this study.

As its next area of focus, the study has established a set of constraints for STLM crew rostering (e.g. minimum and maximum shift lengths) that are specific to the case organisation and within which the alternative personnel scheduling model has been tested in a computational simulation environment. In establishing this set of modelling constraints, various unstructured interactions have taken place between the author of this study and appropriate management personnel within the case organisation's line maintenance function. In order to enhance the validity of the list of constraints that has resulted from these interactions, the two interview respondents introduced in the preceding paragraph have been interviewed for a second time in order to offer their expert opinions and insights on the relevance and scope of these constraints. As with the first set of interviews, a structured interview format has been applied in conducting these constraint reviews. Refer to Appendix D for a copy of the interview format that has been used. In addition, the list of provisional modelling constraints that has been referenced in each interview is included in Appendix E. It should be noted that comments or editions to this list of modelling constraints that are based on the interview feedback have also been inserted in Appendix E in italics so as to avoid unnecessary duplication in presenting the provisional and finalised list of modelling constraints.

As a further measure to support the experimental implementation of the alternative personnel scheduling model, a second physical artefact has been used for the purpose of data collection in this study. In this second instance, the artefact employed is the internal company procedure at the case organisation that prescribes the qualifications, experience levels and limitations for company AMEs to perform and certify maintenance work. This procedure has been evaluated in order to establish appropriate STLM task certification requirements for the alternative scheduling model.

Observation has also been employed as a research instrument in this study in contributing to the development of the alternative model for STLM labour scheduling. In this regard, observation has been used to provide standard time inputs for this model for the various STLM task scopes that are applicable. This has been done by taking on-the-job measurements of the times taken by Airlink AMEs to accomplish these task scopes. The resulting data sets have been analysed statistically in order to establish a suitable standard time for each distinct task scope. These standard times have then been used as fixed inputs in the alternative labour scheduling model in order to ensure that realistic accomplishment times are projected for each STLM task that is called out in the simulated operating environment. Further information on the collection and interpretation of this measured data has been included in Subsections 3.5 and 3.6.

Four distinct categories of archival records have been accessed at the case organisation during the course of this study. The secondary data collected from these archival records has proved to be essential in addressing both of the research questions that have been posed. With respect to Research Question 1, records of the planned airline flight schedule by historical day-of-operations have been accessed and analysed. This analysis has enabled STLM task demand profiles to be reproduced from actual planned flight schedules in the case setting for subsequent use as inputs to the alternative model for STLM crew scheduling.

3.4.2.2   Data Collection Instruments Relating to Research Question 2

In addressing Research Question 2, archival records in the case setting have been used to enable the simulation of realistic profiles of airline flight schedule disruptions and associated variations in demand levels for STLM services. The archival records that have been accessed in this regard are all associated to date ranges within the 2011 calendar year. These records are as follows:

- Records of the planned flight schedule by historical day-of-operations.

- Records of the flights actually flown by historical day-of-operations.

- Records of occurrences of flight delays or flight cancellations.

- Records of occurrences where aircraft technical faults or equipment breakdowns resulted in flight delays or flight cancellations.

A key database that has been assembled from the listed archival records is a six month profile of flight delay data at the case organisation. This database has supported a subsequent analysis process by which relevant statistical information has been determined, such as distribution profiles of flight delays, average percentages of flights delayed and average minutes per flight delay. This information has been filtered by airport location in order to study the patterns of flight delays that are specific to flight operations at Airlink's main base at OR Tambo International Airport (ORTIA). For further information relating to this analysis, refer to Subsection 3.6.

3.5 Procedure for Data Collection

Due to the multitude of data sources that have been used in this case-based study, a number of procedural issues relating to data collection have been identified. These issues are discussed sequentially in the bulleted paragraphs below:

- A total of four formal interviews have been completed in support of this study. This total comprises two separate one-on-one interviews for each of the structured interview formats that are detailed in Appendix D. To assist in maintaining businesslike and professional interactions in the data collection process, each interview has taken place in a workplace meeting area at the case organisation. Furthermore, in order to ensure the highest levels of accuracy in presenting interview transcripts, all interviews have been recorded. Transcripts for each of these interviews are presented in Appendix F.

- In establishing a standard time for each STLM event in the case setting, accomplishment times have been measured according to the aircraft type being serviced (e.g. J41) and the maintenance event in work (e.g. a pre-flight check). On this basis, a total of nine distinct work scopes for STLM events have been identified and subjected to measurement in the case setting, covering the pre-flight check, the transit check and the after-flight check on each of the three aircraft types operated by Airlink. At least 10 on-the-job measurements have been taken of the time needed to accomplish each of these maintenance checks. In this regard, 116 individual task measurements have been taken in support of this study. Records of these measurements are presented in Appendix G. To ensure consistency and to minimise the likelihood of sampling error, a number of stipulations have been applied in the collection of these measurements. Firstly, all measurements have been taken in the workplace environment during the course of routine work activities. Secondly, a formal checklist has been followed for each affected work scope. Thirdly, the measurements have been taken across a number of Airlink station locations, observing different shift teams and work groups at varying times of day. The measurements have also covered multiple AMEs employed within the line maintenance function. In this regard, it was predetermined that the set of 90+ measurements shall be split over a minimum of six observation shifts, covering at least three operational maintenance stations, with no more than 20 individual measurements to be taken per shift. It was also predetermined that the measurement set shall encompass measurements from at least 20 individual technicians. Information on the determination of maintenance event standard times from the measured data is provided in Subsection 3.6.

- In total, four sources of archival records and two physical artefacts have been accessed in the case setting for data collection purposes. In each of these instances, the resulting secondary data has been included in an appendix to this study as a minimum requirement. Details have also been provided of each individual data source that has been accessed (e.g. an electronic data archive) in order to ensure adequate traceability of the affected records or artefact for verification purposes. Refer to Appendix H for further information on these sources and the associated secondary data.

3.6 Data Analysis and Interpretation

The following subsection considers pertinent issues that relate to the analysis and interpretation of data that has been gathered in support of this study. For ease of reference, these issues have been discussed according to the research question to which they apply.

3.6.1 Data Analysis and Interpretation in Relation to Research Question 1

Two significant data analysis issues have been identified with respect to Research Question 1. The first of these issues relates to the analysis of the observations that have been made of task accomplishment times for STLM events in order to establish standard times for these events. The second issue relates to the performance benchmarking of the case organisation's existing model for STLM labour scheduling against the experimental model that has been implemented in the case setting to optimise this scheduling process.

In establishing standard times for the nine applicable STLM events in the case setting, a number of statistical analysis outputs have been developed from the task time measurements that have been taken (refer to Appendix G). These statistical outputs include mean and median values of the task accomplishment time per STLM event, as well as a table of ascending percentile rank values of the task accomplishment time per event (in multiples of 10%). Of these outputs, the standard time measure that has been selected for use in the experimental model is an 80th percentile rank value for each set of task time measurements, rounded up to the nearest multiple of five minutes. In this way, the experimental model caters for the majority of the AMEs at the case organisation, including technicians whose pace of work is moderately slower than the median value for each maintenance event. For AMEs registering in the slowest 20% of task time measurements for a given STLM event type, it is expected that these AMEs will be subjected to remedial actions to improve their job efficiency to at least meet the established standard time for each affected event.

In comparing the existing and experimental STLM labour scheduling models in the case setting in response to Research Question 1, the main focus has been to compare the direct labour costs that are derived from each model. In this regard, the output personnel schedule from each model supplies a given quantity of AME manhours to the STLM function over the duration of each shift cycle. This quantity of manhours has been multiplied by an average hourly wage rate for AME duty time in order to determine an estimated direct labour cost per cycle for each model. Note that this average wage rate has been specified by the Human Resources Department at the case organisation based on recent pay records for the AMEs it employs. By applying a common cycle length for the two personnel schedules it has been possible to compare the direct labour costs associated to each schedule on a like-for-like basis. Note that a common cycle length can be achieved even where different cycle lengths are in effect by applying the lowest common multiple of the respective cycle lengths for the affected schedules.

In addition to direct labour costs, it is also of relevance to compare the overhead costs that have been incurred in constructing the two personnel scheduling models in the case setting. However, these costs have not been specifically quantified in this study. Instead, they have been discussed from a qualitative perspective only based on the interview data that has been collected and the mathematical modelling work that has been implemented by the researcher.

Another labour scheduling performance factor that has been considered in this study is the level of coverage that is provided by the two labour scheduling models in relation to the prevailing demand for STLM services in the case setting. The experimental model that has been implemented in this setting has been specifically designed (through appropriate constraints) to ensure that sufficient staff coverage is provided for the input service demand under the ideal assumption that demand levels are fixed. The coverage provided by this experimental model has thus been confirmed to be adequate through quantitative means in relation to Research Question 1. On the other hand, the adequacy of the staff coverage provided by the case organisation's existing labour scheduling model has not been verified quantitatively in this study. Instead, this factor has been considered from a qualitative viewpoint only through the series of interview questions that have been posed to the managers responsible for line maintenance operations in the case setting.

3.6.2 Data Analysis and Interpretation in Relation to Research Question 2

Two application areas have been identified where issues of data analysis and interpretation are of significance in relation to Research Question 2. The first of these areas relates to the use of the archival data that has been collected in the study to simulate profiles of flight delay occurrences in the case setting. The second area relates to the assessment of the coverage that is provided by the computationally-optimised personnel roster in the case setting where this roster is subjected to unplanned task demand variations based on realistic patterns of airline schedule disruptions.

Expanding on the information presented in Subsection 3.2.3, a key issue that has been considered in this study is whether incidences of flight delays at the case organisation can be modelled to a sufficient level of accuracy using probabilistic methods. In this regard, it has been noted that delay events are generally uncertain in nature and must therefore be reproduced directly from historical flight operations records unless they can be modelled probabilistically in a simulation environment. As a result, a statistical analysis has been carried out on the flight delay occurrences recorded at the case organisation over the six month period from 01 January 2011 to 30 June 2011. In order to conduct this analysis, the affected flight delay records have been aggregated by operational day according to: (1) the percentage of Airlink flights into and out of Airlink's main base at OR Tambo International Airport that were delayed and (2) the sum of the delay durations (in minutes) for these inbound and outbound flights beyond their scheduled times of arrival or departure, as applicable. The data for these variables has been presented in the form of histograms which have then been compared against a selection of equivalent theoretical distributions based on their associated probability density functions. An R^2 value has been used to provide a quantitative measure of the level of correlation between these histograms and the various theoretical distributions to which each has been compared.

With reference to the preceding paragraph, the probability density functions of six different theoretical distribution profiles have been compared against the histograms produced from flight delay records in the case setting. These distributions are the Normal, Poisson, Exponential, Weibull, Gamma and Lognormal distributions respectively. These distributions have been selected based on the literature discussed in Subsection 2.3.4 of the study. Initially, these theoretical distributions have been fitted using equivalent parameter values to the collected case data in terms of their mean, variance and standard deviation. However, in keeping with the work of Mueller and Chatterji (2002), the theoretical distributions have then been modified using a least squares method to give the best possible fit to the collected data. In this respect, Excel Solver has been used to find the optimal values of the modelling parameters for each theoretical distribution that minimises the sum of the squared difference between the theoretical and real-life data profiles across a predetermined set of measurement points.

In order to provide a consolidated representation of the daily flight delay characteristics in the case setting, the template depicted in Table 3 has been used. This template uses a 2-dimensional map to depict both of the flight delay measurement variables from the histogram profiles. The 2-D map format enables the reader to quickly establish the regularity with which a given level of delayed flights and associated total delay minutes is likely to occur within the case setting over the course of any given day-of-operations. In turn, the 2-D maps have been used as an analysis tool to quantify the likely regularity of labour coverage violations during STLM operations that may occur under disrupted flight schedule conditions. These issues are discussed in greater detail in the text that follows Table 3.

Table 3 – Classification Table for Inbound (or Outbound) Flight Delays per Operational Day

		% of Inbound (Outbound) Flights to the Main Base Delayed per Operational Day								
		0-10 %	10-20 %	20-30 %	30-40 %	40-50 %	50-60 %	60-70 %	70-80 %	80-100 %
Total Delay Minutes of Inbound (Outbound) Delays per Operational Day	0-50									
	51-100									
	101-150									
	151-200									
	201-250									
	251-300									
	301-350									
	351-400									
	401-500									
	501-600									
	601-700									
	701-800									
	801-900									
	901-1000									
	1001-1200									
	1201-1400									
	1401-1600									
	1601-1800									
	1801+									

As discussed in Subsection 3.2.3, the sensitivity tests that have been conducted in this study have assessed the robustness of the staff coverage that is provided by the experimental STLM labour planning model that has been implemented in the case setting. This has been done by testing the ability of the output staff roster from this model to provide sufficient staff coverage where the profile of STLM tasks that must be carried out is varied as a result of disruptions to the input flight schedule. The profiles of schedule disruptions that have been used to conduct these sensitivity tests have been developed based on actual flight schedule disruptions and associated operational recovery plans that were recorded at the case organisation over a 20 day period from 01 to 20 June 2011. The variations associated to these disruptions have been introduced into the STLM labour scheduling model as shown in Figure 2 in Subsection 3.4.1.

It is evident from Figure 2 that task demand variations relating to flight schedule disruptions have been introduced into the experimental labour scheduling model between Modelling Steps 1 and 2. In this way, these variations have been unable to influence the predetermined staffing levels that are called out by the duty roster, as would be consistent with a real-life labour planning scenario. However, they have been able to influence the final allocation of tasks to on-duty members of the rostered workforce as unplanned schedule changes have come into being during the course of the day-of-operations under consideration. Where unplanned variations in the timing or scope of STLM tasks have been introduced, the labour scheduling model has attempted to assign the latest list of tasks for the day to the available workforce within the updated time windows for these events depending on the nature of inbound flight delays and other disruptions (e.g. aircraft breakdowns) that are prevalent. If applicable, the model has highlighted any labour coverage violations in the task assignment process as so-called 'missed maintenance events' (MMEs). MMEs have been identified where the optimised labour roster based on an undisrupted flight schedule has been shown to have insufficient on-duty resources to attend to a planned or unplanned STLM check within its adjusted time window under disrupted flight schedule conditions.

The robustness of the experimental labour scheduling model under such disrupted flight schedule conditions has been analysed by reviewing the trigger levels at which MMEs have been induced in the task assignment process of the computational model. These trigger levels have been gauged according to the levels of contributing schedule disruptions on the day, whether on inbound or outbound flight legs, as well as the sum of associated delay minutes. Wherever a MME has been shown to have occurred, an assessment has been made in terms of three possible outcomes or responses as follows:

- The affected task can be carried out at a later time of day as soon as the required labour resources become available. If this response is implemented, the MME effectively induces a departure delay into the operating schedule of the airline. The duration of this induced delay is an important performance measure, as is the potential knock-on effect of the delay if the series of flights for the affected aircraft includes further arrivals at the base station later in the day.

- The task can be carried out at as close as possible to its required time window by calling out additional labour resources to support the workforce members already on duty. If this response is implemented, key measures include the costs of instituting a callout as well as the response time to such a callout.

- Where a MME has occurred due to an inbound flight being delayed to the extent that a STLM check can only be implemented partly or wholly beyond the finish time of the latest working shift for the day, the affected task can be completed by allocating one or more members of the on-duty labour force to work reasonable periods of overtime. In this case, the cost of overtime worked and the potential knock-on effect of subsequent rest periods for the personnel that are assigned to work this overtime are the key performance factors that must be considered.

The occurrence of MMEs as a result of flight schedule disruptions in the case setting has therefore been reduced to a common measure in terms of the additional operating costs that are associated to induced delays, overtime hours worked or additional labour resources called out to duty. In this regard, the delay costs, overtime rates and callout rates detailed in Appendix E have been applied. The likely frequency of MMEs during ongoing operations has also been evaluated by comparing the levels of delayed flights and associated delay minutes on days in which MMEs occurred within the robustness testing period against the wider six month profile of flight delay data that has been collected in the case setting. Additional costs relating to MME occurrences have then been estimated and added to the baseline labour costs determined for the experimental staff scheduling model under ideal conditions (i.e. no flight schedule disruptions). Summing these costs provides a more holistic measure for comparing the total staffing costs associated to the experimental model against the staffing costs attributable to STLM activities in the case organisation's current line maintenance labour planning model.

3.7 Limitations of the Study

There is an important limitation in this study in that the research design that has been implemented is based on a single case organisation. In this regard, the experimental labour scheduling model that has been developed employs a number of modelling constraints that are specific to operations at the case organisation. It is possible that significant differences may exist in these constraints at other airlines and associated aircraft maintenance organisations. Furthermore, the analysis and profiling of flight delays that has been conducted in this study uses records extracted from a single regional airline company with its own unique operating environment, resource mix and strategy for service delivery. The use of a single case methodology limits the 'generalisability' of the research outcomes that have been achieved and thus hampers efforts to extend these outcomes readily to the operations of other airlines and their associated maintenance organisations or maintenance service providers. This issue is discussed further in Subsection 3.8.1.

Another limitation of the methodology that has been implemented in this study relates to the use of standard times in modelling STLM operations in the case setting. With reference to the set of task time measurements in Appendix G, it became apparent while recording these measurements that the affected STLM tasks were not being conducted in surroundings with high levels of process and environmental control such as would be likely for a workshop or a factory production line. Without sufficient levels of control in these areas, job times will tend to vary and the accuracy of using fixed standard times may become questionable. The following operating factors have been identified which tend to result in lower levels of process and environmental control in the case organisation's STLM activities:

- At its main base at ORTIA (airport code 'JNB'), STLM tasks are carried out over a wide area of operations that includes a significant portion of the airport parking apron as well as twin maintenance hangars with an adjacent concrete holding area. This spatial feature limits the capability of the case organisation to implement direct supervision of the STLM jobs that are in progress at any given time. As a result, supervisory oversight of these jobs is carried out predominantly by means of handheld radio communication.

- STLM tasks are carried out at different times of day and with significant differences in the quality of light that is available for inspection purposes, which can range anywhere from headlamp light to direct sunlight. Lighting quality can impact significantly on the time that is necessary to perform aircraft inspections and servicing actions in a satisfactory manner. Furthermore, differences in the times of day at which STLM tasks are performed can have significant productivity implications due to issues such as varying levels of alertness and fatigue amongst affected AMEs.

- STLM tasks are carried out in a variety of weather conditions, including the hottest days of summer and the coldest nights of winter. Where these tasks are carried out in the open, which is the case for the majority of STLM events, affected AMEs may also be exposed to adverse conditions such as high winds, rain, etc.

Based on the above factors, one would expect to see significant levels of variation in the task time measurements that have been taken to establish standard times for each STLM work scope that is carried out at the case organisation. This expectation has been borne out in the data sets that are presented in Appendix G. As a typical example, the time measurements that have been taken for the after-flight check work scope on the J41 aircraft type range from a minimum time of 35 minutes up to a maximum time of 90 minutes (i.e. 257.1% of the minimum time). The result of these high levels of variability is that reasonably conservative standard times have been used to model the case organisation's STLM operations. This issue may lead to the prediction of higher levels of AME inputs and associated manpower costs than are true in reality. In turn, this may impact negatively on the levels of labour scheduling optimisation that are deemed to be possible through the computational modelling methods that have been implemented.

3.8 Validity and Reliability

This subsection assesses the validity and reliability of the study according to three distinct aspects or concepts, namely 'external validity', 'internal validity' and 'reliability'. A description of each of these concepts, based on appropriate literature sources, has been included to assist the reader.

3.8.1 External Validity

As per Lynch (1982), researchers have developed three perspectives on external validity. One of the perspectives that Lynch highlights is that of statistical 'generalisability', where the main issue is whether the results from a study using a particular sampling approach can be generalised to the larger population of interest. The second perspective discussed by Lynch is that of the robustness of a relationship found in an experiment and whether this can be replicated with different subjects, research settings and time intervals. The third perspective is that of realism, which may also be referred to as 'ecological validity'. This perspective relates to whether the affected research study (tasks, stimuli, settings) was realistic and, therefore, whether the results of the study are likely to be generalisable to a more natural or realistic environment for the associated issue.

The case study method that has been applied in this study has employed operational records and on-the-job observations that have been extracted directly from the case airline and its associated maintenance organisation. Due to its use of operational data from an active airline environment to simulate the STLM labour scheduling problem at hand, the study has been deemed to have high levels of ecological validity. This assessment is consistent with the remarks of Voss *et al.* (2002), as referred to in Subsection 3.2.5, with regards to case research having high levels of validity as viewed by operations management practitioners.

On the issue of whether the results from the study can be generalised to the larger population of interest, there is a minor concern relating to the flight delay data that has been analysed. In this regard, the use of a six month sample of flight delay records from the case organisation may have excluded certain seasonal influences on flight delay occurrences. It is feasible that such influences could skew the flight delay sample to some degree with respect to the broader patterns of flight delays that are encountered at the case organisation over an entire year or multiple years of ongoing operations. Nevertheless, the flight delay data sample that has been collected is deemed to be sufficiently large to provide a reasonable basis for modelling patterns of flight delays for simulation purposes, irrespective of the time of year.

There is a much more significant concern in terms of the external validity of this study relating to whether the study outcomes can be reproduced to the same or similar levels in the operating environments of other airlines and their associated maintenance organisations. This concern is a typical feature of case-based research studies, as alluded to in the work of Voss *et al.* (2002) and Zainal (2007) that has been referenced in Subsection 3.2.5. In this regard, the use of various organisation-specific modelling constraints in the case setting, as well as the application of certain constraints based on South Africa's national regulatory requirements, has meant that the modelling results from this study may not be possible to replicate to comparable levels in similar maintenance operations in other organisational settings and regulatory jurisdictions. Of course, the study outcomes may be reinforced even more strongly when transferred to other organisational settings, but they may also be negated either partially or completely. Given that this is a typical limitation of case study research, its relevance has been carefully noted and has been used in determining the recommendations for further research to follow from this study.

3.8.2 Internal Validity

Winter (2000) describes internal validity as a measure of whether the findings or results of a given research study are causally related to the phenomena that are under investigation, and not to other influences that have not been accounted for. This author asserts that:

- Causality must be established for a test within a quantitative research environment to be valid and useful.

- Unwanted factors that influence test results cannot be fully isolated and stripped away as a general rule.

- A study that is determined to have a notable level of unaccounted for influences can be described as having low internal validity.

Looking specifically at simulation and modelling, Davis, Eisenhardt and Bingham (2007) highlight that simulation-based research is well suited to simple theory development due to its strengths in improving theoretical precision and related internal validity, as well as in enabling the elaboration and exploration of theories through computational experimentation. Furthermore, these authors assert that, while simulation relies on some theoretical understanding of the phenomena that are under investigation in order to construct a computational model, simulation also depends on an incomplete theoretical understanding such that additional theoretical insights are possible from the experimentation that this methodology enables. In summary, Davis *et al.* (2007) conclude that strengths of simulation-based research include internal validity and the ability of this methodology to deal with longitudinal, nonlinear and process phenomena. Furthermore, these authors point out that this methodology is best suited to emerging or new theory. In contrast, the authors point out that well-developed theories offer fewer opportunities for new theoretical insights using the logical precision and experimentation of simulation.

Considering the research work that has been carried out in this study, a series of computational simulation exercises have been implemented whereby sophisticated modelling concepts extracted from contemporary personnel scheduling literature have been adapted to the given case setting. These concepts have then been extended with the aim of improving the understanding of a known and previously unaccounted-for influence that is highlighted in the work of Belien *et al.* (2010), i.e. uncertainty in the timing and scope of maintenance workloads due to flight schedule disruptions. In this regard, the study has sought to either demonstrate the robustness of existing modelling concepts when faced with these uncertainties, or to provide insights into the further development of existing models to improve their robustness to such influences. As a result, and with reference to the writings of Davis *et al.* (2007), this study has sought to increase the internal validity of the modelling approaches on which it is based. Furthermore, due to its grounding in previous literature work, including that of authors such as Yang *et al.* (2003), Ip *et al.* (2010) and Belien *et al.* (2010), it is assumed that the causality of the computational model that has been implemented is already well established and does not need to be questioned in this study.

Another noteworthy factor that has been identified with respect to the internal validity of this study is the issue of researcher bias. Finn (2006) defines ‘bias’ in a research context as a phenomenon by which the findings of a given study are systematically distorted due to subjective influences. This factor has been identified as a potential concern in this study as the researcher is an employee of the case organisation and is currently posted in the area of maintenance operations management. As such, it has been deemed necessary to take steps to prevent the researcher’s subjective opinions from being reflected in the research outcomes. The principal area where steps have been taken in this regard is through the use of structured interviews with senior management personnel at the case organisation. These structured interviews have used predefined interview templates to review the existing method for STLM labour scheduling in the case setting as well as the constraints that have been applied in testing the experimental STLM labour planning model in this setting. The use of templates has discouraged any manipulation of the interview process and outcomes by the researcher. Furthermore, each interview has been conducted independently with two respondents from different levels of management within the case organisation’s maintenance division, thereby enabling the consistency of interview responses to be checked. Note that one senior manager and one executive manager have been interviewed in this regard. Apart from the interview data that has been collected, the remaining research data and the associated research outcomes are based on historical records, physical artefacts and numerical processes. These sources of data are non-subjective in nature and are thus not of concern with respect to researcher bias and its potential impact on internal validity.

3.8.3 Reliability

Kalof, Dan and Dietz (2008) offer a comparatively simple definition of the concept of reliability in a research context. These authors assert that research can be considered to be reliable if the findings are uncovered consistently in repeated applications of the research. Kirk and Miller (1986) offer a more detailed description of reliability that expands on the observations of Kalof, Dan and Dietz. In this regard, Kirk and Miller (1986: pp. 41-42) have identified the following three aspects of reliability that they deem to be applicable to quantitative research studies:

- “The degree to which a measurement, given repeatedly, remains the same”.
- “The stability of a measurement over time”.
- “The similarity of measurements within a given time period”.

Looking at the design of this study, reliability issues within the bounds of the study itself are of relatively low importance. This is because the use of a computational model as the predominant research instrument supports high levels of repeatability of the results for the given case. The one potential area of concern in this regard is where the study has made use of ‘quasi-optimisation’ processes in order to reduce associated computation times. In this regard, it is possible that the quasi-optimisation processes that have been implemented may produce inconsistent results if repeated iterations are performed. The one other area of concern with regards to reliability within the bounds of the study relates to the data collection process whereby standard times have been established for the STLM tasks that are executed in the case setting. As discussed in Subsection 3.7, the on-the-job measurements that have been taken for this purpose have been shown to exhibit high levels of variability between data points due to inherent operational and environmental factors such as changes in the quality of lighting by time of day. This variability may in turn lead to differences in the standard times that are established if repeated sampling attempts are made.

With reference to the work of Kalof *et al.* (2008), the most important issue that has been identified with regards to the reliability of this study is whether the findings at the case organisation will be repeatable in further applications of this research. In this regard, further applications would involve extending this research to other airlines and their associated maintenance organisations, each with their own specific modelling constraints, resource controls and operating environments. This issue has already been addressed under Subsections 3.7 and 3.8.1 and is a general limitation of the case study method that has been employed.

4 Research Results and Discussion

This section describes how the results of the study have been developed and also presents these results according to the associated research question. Thereafter, the results are scrutinised and reduced to research findings. Finally, recommendations are given for future research to develop on the outcomes that have been achieved.

4.1 Results in Relation to Research Question 1

In developing results with respect to Research Question 1, the primary focus has been to critically compare the existing model for STLM labour scheduling that is used in the case setting against the experimental crew scheduling model that has been implemented in this setting as a means of optimising the output labour roster for STLM activities. In doing so, the study has addressed the following issues:

- Firstly, an analysis has been presented of the current labour scheduling model that is used within the case organisation to determine its AME staffing requirements across all facets of the line maintenance function. This analysis includes a concise description of the existing model and its associated characteristics and assumptions as determined from formal and informal interviewing in the case setting. It also includes a description of the output staffing levels that have been determined using this model. In addition, calculations have been performed and presented to determine the portion of the total line maintenance AME compliment that is effectively dedicated to STLM activities.

- Secondly, a concise overview has been provided of the computationally-optimised STLM labour roster that has been developed for the case organisation in an MS Excel simulation environment. This overview shows how the underlying labour scheduling model has been refined from its basic form as shown in Equation 1 in Subsection 3.4.1 according to the set of constraints listed in Appendix E. It also lists the additional assumptions that have been applied in order to limit the model outputs to a realistic number of solutions for optimisation purposes. Thereafter, the optimisation capabilities of the computational model have been analysed in detail and its output, i.e. the optimised personnel roster, has been presented.

- Thirdly, a comparison has been made of the total labour costs that are attributable to the personnel rosters that emanate from the two contrasting labour scheduling models. These costs have been calculated on the basis of hourly wages for AME labour. The comparison includes a justification of the respective wage rates that have been applied.

4.1.1 Analysis of the Current Labour Scheduling Model for the Case Organisation's Line Maintenance Function

4.1.1.1 Description of the Current Shift or Duty Cycle

Airlink's maintenance division does not currently address the STLM requirements of the company's airline operation through a dedicated STLM team or work group. Instead, the Line Maintenance Department of this division operates 24 hours a day and 7 days a week in order to cover all line maintenance requirements of the airline up to A-check level. This coverage includes all requirements for STLM maintenance checks (i.e. all pre-flight, transit and after-flight checks) on company aircraft. Most of these line maintenance services are delivered at the main base of Airlink's maintenance division at OR Tambo International Airport in Johannesburg. However, the division does also perform line maintenance services from a number of satellite maintenance stations at the likes of Cape Town International Airport and King Shaka International Airport in Durban. It must be remembered that this study only considers the main base operations of Airlink's Line Maintenance Department.

The Line Maintenance Department at Airlink's main maintenance base is currently manned by two dedicated shift teams that work 12 hours per duty day. For operational simplicity, each shift team works an equal allocation of on-duty and off-duty days in an alternating shift roster rotation. In this way, the roster provides an equal number of on-duty line maintenance AMEs on any day of the year, irrespective of weekends or public holidays. The two shift teams are called the Yellow Shift and the Green Shift for reference purposes. Prior to 2012, the shift teams alternated in a simple duty cycle of four days on followed by four days off. However, in the early stages of 2012 an agreement was reached to introduce a more elaborate alternating duty cycle as follows: five days on, five days off, four days on, five days off, five days on, four days off. This more elaborate duty cycle has two significant advantages over the previous four days on, four days off cycle, as follows:

- Shift workers have two long weekends off in any four week period, including off-duty days on both Saturday and Sunday. This improves the family and social life of shift workers over the previous duty cycle. Under the previous duty cycle, a shift worker could have as many as five consecutive weeks without a full weekend off depending on the position of the duty cycle in relation to the normal calendar week.

- The latest duty cycle can be synchronised to increment with the normal calendar week once every 28 days, while the previous duty cycle could only be synchronised in this fashion once every 56 days. This characteristic provides greater flexibility in facilitating the movement of personnel between the shift rotation and regular weekday postings.

The Yellow Shift and Green Shift teams are subdivided on a rotational basis into two work groups. The first work group is a day shift team whose rostered hours of work are 06:00 to 18:00, while the second work group is a night shift team whose rostered hours of work are 18:00 to 06:00. In this way, the shift roster covers 24 hours of the day in addition to its 365 days-a-year coverage. It should be noted that the day shift team is considerably smaller than the night shift team as the line maintenance function at Airlink focuses predominantly on implementing aircraft servicing and repair actions overnight after the completion of daily flight operations. Furthermore, there is no dedicated standby system under the current rostering methodology. Table 4 shows an illustration of the current line maintenance duty cycle. For a description of the shift roster notation that has been used, refer to Appendix C.

Table 4 – Description of the Duty Cycle and Work Group Structure that is Currently Applied within the Line Maintenance Department of Airlink's Maintenance Division

The shift roster employs a 28-day cycle length composed of 2 x 14-day shift blocks (O = a day with a rostered duty shift):

O	O	O	O	O						O	O	O	O	<< Shift Block 1
					O	O	O	O	O					<< Shift Block 2

Expanding the above shorthand roster notation to show 1 x 28-day cycle rotation for the two affected shift teams:
>> each shift team is subdivided into 1 x day shift work group (D) and 1 x night shift work group (N)

Yellow Shift	D	D	D	D	D						D	D	D	D						D	D	D	D	D				
	N	N	N	N	N						N	N	N	N						N	N	N	N	N				
Green Shift						D	D	D	D	D					D	D	D	D	D						D	D	D	D
						N	N	N	N	N					N	N	N	N	N						N	N	N	N
	Week 1							Week 2							Week 3							Week 4						

4.1.1.2 Line Maintenance Resource Levels Based on the Current Labour Scheduling Model

The numbers of AMEs that are assigned to the two shift teams described in Subsection 4.1.1.1 have been determined according to the labour scheduling model titled '*Airlink Line Maintenance Labour Scheduling Model (Updated 2012).xlsx*'. This model has been included in Appendix H of the study for reference purposes. The basic premise of this fairly simple computational model is to calculate the quantity of direct maintenance manhours that must be supplied in order for the case organisation's line maintenance function to be able to execute a range of common and predictable line maintenance tasks by aircraft type and quantity of aircraft serviced. These common tasks are generally called out at intervals that are defined either in calendar time, flight hours or flight cycles. As such, the model takes into account a budgeted or assumed flight operations profile for the fleet of aircraft being serviced. Thereafter, the model provides for less predictable or supplementary maintenance inputs by adding extra manhours to the supply requirements according to a ratio of 'unplanned or miscellaneous maintenance manhours per aircraft flight hour' flown. This ratio can be varied in the model according to user preferences with regards to maintenance service levels.

From the resulting sum of manhours, the computational model determines the AME compliment that is needed to deliver the required manhour supply over a 28 day cycle. This is determined by applying an assumed labour efficiency rate and an average number of manhours worked per AME per day based on the duty specifications of the associated AME staff roster. It should be noted that the computational model does not influence the shift cycle pattern used in this staff roster in any way. Instead, the shift cycle pattern is taken as a fixed input to the model and is the basis from which the average number of manhours worked per AME per day is determined.

Including the shift roster input, the following list of assumptions is applied by Airlink's maintenance division in its existing labour planning model for line maintenance:

- Line maintenance AMEs work 168 hours per 28 day cycle, based on 12 hours of work per rostered day and an equal number of on-duty and off-duty days over a 28 day cycle. AME leave days and training days are excluded from consideration in the model.

- Line maintenance AMEs are 70% efficient in converting hours worked to direct manhours applied to aircraft maintenance activities.

- A service level of 1 manhour of unplanned or miscellaneous aircraft maintenance per flight hour flown must be supplied to support efficient flight operations at the parent airline.

- All after-flight checks are undertaken by the night shift work group, while the day shift group focuses on performing pre-flight and transit checks in support of ongoing flight operations during its rostered hours of work. Under this assumption, the day shift work group ensures that all significant line maintenance requirements beyond the scope of pre-flight and transit checks are deferred to the night shift group when there is more time to adequately plan and implement fault tracing procedures as well as planned or unplanned maintenance actions.

- Satellite line maintenance stations within the Airlink network of operating stations do not contribute significantly to maintenance beyond the level of aircraft STLM checks. For any aircraft operating away from main base, it is thus assumed that all planned and unplanned line maintenance beyond the scope of routine pre-flight, transit and after-flight checks shall be deferred to the main base line maintenance function. This shall be achieved using callout support if needed and by regularly routing affected aircraft via the main base.

Table 5 shows summarised results of the most recent iteration of Airlink's current line maintenance labour planning model. According to this table, Airlink has determined that an AME compliment of approximately 59 is needed, including four Crew Chiefs at a supervisory level, to deliver its most common and predictable line maintenance items whilst providing for one additional manhour per aircraft flight hour flown for unplanned and miscellaneous maintenance items. Due to its system of two shift teams within the line maintenance function, Airlink has rounded this figure up to the nearest even number of 60. As such, the organisation has allocated a total of 30 AME posts to each of its shift teams, i.e. the Yellow and Green Shifts, including two Crew Chiefs per shift team.

Table 5 – Outputs of the Current Line Maintenance Labour Planning Model Used at the Case Organisation's Main Base

Aircraft Fleet Operational Profile: Based on Aircraft Utilisation Data from 01 July 2011 to 31 December 2011						
Aircraft Type	**Across 6 Month Period**		**Average Per Day**		**Average Per 28 Days (1 Shift Cycle)**	
	Hrs Flown	**Flights Flown**	**Hrs Flown**	**Flights Flown**	**Hrs Flown**	**Flights Flown**
J41	5,623	5,847	30.73	31.95	860	895
ERJ135	7,697	8,042	42.06	43.95	1,178	1,230
BAE146-RJ85	5,521	3,931	30.17	21.48	845	601

Aircraft Type	**Estimated Direct Manhrs per 28 Day Cycle for Common and Routine Line Maintenance Tasks**	**Total Direct Manhrs per 28 Day Shift Cycle for All Line Maintenance Tasks** << Includes a Variable Component of Unplanned and Miscellaneous Manhrs per Flight Hour as Tabled Below >> << 70% Labour Efficiency Factor is Applied >>				
		0.0	**0.5**	**1.0**	**1.5**	**2.0**
J41	678	969	1,583	2,198	2,812	3,427
ERJ135	708	1,011	1,852	2,693	3,534	4,376
BAE146-RJ85	1,022	1,460	2,063	2,666	3,270	3,873
Total Night Shift Manhours Estimated		**3,439**	**5,498**	**7,557**	**9,617**	**11,676**
# of Night Shift AMEs		**21**	**33**	**45**	**58**	**70**
Subtotal # of AMEs (Add 10 x Day Shift AMEs)		**31**	**43**	**55**	**68**	**80**
Total # of AMEs (Add 4 x Crew Chiefs)		**35**	**47**	**59**	**72**	**84**

Notes:

- The day shift work groups incorporate a total of 10 x AMEs (five per shift team).
- Crew Chiefs (two per shift team) are assumed to perform a supervisory and coordination role only and do not apply direct manhours to maintenance tasks.
- Each line maintenance AME is assumed to work 168 manhrs per 28 day shift cycle at a 70% efficiency factor (i.e. 117.6 direct manhours contributed per AME per 28 day shift cycle).
- Absenteeism, leave and training downtime for AMEs is not included in this model.
- For details on the calculation of maintenance manhours for common and routine line maintenance tasks by aircraft type, refer to the MS Excel file titled '*Airlink Line Maintenance Labour Scheduling Model (Updated 2012).xlsx*' as referenced in Appendix H.

Expanding on the information in Table 5, each shift team at the case organisation is manned by a compliment of 21 x Category A & C AMEs and 7 x Category W AMEs, giving a total of 28 AMEs engaged in direct maintenance activities on company aircraft. These AMEs are supervised and coordinated by two Crew Chiefs. In addition, each shift team incorporates a number of ancillary staff posts, such as an aircraft interior finishes specialist and a crew of aircraft tug drivers, although these staff members are not considered in this study. Of the total compliment of AMEs and Crew Chiefs (excluding ancillary technical personnel), 4 x Category A & C AMEs, 1 x Category W AME and 1 x Crew Chief are allocated to the day shift work group on any given sequence of on-duty days, with the remainder of the on-duty staff compliment being assigned to night duties.

Looking at the reality of the current roster system against the assumptions that have been applied, the primary responsibility of the day shift work group is to perform aircraft transit checks and to respond to unscheduled aircraft breakdowns and technical issues that manifest during day shift working hours. Due to timing constraints based on a 06:00 start time, the day shift work group only performs a limited number of pre-flight checks for later departures that fall after about 07:00 in the morning. Furthermore, this work group does not generally perform any after-flight checks, with the predominant exception of Saturday and Sunday afternoons where it may assist the night shift work group by completing some after-flight checks before 18:00 in the evening. This potential for a day shift input to after-flight maintenance on weekend afternoons comes about due to Airlink's significantly reduced weekend flying schedule compared to normal office days. As a result, the day shift work group is able to assign spare labour capacity to performing after-flight checks on aircraft that complete their daily flight sequences by around 16:30 or earlier on these afternoons.

4.1.2 Implementation of an Experimental STLM Labour Scheduling Model that Employs Computational Optimisation at the Case Organisation

4.1.2.1 Separating the Case Organisation's Broader Line Maintenance Function into a First Line Maintenance Team and a Short Visit Maintenance Team

The research works of Yang *et al.* (2003), Belien *et al.* (2010) and Ip *et al.* (2010) all focus on the optimisation of labour supplies for airline STLM activities where these activities are considered to be a standalone component of the broader line maintenance function. These authors have thus separated STLM activities from other aspects of line maintenance operations (e.g. A-checks) for the purposes of personnel rostering. In order to adapt the optimisation techniques used by these authors to the problem of personnel scheduling for this specific class of line maintenance activity in the case setting, it has been necessary to first separate the line maintenance workforce at Airlink's main base into the following two distinct components:

a) **First Line Maintenance (FLM) Team:**

   This maintenance team is assigned exclusively to meeting the STLM demands of the airline and is thus rostered according to the task demand profile and timing of STLM workloads that are called out by the airline's operating schedule. The AMEs in the FLM Team shall only address minor aircraft defect rectifications and planned maintenance or servicing tasks that fall within the scope and standard time allowances of the STLM checks that they undertake (e.g. re-lamping non-functional cockpit lights, servicing engine oil levels or inspecting wheel assemblies for adequate tyre condition).

b) **Short Visit Maintenance (SVM) Team:**

This maintenance team meets all the line maintenance needs of the airline that are beyond the scope of routine pre-flight, transit and after-flight checks, up to and including A-checks. Where a significant aircraft defect is identified during the course of STLM operations, the fault tracing (if applicable) and rectification actions needed to remedy the defect shall be handed over to the SVM Team by the FLM Team.

By establishing an experimental FLM Team under simulation conditions in the case setting, it has been possible to apply computational modelling techniques to optimise the task efficiency of the AMEs that are incorporated within this team. The aim of these modelling processes has been to minimise the quantity of AMEs, or associated AME manhours, that must be supplied to adequately cover the STLM needs of the operation without compromising on the quality of the maintenance service that is provided. The remaining parts of Subsection 4.1.2 focus on the simulation data that has been generated in this regard. This data has enabled a quantitative assessment to be made of the capability of modern computational optimisation methods to reduce the total labour inputs for line maintenance activities at the case organisation.

4.1.2.2 Mapping of a Representative Flight Schedule and Associated STLM Requirements in the Case Setting

The first step that has been undertaken in establishing a data set with which to model the labour requirements of an experimental FLM Team is the mapping of the case organisation's published flight schedule. This mapping exercise has been performed in order to determine the profile of planned flights and associated departure and arrival times that control the quantity and timing of STLM checks that are called out in the case setting. In this regard, a representative week of operations has been mapped based on the planned flight schedule that Airlink published for the period ranging from Monday the 05th to Sunday the 11th of September 2011. This week of flight schedule data has been used to generate the listing of aircraft movements and associated STLM checks at Airlink's main maintenance base as shown in Spreadsheet 1 in Appendix I. A summary of this schedule information by weekday is presented in Table 6. For reference purposes, copies of the original schedule tables that were published by Airlink's OCC for this date range have been included in Appendix H. Refer to the file titled '*Day-of-Ops Schedule, 05 to 11 Sep 2011.pdf*' in this regard.

Table 6 – Summary of the Planned Flight Movements and STLM Check Requirements at Airlink's Main Base for the Period 05 to 11 September 2011

Weekday	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Earliest Departure / Arrival Event	6:15	6:15	6:15	6:15	6:15	6:35	9:00
Latest Departure / Arrival Event	20:35	20:35	20:35	20:35	20:35	17:40	20:35
Time Window >> Earliest to Latest Departure / Arrival	14:20	14:20	14:20	14:20	14:20	11:05	11:35
Number of Pre-Flight Checks Called Out	15	14	13	14	15	11	14
Number of Transit Checks Called Out	23	23	25	26	26	9	12
Number of After-Flight Checks Called Out	15	14	13	13	14	12	14
Total Number of Short-Term Layover Maintenance Checks Called Out	53	51	51	53	55	32	40

4.1.2.3 Supplementary Discussion Points for the Refinement of the Computational Model

At this point of the research report, the planned flight schedule at the case organisation's main maintenance base has been suitably mapped over a representative week of flight operations and the associated demand triggers for the various categories of STLM tasks have been specified. In addition, the generic structure of the labour force optimisation model that has been used to build a staff roster to meet this STLM demand has been presented (see Equation 1 in Subsection 3.4.1) along with supporting modelling constraints. It is now possible to update Equation 1 by inserting a relevant set of case-specific parameters and constraints to enable the model to be resolved to useful quantitative outputs. Before doing so, however, some final discussion points are presented in Table 7 that supplement the assumptions listed in Subsection 1.7 and the modelling constraints described in Appendix E. It should be noted that the information in Table 7 is in a summary format and each discussion point is described more fully in Appendix J.

Table 7 – Summarised Descriptions of the Supplementary Discussion Points for Refining the Computational Model

#	Description of Discussion Point
1	Airlink's maintenance division has implemented an internal procedure that allows for a Category A and C LAME with a rating on any aircraft type to be granted limited certification powers, referred to as 'limited line release', on one or more Airlink aircraft types subject to completing a basic systems overview and maintenance course per type. The requirements for a 'limited line release' authorisation are significantly less onerous than the on-type training and experience requirements specified for full line release certification.
2	Following on from Point 1, a valuable characteristic of the limited line release approval is that it allows the holder to perform and certify all of the STLM checks on a given aircraft type. It has been assumed in this study that all AMEs on the FLM Team are Category A and C license holders on at least one aircraft (and engine) type and have been trained and authorised to the level of at least limited line release approval on all three Airlink aircraft types.

Table 7 – Summarised Descriptions of the Supplementary Discussion Points for Refining the Computational Model (Continued)

#	Description of Discussion Point
3	Standard times for the nine distinct STLM events that are applicable in the case setting have been established as shown in Table 8. Each standard time is based on an 80th percentile rank value of the associated on-the-job time measurements, rounded up to the nearest multiple of five minutes.
4	Where more than one AME is assigned to a given STLM task, it has been assumed that the time for the task to be completed is determined by dividing the standard time for the task by the number of AMEs assigned to it and then rounding up to the nearest multiple of five minutes.
5	It has been assumed that on-duty AMEs on the FLM Team can transit between any two work locations at the main base for successive STLM tasks within a time window of five minutes.
6	AME meal and tea break times have not been modelled as hard constraints in the labour optimisation model. Where required, manual adjustments have been made to ensure the provision of adequate break periods at convenient times based on the work demands of the day.
7	In quantifying the study results, it has been assumed that each AME employed within the Airlink Line Maintenance Department earns a fixed and equal hourly wage. In addition, the study has also considered the implications of paying a fixed and equal monthly salary per AME.
8	The nature of the present line maintenance duty cycle at the case organisation is such that each shift team shall be rostered to work two duty shifts on each day of the week (i.e. Monday through Sunday) in any four week period. By retaining this duty cycle in the labour optimisation model, each shift team has had to be allocated an equal quantity of AMEs. In addition, the staff allocation per shift team has had to provide sufficient personnel coverage to meet the worst-case maintenance demand condition on any weekday. This characteristic may result in sub-optimal labour allocations on weekdays of lower STLM demands.
9	To mitigate the potential for inefficiencies relating to the preceding point, it has been assumed that the AMEs rostered for duty on the FLM Team can support the SVM Team, or even heavy maintenance teams, during periods of idle time in their working schedule of 90 minutes or longer. Furthermore, any on-duty AME from the FLM Team that is deemed to be surplus to requirements on a given workday can be allocated to work on the SVM Team for the full duration of the affected shift.

Table 8 – Standard Times in Manminutes for STLM Events at the Case Organisation as Determined by Observation and Supporting Statistical Analysis

Aircraft Type	Event	No. of Time Measurements	Statistical Data for Event Accomplishment Time (in Manminutes)			
			Average	Median	80th %ile	80th %ile (Rounded)
J41	After-Flight Check	10	69.6	82.5	85	**85**
J41	Pre-Flight Check	10	21.3	20.0	25	**25**
J41	Transit Check	14	15.1	15.0	20	**20**
ERJ135	After-Flight Check	10	86.7	90.0	103	**105**
ERJ135	Pre-Flight Check	11	23.3	20.0	20	**20**
ERJ135	Transit Check	30	13.2	12.0	15	**15**
RJ85	After-Flight Check	10	100.7	102.5	110	**110**
RJ85	Pre-Flight Check	11	34.8	35.0	45	**45**
RJ85	Transit Check	10	13.3	14.5	15	**15**

4.1.2.4 *Refinement of the Basic Computational Model to a Practical Working Model Adapted to the Case Organisation*

Based on the set of modelling constraints and assumptions that has been presented, the generic mathematical model in Equation 1 (see Subsection 3.4.1) has been refined to a practical working model specific to the case organisation as shown in Equation 2 below:

$$TC = \sum_{c\in C} \sum_{s\in S} \sum_{d\in D} M_{sc} \times W_{scd} \times z_{scd}$$

$$TC = \sum_{c\in C} \sum_{s\in S} \sum_{d\in D} M_{sc} \times H_{scd} \times D_{scd} \times z_{scd}$$

$$TC = H \times \sum_{c=1}^{2} \sum_{s\in S} \sum_{d=1}^{28} M_{sc} \times D_{scd} \times z_{scd} \qquad (2)$$

The following parameter descriptions and values are applicable to Equation 2 on the basis of the modelling constraints that have been established:

- H is a constant hourly wage rate per AME
- d = 1 to 28 depending on the day within the 28-day cycle
- c = 1 or 2 for the two shift groups (i.e. the Yellow Shift and the Green Shift respectively)
- z_{scd} = {1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0}
  << for all work groups where c = 1 (i.e. the Yellow Shift team) and for d = 1 to 28 >>
- z_{scd} = {0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 1, 1, 1, 1}
  << for all work groups where c = 2 (i.e. the Green Shift team) and for d = 1 to 28 >>

Excluding the predefined parameters H and z_{scd}, the minimisation of the labour cost *TC* resolves to (a) finding an optimal combination of work groups per shift team to ensure that sufficient on-duty AMEs are supplied throughout each day-of-operations to meet the instantaneous demand level for STLM activities, (b) with minimal levels of AME idle time and (c) across the full 28 day cycle length. In this regard, each work group is manned by *M* AMEs where the number *M* may vary from one work group to another within a particular cycle (or shift team), but not between equivalent work groups on the two opposing cycles. In addition, each work group within the roster is assigned a particular shift type (i.e. a ‘morning shift’, an ‘afternoon shift’ or a ‘night shift’), with a specified start time and duration *D*, for each on-duty day in the 28 day cycle.

In theory, any positive integer number of shift teams (or cycles) can be considered in the process of developing an optimised labour roster using Equation 2. The same characteristic applies to the number of work groups that make up each shift team, should the nature of a shift roster allow for the subdivision of shift teams. However, Belien *et al.* (2010) have commented in their study that a personnel schedule composed of a high number of cycles complicates the task of the operations manager. In this regard, these authors have advised that it is unrealistic to try to work with four or more cycles in a given rostering scenario. Instead, the authors recommend that only schedules of one, two or three cycles should be evaluated in practice. Adapting these comments to this study where the number of cycles has been fixed at a value of two, the number of work groups per cycle that has been considered in the optimisation model has been limited to a maximum value of three.

An important factor that constrains the minimum number of work groups allocated to each cycle is the ratio of the maximum duration of a single duty shift to the minimum hours of shift coverage that are needed on a given day-of-operations. This issue has been evaluated using the flight schedule information for the date range 05 to 11 September 2011. Firstly, the minimum time period of shift coverage that is needed on each day has been estimated by calculating the difference between the maximum start time for the STLM task relating to the earliest planned aircraft movement of the day and the minimum finish time for the STLM task relating to the latest planned aircraft movement of the day. This period of coverage has then been divided by the maximum shift length for a single duty shift (i.e. 12 hours) in order to obtain a 'coverage ratio'. These calculations are presented in Spreadsheet 2 in Appendix I and show that the coverage ratio varies between a minimum value of 1.10 and a maximum value of 1.38 depending on the weekday. This data indicates that it is not possible to meet the STLM task demand on any weekday using just a single work group. As such, the study has tested shift configurations using either two or three work groups per cycle.

4.1.2.5 Assessing the Potential for Demand Optimisation using Task Timing Flexibility

The computational model as presented in Equation 2 is sufficiently developed for use in generating an optimised AME supply configuration for STLM operations at the case organisation. However, in order to proceed with the generation of this output supply profile, an input demand profile for STLM tasks in the case setting is required. This is an important issue as the task demand profile on any given day is a variable modelling parameter. As has already been discussed in Subsection 1.2.2 of the study, the main requirement for the timing of a STLM event is that the maintenance takes place within the time interval between the scheduled time of arrival (STA) and the next scheduled time of departure (STD) of the affected aircraft. If the timing constraints listed in Table E3 in Appendix E are applied, it is possible to develop a multitude of feasible configurations of the STLM task demand profile for each weekday of the representative operational week in the case setting, even under the ideal assumption that the airline achieves a 100% on-time performance level.

In order to determine the number of feasible configurations of the STLM task demand profile on a given weekday, it is first necessary to establish a minimum time interval that will be used to set the number of potential starting points, or starting times, for each task. The lowest time interval that is applied at the case organisation in specifying its flight schedule is five minutes. As a result, it has been deemed to be a logical action to apply the same minimum time interval for the task demand modelling processes, particularly as this precludes the need for rounding adjustments of the flight departure and arrival times specified in the airline operating schedule. It is also of note that this minimum time interval is a common multiple of the various time interval contraints that are listed in Table E3 in Appendix E.

Applying a five minute time interval base, a set of calculations has been performed to calculate the number of feasible STLM task demand profiles for each day of the representative operational week that has been scrutinised in the study. The results of these calculations are shown in Table 9. The data in this table assumes that each STLM task is attended to by a single AME. Furthermore, this data has been generated using a simplified set of timing constraints for the three basic STLM task categories that has been adapted from the specifications of Table E3 in Appendix E. A description of these simplified timing constraints is included in the table. The detailed calculations that support the data in Table 9 have been included in Spreadsheet 3 in Appendix I for reference purposes.

Table 9 – Summary of the Number of Feasible STLM Task Demand Profiles by Weekday at the Case Organisation's Main Base, Applying a Five Minute Time Interval Base and Modified Timing Constraints for STLM Checks

Modified Timing Constraints for STLM Checks (See Table E3 in Appendix E)		
Event	**Lower Bound Limit(s)**	**Upper Bound Limit(s)**
After-Flight Check	Start time >= arrival time + 40 mins	Start time <= 24:00
Pre-Flight Check	Start time >= 05:00 Finish time >= departure time less 60 mins (assuming 1 x AME in attendance)	Finish time <= departure time less 30 mins (assuming 1 x AME in attendance)
Transit Check	Start time >= arrival time	Start time >= arrival time + 10 mins

Number of Feasible STLM Task Demand Profiles by Weekday							
Weekday	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
No. of STLM Events	53	51	51	53	55	32	40
No. of Feasible Task Demand Profiles	1.53×10^{50}	9.02×10^{47}	1.37×10^{45}	2.09×10^{47}	1.04×10^{49}	1.43×10^{37}	7.20×10^{42}

It is clear from Table 9 that the count of feasible profiles for the STLM task demand at Airlink's main base on each weekday is a very large number. This is exacerbated by the fact that the counts presented in Table 9 exclude the additional task demand profiles that can be generated by varying the number of AMEs that are assigned to each maintenance task. To consider all the available configuration options on any weekday in order to find an optimal task demand profile thus requires significant computing power. It has been found during the course of this study that these numbers of configuration options are well beyond the processing capability of a contemporary personal computer running MS Excel software. Therefore, for this problem to be considered in an MS Excel environment on a personal computer, a method is needed by which to limit the number of feasible solutions that are evaluated in a way that establishes a good or near-optimal solution.

To put the potential value of optimising the STLM task demand profile at the case organisation into perspective, a useful measure is to consider the difference in the number of AMEs that must be rostered on a given day-of-operations for the following three cases:

- Case 1: An optimal, or near-optimal, scenario that minimises local peaks in the number of tasks being worked concurrently to maximise the occupancy levels of on-duty AMEs,

- Case 2: A test scenario that uses a fixed start time for each STLM event relative to the associated aircraft departure or arrival time, and

- Case 3: A worst-case scenario where the timing of the set of maintenance tasks produces the maximum possible instantaneous peak of tasks being worked concurrently.

Table 10 shows a representation of these three cases at Airlink. For the first scenario, the table shows the number of AMEs that is needed to meet a demand profile where each on-duty worker is utilised at an average occupancy level of 80 percent over an average shift length of nine hours to achieve the required number of manhours that is called out by the associated set of STLM tasks. For the second scenario, the table shows the number of AMEs that is needed to meet a demand profile where fixed start times are applied for each STLM event. In this regard, all aircraft pre-flight checks have been set to commence 80 minutes prior to the departure time of the associated flight, while all transit checks have been set to commence at the time of arrival of the associated flight. Aircraft after-flight checks have been set to begin 40 minutes after the arrival time of each affected flight in this scenario. For the third scenario, the table shows the maximum instantaneous demand loading of AMEs that is possible for each weekday at the case organisation on the assumption that a single AME is assigned to each active maintenance task. This worst-case scenario has been developed by considering the total time window between the earliest possible start time and the latest possible finish time for each affected STLM task. By comparing this time window for each affected task it is possible to determine the maximum number of STLM tasks that can be worked concurrently on a given day. This maximum instantaneous demand load is equal to the minimum number of AMEs that would need to be rostered to meet the worst-case STLM task demand profile for an affected day-of-operations. Note that the detailed calculations that underpin the data in Table 10 have been included in Spreadsheet 4 in Appendix I for reference purposes.

Table 10 – Comparison of the Best Case and Worst Case AME Resource Requirements for STLM Activities by Weekday using Task Timing Flexibility, 05 to 11 September 2011

Weekday	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Number of STLM Tasks Worked	53	51	51	53	55	32	40
Manhours to be Applied to Meet the STLM Demand for the Day	38.67	36.08	34.83	35.42	37.75	27.67	33.42
Scenario 1: AMEs Needed Assuming 80% Occupancy and 9 Hrs of Duty per Day	6	6	5	5	6	4	5
Scenario 2: Maximum Instantaneous AME Demand, Assuming 1 x AME per STLM Task and Fixed Task Timing	9	8	10	7	9	7	8
Scenario 3: Maximum Instantaneous AME Demand, Assuming 1 x AME per STLM Task and Flexible Task Timing	15	14	13	13	14	12	14

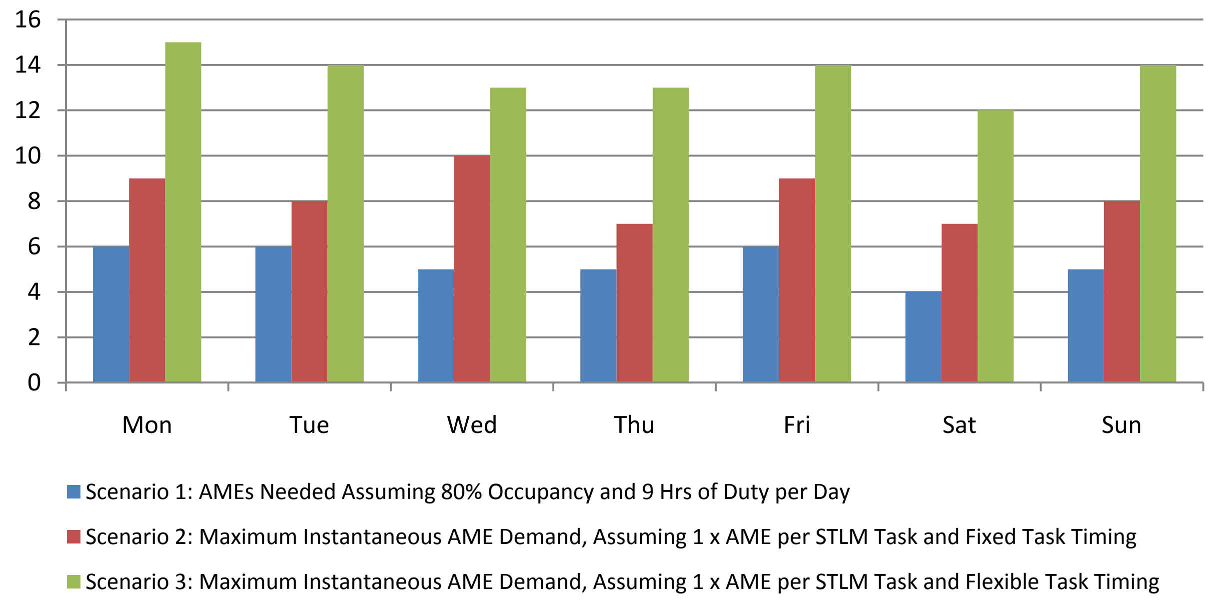


Table 10 clearly shows that, at an average occupancy level of 80% per AME, the total number of AMEs that is needed to meet the STLM demand at the case organisation on any weekday in a flexible task timing scenario is less than the peak AME demand level under a fixed task timing scenario. In addition, it has already been shown that at least two shift groups are needed to crew the STLM operation on each weekday. As such, unless this peak AME demand level in the fixed timing scenario (as well as other localised demand peaks) can be covered by a suitable overlap of the on-duty shift groups, then the total number of AMEs allocated to these shift groups will exceed the peak AME demand level that has been illustrated. It can therefore be concluded that there is a significant opportunity to optimise the supply of AMEs that must be rostered for STLM activities in the case setting if flexibility in the timing of tasks can be exploited to achieve average occupancy levels for AMEs of around 80% or higher. It is also evident from Table 10 that sub-optimal management of the timing flexibility for STLM tasks can result in significantly higher AME demand peaks when compared to the fixed timing scenario. As such, the exploitation of timing flexibilities for these tasks should be a managed process during ongoing operations.

4.1.2.6 Optimising the Demand Profile for STLM Activities at the Case Organisation through Task Timing Flexibility

At this point, it has been established that savings can be achieved in the numbers of AMEs that are required for STLM operations if it is possible to achieve high average occupancy levels in the region of 80% for each on-duty AME. Due to the application of a minimum shift length of eight hours in this study, there are significant practical limitations to attempts to achieve high occupancy levels by optimally matching the supply profile of AMEs against a task demand profile that exhibits high levels of variability across the course of a given day-of-operations. As such, it is of value to utilise the available flexibility in the timing of STLM tasks to reduce local peaks in AME demand, thereby producing the flattest possible demand profile against which to develop an optimal AME supply profile. However, it has also been established that it is unfeasible to test every possible timing configuration for STLM tasks in an operating environment of the same or similar scale to that of the case organisation. A method is thus needed by which to find near-optimal solutions in terms of minimising local AME demand peaks throughout each day without testing more than a small fraction of the vast number of feasible task demand profiles. As a result of this requirement, a three-step, semi-automated method has been developed in this study for optimising the STLM task demand profile in the case setting to eliminate localised AME demand peaks. This method makes use of both heuristics and mathematical programming concepts in an MS Excel model.

The optimisation method described in the preceding paragraph utilises an integer programming model in Excel that displays the AME demand level throughout an operational day for any feasible set of task start times that satisfies the constraints of the aircraft operating schedule and the timing specifications laid out in Table 9. In this regard, the AME demand level is displayed across a 24 hour day in time intervals of five minutes. The model is able to set the start time for each STLM task at any point within its predefined start time bounds using random number generation and subject to a minimum time increment of five minutes. In the first step of the optimisation process, an Excel Macro is used to randomly generate 20,000 feasible task start time profiles. In this initial step, the maximum possible flexibility in the start time for each task is used and the model calculates the maximum instantaneous AME demand level for each task start time profile that it generates. Each maintenance task is assumed to be performed by a single AME in this stage of the process. From these 20,000 iterations, the start time profile with the lowest peak value in terms of instantaneous AME demand is isolated and extracted for further analysis. This outcome represents the first stage 'global search'. Should more than one task start time profile provide the same minimum value in terms of the peak AME demand level, one of the affected profiles must be randomly selected for the next round of processing.

In the second step of the demand optimisation process, the 'global search' of the preceding step is refined to a 'local search' wherein task start times are again randomly generated. In this step, the same constraints on task start times remain valid as per the specifications of Table 9. However, an additional constraint is now applied that limits the start time of each STLM event to within plus or minus 15 minutes of the matching start time that was determined in the first processing step. This local search is also performed using an Excel Macro and a further 20,000 feasible task start time profiles are randomly generated. Again, it is assumed that a single AME is assigned to each maintenance task and the output profile that produces the lowest peak AME demand across all five minute intervals for the day is selected as the best near-optimal solution. If it is found that more than one task start time profile generates the same minimum value in terms of its maximum instantaneous AME demand level across the operational day, then a further decision criterion is applied to select the task profile with the lowest standard deviation in terms of peak AME demand values, calculated in 30 minute increments, across the operational day.

Finally, a third processing step may be implemented on a discretionary basis to manually adjust the start times of some or all of the applicable STLM tasks within their feasible task time bounds to further reduce localised peaks in AME demand. In this step, the expanded set of task time bounds detailed in Table E3 in Appendix E, as opposed to the modified set described in Table 9, can be applied and soft constraints may be violated if there is reasonable justification to do so. It is also possible to achieve additional task demand optimisation in this third step by manually adjusting the number of AMEs that are assigned to each maintenance task within the limits detailed in Table E2 in Appendix E. In this regard, additional AMEs can be assigned to STLM tasks during periods of lower task demand in order to finish the affected tasks in a shorter time period, thereby potentially avoiding overlaps with tasks that start later in the day and in periods of higher task demand.

The demand optimisation process detailed in the preceding three paragraphs has been applied in this study using the flight schedule information for each day of the representative operational week from 05 to 11 September 2011. For reference purposes, Spreadsheet 5 in Appendix I shows the output task demand profile that has been determined for each day in this date range. In addition, Figure 3 shows an illustration of the near-optimal task demand profile that has been developed using the schedule information for Monday the 05th of September 2011. This near-optimal task demand profile has been compared to an equivalent task demand profile based on the fixed timing parameters for STLM events used in Table 10, as well as to the most sub-optimal task demand profile that was developed during the iterative optimisation process. Note that Scenarios A and B in Figure 3 assume that a single AME is allocated to each STLM task. The comparisons in Figure

3 show significant optimisation potential even at a cursory glance. The fixed timing scenario spans a demand window of approximately 18 hours with a morning demand peak of 7 x AMEs and an evening demand peak of 9 x AMEs. For the most sub-optimal case, the demand window extends to approximately 21 hours, with a morning demand peak of 8 x AMEs and an evening demand peak of as many as 13 x AMEs. For the best near-optimal solution that has been developed, the demand window spans approximately 20 hours of the day with a demand peak of only 4 x AMEs for both the morning and the evening.

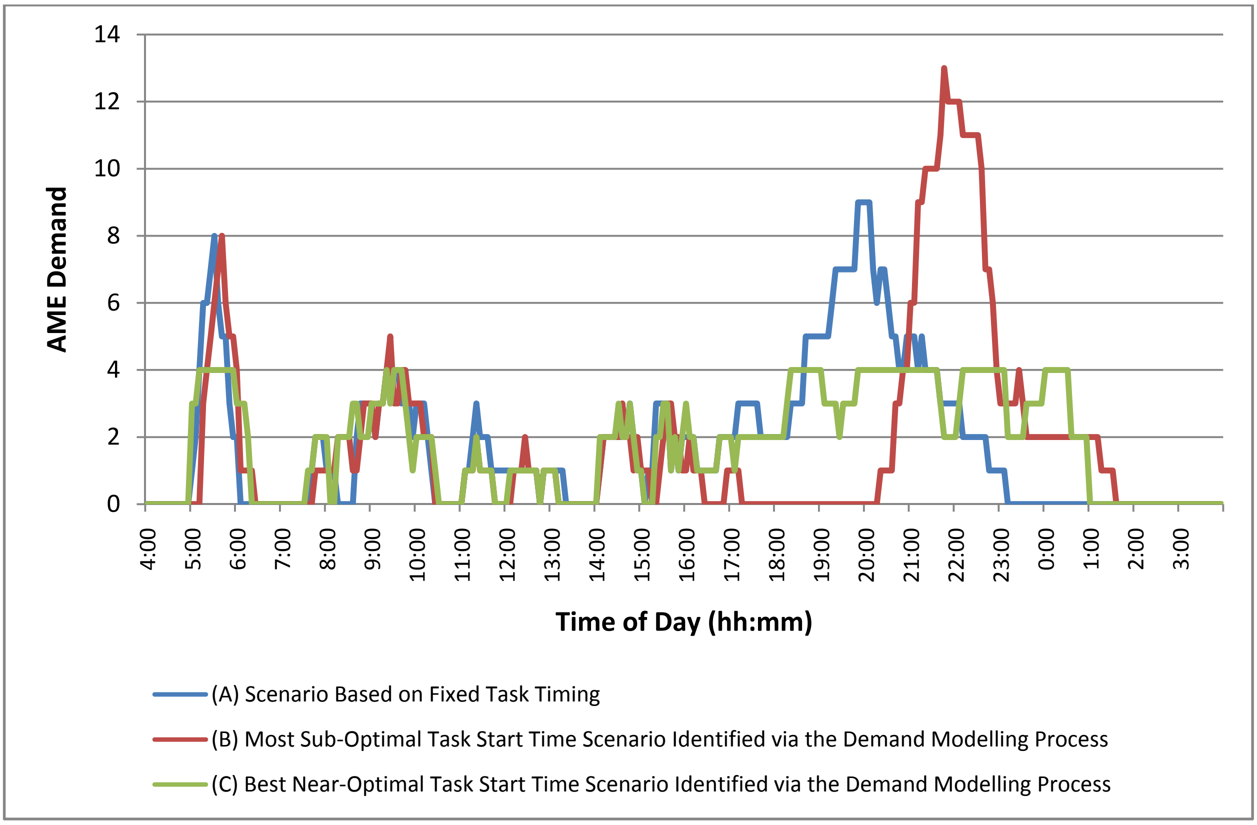


Figure 3 – Comparison of AME Demand Profiles for STLM Activities for 05 September 2011 for the Following Scenarios: (A) Task Start Time Set Based on Fixed Task Timing, (B) Most Sub-Optimal Task Start Time Set and (C) Best Near-Optimal Task Start Time Set

Although useful outcomes have been achieved through the task demand optimisation process, the multiple-step calculation method that has been used in this study has been found to be time consuming in terms of the processing times that are needed for the Excel-based Macros that have been employed. Using a contemporary laptop computer, it has been found that each calculation run of 20,000 iterations takes approximately 10 hours to complete. As a result of this processing requirement, calculations were generally executed overnight during the course of the study and it took at least two days to generate an output task demand profile for each operational day that was modelled. This requirement for lengthy processing times is a drawback of this type of optimisation modelling. However, the rapid pace of development in the processing capabilities of personal computers should act to mitigate this challenge in the medium to long term.

4.1.2.7 Finding the Best AME Supply Profile to Match the Optimised Demand Profile for STLM Activities on each Weekday at the Case Organisation through Task Timing Flexibility

Spreadsheet 5 in Appendix I, titled '*Optimised Task Demand Profiles by Weekday - 05 to 11 Sep 2011.xlsx*', includes a tab titled '*Demand Profile in Half Hours*'. This tab summarises the demand profile for AMEs in half hour increments for each day of the representative week of operations. In this regard, it should be borne in mind that the modelling constraints that have been established dictate that shift starting times must fall either on the hour mark or at an intermediate half hour marker. Furthermore, shift lengths may only be varied in half hour increments as a minimum. As such, matching AME supply to AME demand can be done by ensuring that the supply of AMEs in any half hour period matches or exceeds the maximum demand level for that period. Using these task demand profiles, the computational model for optimising the AME labour supply for STLM activities that is described in Equation 2 can be applied to generate meaningful outputs.

To optimise the supply of AMEs on any given day-of-operations, the labour scheduling model must search for an optimal or near-optimal feasible solution based on the following parameters:

- The number of work groups per cycle (i.e. two or three),

- The number of AMEs assigned per work group (note that this number has been limited to values of two, three and four due to the maximum instantaneous AME demand load of four that has been determined through the demand optimisation process),

- The starting time of each working shift (variable in half hour increments according to the constraints described in Appendix E), and

- The duration of each working shift (8:00 to 12:00 hours incrementing in half hour steps).

Note:
For scenarios where two work groups are used, it has been assumed that a morning shift and a night shift shall be allocated per day. Where three work groups are used, it has been assumed that a morning shift, an afternoon shift and a night shift shall be allocated per day.

Applying Equation 2 and the parameter limitations that have been established, an Excel-based computational model has been used to test a vast number of possible solutions in terms of AME roster arrangements. Each solution that has been found to generate a supply of AMEs that is sufficient to meet the AME demand level in any half hour period throughout the operational day has been accepted as a feasible solution. All other solutions have been rejected immediately on the basis of them being unfeasible to meet the prevailing demand. The computational model has then been used to refine the list of feasible solutions by eliminating each solution that violates any of the so-called 'hard modelling constraints' that have been specified. Finally, the model has been used to search for an optimal (or near-optimal) feasible solution that generates the lowest quantity of rostered AME manhours and, if necessary, the lowest quantity of rostered AMEs.

Table 11 shows the upper and lower bounds of the modelling parameters for the labour supply optimisation problem that have been applied for each day of the representative week of STLM operations at the case organisation. Parameter values are shown for both of the basic shift arrangements, i.e. either two or three work groups per shift cycle. Table 11 also shows the number of possible shift roster configurations that can be generated for each of the two shift arrangements on any given day. For an operation where only two work groups per shift cycle are considered, the number of possible shift arrangements per operational day is below 100,000. In such a case, the entire set of possible shift arrangements can be processed in Microsoft Excel with little difficulty. However, the number of possible shift arrangements for a roster that contains three work groups per shift cycle is far higher at approximately 55 million per operational day. This issue complicates the task of finding an optimal or near-optimal solution in an MS Excel environment, as it has been found that the software presents processing errors with the supporting calculations where the number of iterations in a single spreadsheet exceeds quantities of around 150,000 (i.e. approximately 0.27% of the total number of possible solutions).

Table 11 – Modelling Parameters and Numbers of Possible Solutions for the STLM Labour Supply Optimisation Problem at the Case Organisation

2 WORK GROUPS PER SHIFT CYCLE						
Parameter	**Shift Length**		**Number of AMEs Per Work Group**		**Shift Start Time**	
	Morn	**Night**	**Morn**	**Night**	**Morn**	**Night**
Lower Boundary	8:00	8:00	2	2	5:00	12:00
Upper Boundary	12:00	12:00	4	4	8:00	21:00
Increment	0:30	0:30	1	1	0:30	0:30
Number of Solutions	9	9	3	3	7	19
Total Number of Possible Solutions	96,957					

3 WORK GROUPS PER SHIFT CYCLE									
Parameter	**Shift Length**			**Number of AMEs Per Work Group**			**Shift Start Time**		
	Morn	**Aft'n**	**Night**	**Morn**	**Aft'n**	**Night**	**Morn**	**Aft'n**	**Night**
Lower Boundary	8:00	8:00	8:00	2	2	2	5:00	8:00	12:00
Upper Boundary	12:00	12:00	12:00	4	4	4	8:00	18:00	21:00
Increment	0:30	0:30	0:30	1	1	1	0:30	0:30	0:30
Number of Solutions	9	9	9	3	3	3	7	21	19
Total Number of Possible Solutions	54,974,619								

In order to manage the issue of the high number of possible solutions where three work groups are allocated per shift cycle, two approaches have been employed in this study to find a near-optimal solution without considering every single possible solution. In the first instance, it has been found that it is possible to reduce the number of shift profiles being evaluated by manually removing obviously unfeasible parameter values. This approach requires a careful review of the associated AME demand profiles. For example, on Monday through Friday of the representative week of operations, it has been assumed that it is not possible to generate an efficient work roster where the night shift remains on duty over the idle period between the final STLM workloads for a given day-of-operations and the initial workloads of the next day. As such, the only feasible start time for the morning shift work group is 05:00 and the only feasible number of AMEs manning this work group is 4 based on the morning demand peak between 05:00 and 08:00 when the morning shift is the only work group on duty. Fixing these two parameter values at 05:00 and 4 respectively reduces the number of possible shift configurations by a factor of 21. In the second instance, a progressive search process may be used to reduce the number of solutions that is considered. In this regard, it is possible to run multiple iterations of the supply model, starting with higher increment settings by modelling parameter (e.g. shift lengths incrementing in hours as opposed to half hours). Once the best solution has been found at the higher increment settings per modelling parameter, the upper and lower bounds of each parameter are then progressively tightened in the region of the best current solution, while reducing the increment setting of each affected parameter concurrently. This approach is effectively a progressive 'global-to-local search' process.

Using the mixed manual and automatic methods of computation that are described in this subsection, an optimal shift roster for each weekday of the representative week of operations in the case setting has been generated as presented in Table 12. This table shows the results for both shift roster configurations that have been considered, i.e. either two or three work groups per shift cycle. In addition, Spreadsheet 6 in Appendix I maps the optimised AME supply profile for each weekday against its associated optimised AME demand profile. This spreadsheet confirms that the AME supply profile for each weekday is sufficient to meet the AME demand levels throughout each affected day-of-operations. Table 12 shows that a shift roster configuration comprising three work groups per cycle provides a more efficient labour supply than a structure employing two work groups per cycle on normal office days (i.e. Monday to Friday). However, this scenario reverses over weekends (i.e. Saturdays and Sundays) where the peak instantaneous AME demand load is only three. On these weekend days, the specification that at least two AMEs shall be assigned to each work group leads to sub-optimal results for a shift roster configuration employing three work groups per cycle in comparison to a roster with just two work groups allocated per shift cycle. In total, the best weekly AME manhour requirement that can be achieved for a shift roster employing three work groups per cycle is 501 manhours. The corresponding result for a shift roster that utilises two work groups per cycle is 507 manhours.

Table 12 – Best Shift Solutions by Weekday for STLM Activities at the Case Organisation as Determined by Optimisation Modelling

Weekday >>	MONDAY				TUESDAY			
Best 2 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	14:00	36.00	4	5:00	14:00	36.00
Night Shift	4	14:00	1:00	44.00	4	14:00	0:30	42.00
Totals >>	**8**			**80.00**	**8**			**78.00**
Best 3 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	13:00	32.00	4	5:00	13:00	32.00
Afternoon Shift	2	13:00	0:30	23.00	2	13:00	0:30	23.00
Night Shift	2	14:30	1:00	21.00	2	14:30	0:30	20.00
Totals >>	**8**			**76.00**	**8**			**75.00**
Weekday >>	**WEDNESDAY**				**THURSDAY**			
Best 2 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	14:00	36.00	4	5:00	14:00	36.00
Night Shift	4	14:00	1:00	44.00	4	14:00	0:30	42.00
Totals >>	**8**			**80.00**	**8**			**78.00**
Best 3 x Work Group Roster:	Number of AMEs	Start Time	Finish Time	MH	Number of AMEs	Start Time	Finish Time	MH
Morning Shift	4	5:00	13:00	32.00	4	5:00	13:00	32.00
Afternoon Shift	2	13:00	0:30	23.00	2	13:00	23:30	21.00
Night Shift	2	14:30	1:00	21.00	2	15:30	0:30	18.00
Totals >>	**8**			**76.00**	**8**			**71.00**
Weekday >>	**FRIDAY**				**SATURDAY**			
Best 2 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	15:00	40.00	3	5:30	14:30	27.00
Night Shift	4	15:00	1:00	40.00	3	14:30	23:30	27.00
Totals >>	**8**			**80.00**	**6**			**54.00**
Best 3 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	13:00	32.00	3	5:30	13:30	24.00
Afternoon Shift	2	13:00	1:00	24.00	2	13:30	23:00	19.00
Night Shift	2	14:30	1:00	21.00	2	14:30	23:30	18.00
Totals >>	**8**			**77.00**	**7**			**61.00**
Weekday >>	**SUNDAY**							
Best 2 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**				
Morning Shift	3	7:00	15:00	24.00				
Night Shift	3	15:00	2:00	33.00				
Totals >>	**6**			**57.00**				
Best 3 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**				
Morning Shift	3	7:00	17:00	30.00				
Afternoon Shift	2	17:00	2:00	18.00				
Night Shift	2	17:00	1:00	16.00				
Totals >>	**8**			**64.00**				
Note: MH = manhours								

The data in Table 12 has been used to generate an optimised shift roster configuration for the FLM Team at the case organisation's main base. To produce the output shift roster, a final round of manual checks has been performed and adjustments have been made where necessary in order to ensure that the constraints that have been specified for daily shift start time variations are satisfied. The output shift roster for the FLM Team is described in Table 13. Note that this shift roster utilises three work groups per shift cycle, although the roster adjusts to mimic the structure of a two-work-group-per-cycle configuration over weekends (with three AMEs per shift group). In this regard, one spare AME from the morning shift work group and one from the night shift work group are released as surplus labour resources to work on the SVM Team, or elsewhere at the discretion of the affected operations manager, over weekends.

Table 13 – Final Optimised Shift Roster for the FLM Team at the Case Organisation

Weekday >>	**MONDAY**				**TUESDAY**			
Best 3 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	13:00	32.00	4	5:00	13:00	32.00
Afternoon Shift	2	13:00	0:30	23.00	2	13:00	0:30	23.00
Night Shift	2	14:30	1:00	21.00	2	14:30	0:30	20.00
Totals >>	**8**			**76.00**	**8**			**75.00**
Weekday >>	**WEDNESDAY**				**THURSDAY**			
Best 3 x Work Group Roster:	Number of AMEs	Start Time	Finish Time	MH	Number of AMEs	Start Time	Finish Time	MH
Morning Shift	4	5:00	13:00	32.00	4	5:00	13:00	32.00
Afternoon Shift	2	13:00	0:30	23.00	2	13:00	23:30	21.00
Night Shift	2	14:30	1:00	21.00	2	15:30	0:30	18.00
Totals >>	**8**			**76.00**	**8**			**71.00**
Weekday >>	**FRIDAY**				**SATURDAY**			
Best 3 x Work Group Roster:	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**	**Number of AMEs**	**Start Time**	**Finish Time**	**MH**
Morning Shift	4	5:00	13:00	32.00	4*	5:30	14:30	36.00
Afternoon Shift	2	13:00	1:00	24.00	2	14:30	23:30	18.00
Night Shift	2	14:30	1:00	21.00	2*	14:30	23:30	18.00
Totals >>	**8**			**77.00**	**7**			**72.00**
Weekday >>	**SUNDAY**				Note: MH = manhours *On Saturdays and Sundays, 1 x AME from the Morn Shift and 1 x AME from the Night Shift are surplus to requirements and shall be released as a spare resource to work on the SVM Team, or as otherwise allocated.			
Best 3 x Work Group Roster:	Number of AMEs	Start Time	Finish Time	MH				
Morning Shift	4*	7:00	15:00	32.00				
Afternoon Shift	2	15:00	2:00	22.00				
Night Shift	2*	15:00	2:00	22.00				
Totals >>	**8**			**76.00**				

Key Shift Roster Statistics with the Case Organisation's Duty Cycle Applied	
Average weekly working hours for AMEs allocated to the Morning Shift	28.50
Average weekly working hours for AMEs allocated to the Afternoon Shift	38.50
Average weekly working hours for AMEs allocated to the Night Shift	35.25
Average long-term weekly working hours per AME where a periodic rotation of AMEs is implemented between the 3 work groups in each shift cycle	**32.69**

Based on the information presented in Table 13, it is proposed that each shift cycle of the case organisation's FLM Team should incorporate eight permanent AME posts and each cycle should be composed of three distinct work groups. For the two shift cycles that are in operation, this means that a total of 16 AMEs should be rostered for STLM activities at the case organisation. The table also shows that the average weekly working hours for each AME that is included in this proposed structure will be approximately 33. This average can be achieved via a rotation policy for AMEs such that they are allocated to work on each of the three work groups equally over a given number of cycle repetitions.

Referring back to the optimisation formula described in Equation 2, the total cost for the shift roster solution that has been developed has been calculated by inserting values for the parameters *s*, M_{sc} and D_{scd} according to the roster structure described in Table 13. In addition, the fixed labour rate parameter *H* has been established based on the average hourly labour rate for the 2012 financial year for all line maintenance AMEs employed by the case organisation. This labour rate has been derived by dividing the average monthly salary for line maintenance AMEs at the case organisation by the average number of monthly working hours that are rostered per line maintenance AME, i.e. 182.5 manhours. Based on data supplied by the Senior Accountant at Airlink's Maintenance Division, a rate of 164.70 South African rand (ZAR) per labour hour has been used.

The use of this average labour rate is thought to be reasonable in that AMEs that are allocated to work on the FLM Team must all be LAMEs who hold limited line maintenance release certifications on Airlink's three aircraft types. In general, these AMEs would be above the level of junior unlicensed AMEs in terms of their maintenance experience, aircraft type training and associated pay grading. However, given that STLM checks are highly routine in nature and require very little in the way of disassembly and functional testing of aircraft systems, these AMEs would be at the low end of the case organisation's LAME pool in terms of experience, in-depth aircraft type training and associated pay grading. Thus, it is not unreasonable to assume that AMEs on the FLM Team are paid at approximately the average salary level for all line maintenance AMEs.

Using the finalised parameter values referred to this subsection, the following key results have been determined:

- Rostered AME manhours to attend to the case organisation's STLM maintenance needs across a single 28 day shift cycle rotation = 2,092.

- Number of AMEs employed on the FLM Team = 16.

- Average number of rostered duty hours per AME employed on the FLM Team across a single 28 day shift cycle rotation = 131.

- Total direct cost of AME labour on the FLM Team across a single 28 day shift cycle rotation = 344,552.40 ZAR.

At this point, it has been shown how an optimised labour supply profile has been developed for the STLM requirements at the case organisation. However, referring to Figure 1 in Subsection 3.4.1, this is only the first step in the modelling process that has been presented. The second step of the modelling process covers the allocation of individual tasks amongst the members of the on-duty workforce on any given day in order to produce a feasible work profile per AME. This processing step has received lesser attention in this study than the first processing step as it does not influence the optimisation of the AME labour input that is supplied. However, the automation of this process is potentially of significant benefit in reducing the workload on operations managers who are responsible for developing labour plans for airline STLM operations.

4.1.2.8 Allocating the Task Demand Queue for STLM Activities to the On-Duty Workforce

An automated task allocation process has been developed and tested in this study using zero-one integer programming in combination with a series of binary logic switches. The implementation of this process has been carried out in a Microsoft Excel spreadsheet that is then solved using the built-in Excel Solver software feature. While this experimental model has shown that it is capable of producing feasible task allocations with no 'double allocations' of an individual AME at any given time, it is interesting that the model always allocates the next task in the demand queue to the first unoccupied on-duty AME (or AMEs) in the resource supply queue. For a team of 4 x AMEs, the model will therefore tend to allocate most of the tasks against AMEs 1 and 2 and will only use AMEs 3 and 4 where more than two individuals are required to work concurrently in order to meet the resource demands of the maintenance tasks that are currently in progress. This characteristic has a potentially negative connotation in that it raises concerns about the equitable allocation of tasks amongst the AMEs on a given on-duty shift. However, there is also a positive connotation in that the allocation process in its experimental form tends to maximise the occupancy of the earlier AMEs in the resource supply queue whilst exposing potential idle periods in the duty shifts of the later AMEs in the queue. These idle periods can then be used for supplementary duties such as supporting the SVM Team or for participating in training or administrative activities.

With reference to Discussion Point 9 in Appendix J, a particular logic has been applied in this study for the management of idle time in between successive STLM tasks. According to this logic, any idle period of 90 minutes or longer for an individual AME on the FLM Team has been assumed to be transferrable to the SVM Team, but subject to a 10 minute transit window each way between the respective teams. This logic has enabled improved occupancy levels to be achieved for the AMEs employed on the FLM Team. The application of this logic has been made in conjunction with a hybrid approach that combines the automatic task allocation model with a series of manual adjustments. These manual adjustments have been based on decision criteria such as ensuring equitable task allocations amongst the on-duty workforce, as well as providing reasonable periods of rest or refreshment for AMEs in between sequences of consecutive tasks.

Spreadsheet 7 in Appendix I, titled '*Finalised Task Allocation Profiles by AME and Shift Group, 05 to 11 Sep 2011.xlsx*', shows the finalised task allocation by AME per weekday of the representative operational week in the case setting (i.e. 05 to 11 September 2011). This spreadsheet also shows the time sequences per AME that may be allocated in support of the SVM Team based on the identification of 90 minute time gaps between successive STLM tasks. In determining the finalised AME allocation by weekday, it should be noted that one of the soft modelling constraints as per Table E3 in Appendix E has been violated on Sunday the 11th of September 2011. In this regard, an after-flight check on this date breaks a soft constraint by starting between midnight and 01:00 in the morning. Other than this soft constraint violation, all hard constraints are satisfied and no other soft constraint violations are registered on any other day of the representative week of operations.

Based on the task allocation process for STLM activities that has been implemented in this study, the following statistics have been generated with regards to the AME occupancy levels that can be achieved with the optimised labour roster for the FLM Team:

- Rostered AME manhours on the FLM Team for 1 x 28 day shift cycle = 2,092.

- AME manhours demanded for all STLM tasks over 1 x 28 day shift cycle, based on the flight schedule information for 05 to 11 September 2011 = 975.

- Minimum number of spare manhours on the FLM Team that can be allocated to support the SVM Team over 1 x 28 day shift cycle = 148.

  Note:
  This figure of 148 manhours relates to the spare labour resources that are released from the FLM Team on Saturdays and Sundays as described in Table 13.

- Proposed number of spare manhours on the FLM Team that can be allocated to support the SVM Team over 1 x 28 day shift cycle = 567.

- Average AME occupancy level on the FLM Team if no support is provided to the SVM Team = 46.6%.

- Average AME occupancy level on the FLM Team if the minimum level of support is provided to the SVM Team = 53.7%.

- Average AME occupancy level on the FLM Team if the proposed level of support is provided to the SVM Team = 73.7%.

Note that the data listed in the preceding series of bullet points is described in greater detail, along with relevant supporting calculations, in Spreadsheet 8, titled '*Performance Characteristics of Output Shift Roster for FLM Team.xlsx*', that has been included in the contents of Appendix I.

4.1.3 Comparison of the STLM Labour Force Optimisation Modelling Results against the Outputs of the Case Organisation's Current Line Maintenance Labour Model

Subsection 4.1.1 of this study describes the existing labour plan for line maintenance that is used by the case organisation. This labour plan is based on a fairly rudimentary mathematical model. Thereafter, Subsection 4.1.2 describes a proposed labour schedule for an FLM Team that focuses specifically on STLM tasks as its primary function. In this regard, the proposed schedule has been developed in an experimental environment using sophisticated computational modelling methods. At this point, it is necessary to establish an appropriate basis by which to compare these two contrasting labour plans in order to determine if the latter plan offers any measurable advantages over the former, thereby justifying the application of sophisticated numerical modelling methods to this operations management problem.

Although not explicitly specified in the case organisation's current labour planning model for line maintenance (see Table 5 in Subsection 4.1.1.2 and the associated spreadsheet in Appendix H), it is possible to determine the portion of the model's recommended manhour supply that is effectively dedicated to performing STLM tasks. In this regard, Airlink's STLM needs at its main maintenance base are currently met by a combination of day shift and night shift labour, as follows:

- <u>Day Shift Labour Component:</u>

  The day shift work groups within the Line Maintenance Department utilise five AMEs per duty shift, with two alternating shift cycles. Each AME works 12 hours per shift. These two work groups currently perform all aircraft pre-flight and transit checks that occur from 06:00 in the morning up to 18:00 in the evening. For the purposes of this study, it has been assumed that these work groups perform all the pre-flight and transit check tasks that are called out at the main maintenance base, irrespective of the time, although in reality a portion of these pre-flight checks are generally performed by the preceding night shift work group for early departures leaving at or before 06:45 in the morning.

  The day shift work groups also respond to aircraft technical issues or faults that are identified and reported by flight crews during day shift hours, or which are noted during aircraft pre-flight or transit checks. For these unscheduled issues, the on-duty day shift group will generally implement soft reset actions or apply maintenance deferral allowances as far as these are safe and viable in order to enable an affected aircraft to continue operating for the remainder of the day. The aircraft in question will generally be subjected to more comprehensive hard maintenance actions at its next overnight stopover. This approach to unscheduled maintenance is brought about by the need to keep the airline flight schedule operating on-time as far as possible without compromising flight safety, as well as the requirement to meet subsequent STLM tasks whenever a current routine check becomes extended due to unplanned maintenance inputs. In turn, it also gives rise to a scenario where the maintenance inputs that are provided by the day shift work groups for unscheduled aircraft technical faults or breakdowns are often unproductive in terms of contributing to the final resolution of these technical issues.

- Night Shift Labour Component:

  The night shift work groups within the Line Maintenance Department utilise 23 AMEs per duty shift. Again, there are two alternating shift cycles and each AME works 12 hours per shift. Currently, the night shift work group that is on duty on a given day allocates a portion of its available manhour supply to performing the aircraft after-flight checks that are called out as a result of the current day-of-operations. These checks are performed from 18:00 in the evening and are required to be completed and certified before the shift closing time at 06:00 the following morning (or earlier if the airline flight schedule demands it). The case organisation has applied standard times for these after-flight checks as detailed in the spreadsheet titled '*Airlink Line Maintenance Labour Scheduling Model (Updated 2012).xlsx*' in Appendix H. These standard time specifications allow for an AME complement to be determined that is effectively allocated exclusively to performing after-flight checks within the night shift work groups. In reality, the required after-flight checks may be allocated across all or most of the on-duty night shift AMEs at the discretion of the supervising Crew Chief. However, for the purposes of this study, a minimum complement of AMEs to meet all of the after-flight checks on the night shift has been calculated and applied.

Table 14 shows the labour supply statistics for STLM activities that have been determined for the current labour planning methodology at the case organisation. Comparing this data to the outputs of the experimental computational modelling approach (as per the four bullet points on page 96), some significant benefits have been identified in terms of reduced labour resources where the experimental model is used. These benefits include a 33% reduction in the number of AMEs that are allocated to STLM duties (down from 24 to just 16), as well as a 48% reduction in the number of manhours that are supplied and the associated labour costs where the fixed hourly labour rate presented on page 96 is employed in both modelling approaches. These figures do not consider the supplementary manhours that may be supplied by the FLM Team in support of the SVM Team, although these manhours may be offset by the contributions that are made by the day shift work groups to unscheduled maintenance activities under the existing labour scheduling regime.

The results presented in the preceding paragraph support the assertion that the implementation of advanced computational modelling methods can yield potentially significant cost savings as well as resource optimisation gains for the case airline and its maintenance services provider. This finding suggests that the current labour planning approach that is employed by the case organisation for its line maintenance activities is inadequate in comparison to the more sophisticated numerical optimisation processes that have been tested in this study and which are based on contemporary developments in the field of operations research. It is of note that these experimental processes have been implemented using PC hardware and software tools that are generally readily available to the modern operations manager. This finding supports the wider application of such methods in addressing comparable resource planning problems in similar operational or business settings.

Table 14 – STLM Labour Resources as per the Current Labour Scheduling Model at the Case Organisation

Description	Value
Total direct maintenance manhours for after-flight checks only, per 28 day cycle	1,596
Total rostered manhours for after-flight checks only, per 28 day cycle << Assumes a 70% labour efficiency factor >>	2,280
Total AMEs required for after-flight check activities only << Assumes 168 manhours per 28 days based on 12 hours per shift and 14 duty shifts >>	13.57
Total AMEs required for after-flight check activities only << Rounding up to the nearest integer value >>	14
Total AME complement effectively dedicated to short-term layover maintenance << Adding 10 x AMEs for day shift operations, i.e. 5 per cycle across 2 shift cycles >>	24
Total AME manhours effectively rostered for short-term layover maintenance << Applying 168 manhours per 28 days based on 12 hours per shift and 14 duty shifts >>	4,032
Total direct labour cost in ZAR << Assuming 164.70 ZAR per AME labour hour >>	664,070.40

Some very promising results have been presented in this subsection relating to the use of the experimental labour scheduling model in the case setting under the ideal condition of no flight schedule disruptions. However, closer scrutiny reveals that the integrity of the case organisation's existing labour planning model for line maintenance activities is questionable in certain areas. In particular, it has been observed that the standard times that are applied for after-flight checks in Spreadsheet 5 in Appendix H are significantly longer in duration than the corresponding standard times that have been determined through direct measurement in this study. In addition, the number of after-flight checks that are called out per day in this spreadsheet is notably higher at a value of 20 than the maximum number of such checks that are required to be performed on any weekday (i.e. 15 on Mondays) as per the contents of Table 6 in Subsection 4.1.2.2.

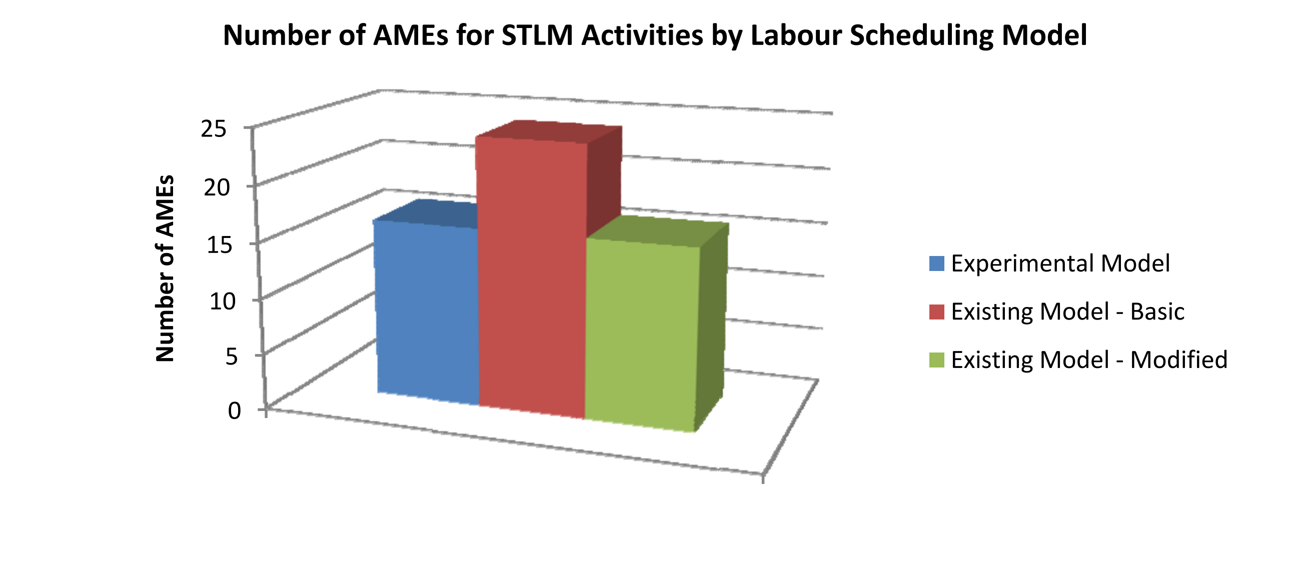
In order to provide a more realistic comparison of the existing and experimental labour planning approaches in the case setting, Table 15 shows an adjusted set of resource outputs for the case organisation's existing line maintenance model. The data presented in this table excludes the effects of over-provisions in respect of the quantity and duration of after-flight check events. In this regard, a summary of the associated parameter modifications has been provided in the table.

Table 15 – STLM Labour Resources as per a Modified Version of the Current Labour Scheduling Model at the Case Organisation

Refinement of the Existing Line Maintenance Labour Planning Model at the Case Organisation	
Summary of parameter changes: • Number of daily J41 after-flight checks performed at the main base reduced from 7 to 5. • Manhours for each J41 after-flight check reduced from 2.00 to 1.42. • Number of daily ERJ135 after-flight checks performed at the main base reduced from 6 to 5. • Manhours for each ERJ135 after-flight checks reduced from 2.50 to 1.75. • Number of daily RJ85 after-flight checks performed at the main base reduced from 7 to 5. • Manhours for each RJ85 after-flight check reduced from 4.00 to 1.83.	
Total direct maintenance manhours for after-flight checks only, per 28 day cycle	700
Total rostered manhours for after-flight checks only, per 28 day cycle << Assumes a 70% labour efficiency factor >>	1,000
Total AMEs required for after-flight check activities only << Assumes 168 manhours per 28 days based on 12 hours per shift and 14 duty shifts >>	5.95
Total AMEs required for after-flight check activities only << Rounding up to the nearest integer value >>	6
Total AME complement effectively dedicated to short-term layover maintenance << Adding 10 x AMEs for day shift operations, i.e. 5 per cycle across 2 shift cycles >>	16
Total AME manhours effectively rostered for short-term layover maintenance << Applying 168 manhours per 28 days based on 12 hours per shift and 14 duty shifts >>	2,688
Total direct labour cost in ZAR << Assuming 164.70 ZAR per AME labour hour >>	442,713.60

Looking at the modified outputs for the case organisation's current labour scheduling model as have been detailed in Table 15, the relative benefits of the experimental optimisation model are much more modest than the initial comparison showed. In fact, this second comparison shows no relative reduction in the number of AMEs allocated to STLM duties (16 AMEs in both cases), although a significant reduction in the number of manhours supplied and associated labour costs of 22% is still realised. This data gives an indication of the importance of accurate demand modelling in the generic labour forecasting process, which is an issue where the case organisation appears to have lacked in its attention to detail and its application of a logical method. Figure 4 summarises the key statistics that have been used to compare the performance capabilities of the experimental optimisation model for STLM labour planning to the case organisation's existing line maintenance labour planning model in both its basic and modified forms.

In conclusion, the more realistic comparison of the competing models suggests that there is limited scope to reduce the number of AMEs that are employed for STLM activities via the optimisation modelling methodology that has been proposed. However, this methodology can generate valid solutions that reduce the number of rostered manhours for affected AMEs by as much as 20% or more. This reduction is achieved by eliminating idle time to the greatest extent that is possible for the given modelling constraints and problem size. Where AME salaries are based on an hourly wage, these manhour savings can be applied to realise significant maintenance cost savings. For the case setting, the labour cost savings over a single 28 day cycle rotation correspond to almost 1.3 million rand of savings when extended over a full calendar year. In a fixed monthly salary environment, manhour savings can instead be used to improve the working conditions of affected shift workers by reducing exposure to fatigue, which is a concern at the case organisation under its current regime of 12 hour shifts for line maintenance. Alternatively, the manhours saved can be applied to routine requirements such as AME training courses, or to the relief of other maintenance teams that may suffer from short-term fluctuations in workload (such as the SVM Team). For the case at hand, these spare manhours can be as many as 37 manhours per AME per 28 day cycle. This number has been derived by comparing the average duty hours per AME per cycle for the experimental model (i.e. 131 manhours) against the 168 duty hours that are allocated per AME per cycle under the existing line maintenance staffing regime.



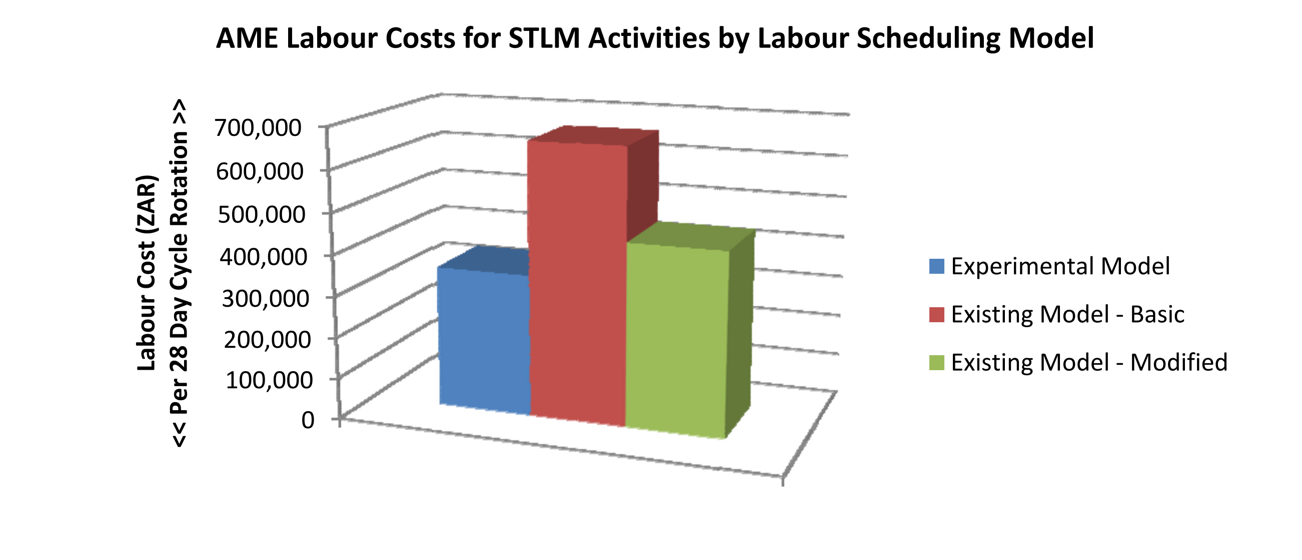


Figure 4 – Comparison of the STLM Resource Outputs from the Experimental Optimisation Model and the Case Organisation's Existing Line Maintenance Labour Model

As a final discussion point in relation to Research Question 1, it is noteworthy how AME occupancy levels in the experimental model have been significantly improved by allocating suitable periods of idle time in between STLM tasks to the support of the SVM Team. By applying this approach in a structured fashion, it has been possible to increase the average AME occupancy level in the case setting from a level of around 50% to more than 70%, even with the constraint of a minimum shift length of eight hours applied that essentially precludes the use of short-time workers to maximise AMEs efficiency levels. Through this approach, AMEs on the FLM Team can contribute more than 500 manhours of support to the SVM Team over a 28 day cycle rotation. These manhours are equivalent to the normal working hours of at least three full-time AMEs on the SVM Team. It is possible that these manhours could be allocated in a formal fashion in order to reduce the number of AMEs that need to be employed on the SVM Team, thereby providing further resource savings to the case organisation in addition to those already quantified.

4.2 Results in Relation to Research Question 2

The study results in respect of Research Question 2 make considerable use of the data that has been developed in answering Research Question 1. In this regard, the primary focus in relation to Research Question 2 has been to carry out testing to determine whether the optimised labour roster that is described in Table 13 in Subsection 4.1.2.7 is robust to the effects of flight schedule disruptions (such as flight delays) that occur routinely during real-life airline operations. Attention has also been given to the profiling of the most common category of flight schedule disruption in the case setting, namely flight delays, to determine if the incidence characteristics of these delays can be approximated to a reasonable degree of accuracy through the use of probabilistic modelling techniques. In summary, the study has addressed the following problem areas in its response to Research Question 2:

- Firstly, an analysis has been presented of flight delay incidence rates and delay durations at the case organisation. This data is based on an analysis of every flight delay event into and out of the case organisation's main base that was recorded by the case organisation over the six month period from 01 January 2011 to 30 June 2011. The historical delay data has been analysed in terms of the percentage of aircraft arrivals or departures that were delayed per day-of-operations, as well as the time duration (in minutes) per flight delay event over the recording period.

- Secondly, the flight delay incidence rate and duration profiles that have been developed from archival records in the case setting have been mapped against a selection of theoretical probability distributions. These comparisons have been used to assess whether the observed profiles of flight delay characteristics can be approximated to a reasonable degree of accuracy using probabilistic modelling techniques. In order to ensure the best fit of the theoretical profiles to the observed data, a least squares adjustment method has been adapted from a contemporary literature source on flight delay profiling and utilised in the data mapping process. The outcomes of the data mapping process have been applied to assess the viability of generating flight delay profiles automatically using probabilistic models in future developments of this area of research. This will reduce the need to collect historical flight delay data from relevant case sites or population samples.

- Thirdly, the primary focus area of Research Question 2 has been investigated by subjecting the optimised labour schedule for STLM activities in the case setting to tests for robustness against the effects of unplanned flight schedule disruptions at the case airline. This testing has utilised records of actual schedule disruptions and associated recovery decisions at the case organisation whereby reactive adjustments were made to the flight schedule profile on selected test days. These changes alter the demand profile for STLM tasks that must be met by the FLM Team on these test days. The adjusted task demand profile on each test day has been analysed against the predetermined FLM labour supply for the day in order to determine if AME demand exceeds supply at any time and to assess the likely workforce management implications. These implications may include call-outs of standby AMEs or the allocation of overtime to on-duty workers.

4.2.1 Analysis of Flight Delay Incidence Rates and Durations at the Case Organisation

In order to measure its performance in delivering an on-time airline service, Airlink maintains a flight delay database as part of its operational records. This database holds information such as the date, flight number, duration and reason of each flight delay event that has been experienced by the airline during its ongoing commercial flight operations. Information from this database has been analysed in this study in order to develop distribution profiles of the incidence rates and time durations of flight delays at the case organisation. In this respect, records of all Airlink flight delays for the six month period from 01 January 2011 to 30 June 2011 have been aggregated for the purpose of statistical analysis. This set of flight delay information is incorporated in Spreadsheet 3 in Appendix H, titled '*Airlink Flight Delays, 01 Jan to 30 Jun 2011.xlsx*'.

In analysing the set of flight delay data that has been collected at Airlink, the data has been filtered into distinct analysis categories relating to departure and arrival delays at the case organisation's main base. The reasons for this filtering are explained in detail in Subsection 4.2.3 and relate to the causality that exists between flight delays and the STLM tasks that are associated to arrival or departure movements of affected aircraft. Figures 5 to 7 illustrate profiles of the incidence rates and durations, respectively, of departure and arrival delays for the period from 01 January 2011 to

30 June 2011 at the case organisation's main base at OR Tambo International Airport. In this regard, the underlying analysis has considered a departure to be delayed if its ATD is five minutes or more beyond the STD of the affected flight. Similarly, the analysis has considered an arrival to be delayed where the ATA of the affected flight exceeds its STA by five minutes or more. The reason for the adoption of a five minute baseline is that it corresponds to the minimum time interval at which resource levels are checked in the STLM labour scheduling model that has been used in the study.

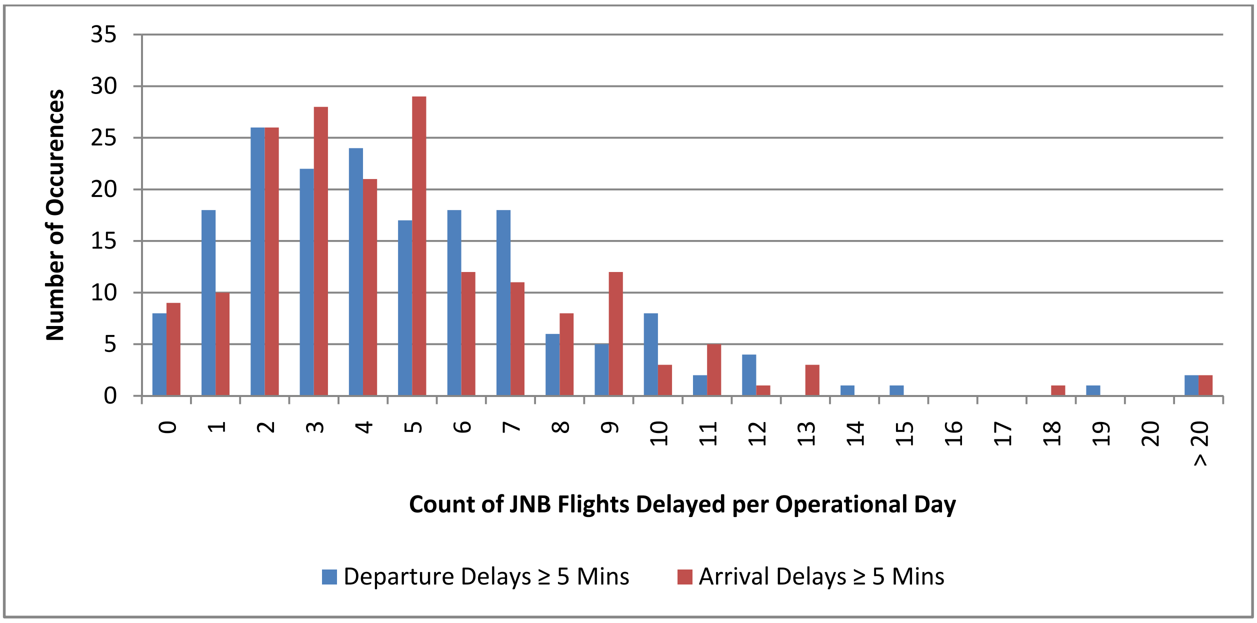


Figure 5 – Count of Flight Delays at the Case Organisation's Main Base per Operational Day for the Period 01 January 2011 to 30 June 2011

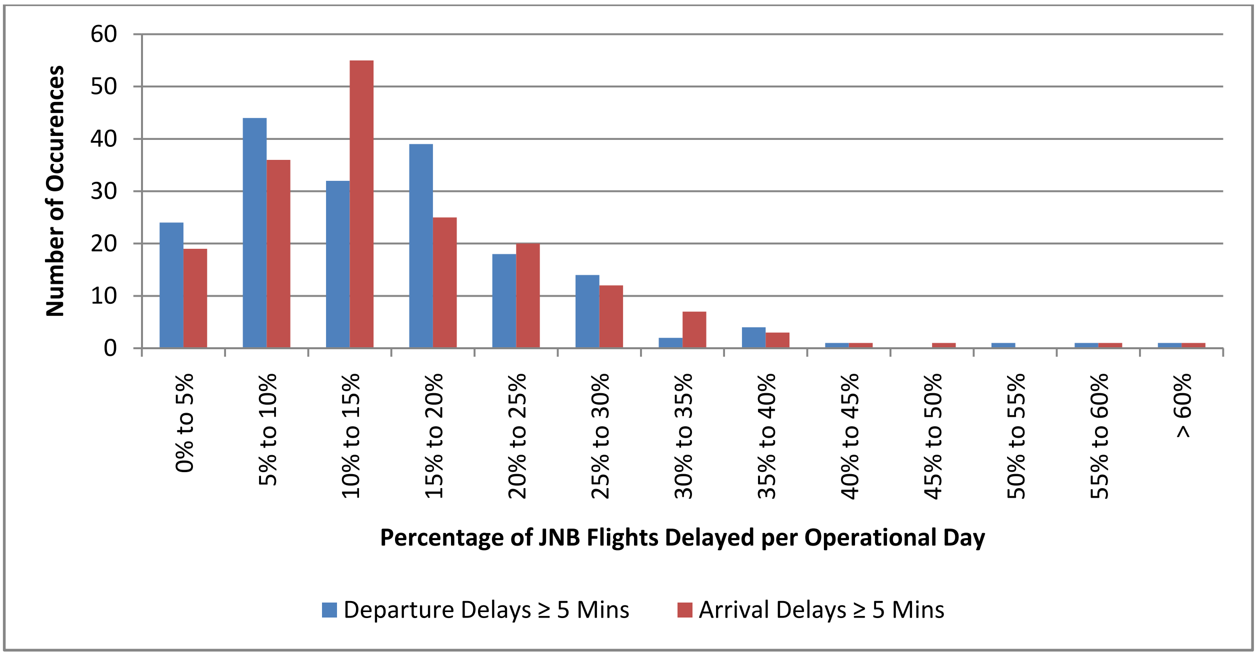


Figure 6 – Percentage of Flights at the Case Organisation's Main Base that are Delayed per Operational Day for the Period 01 January 2011 to 30 June 2011

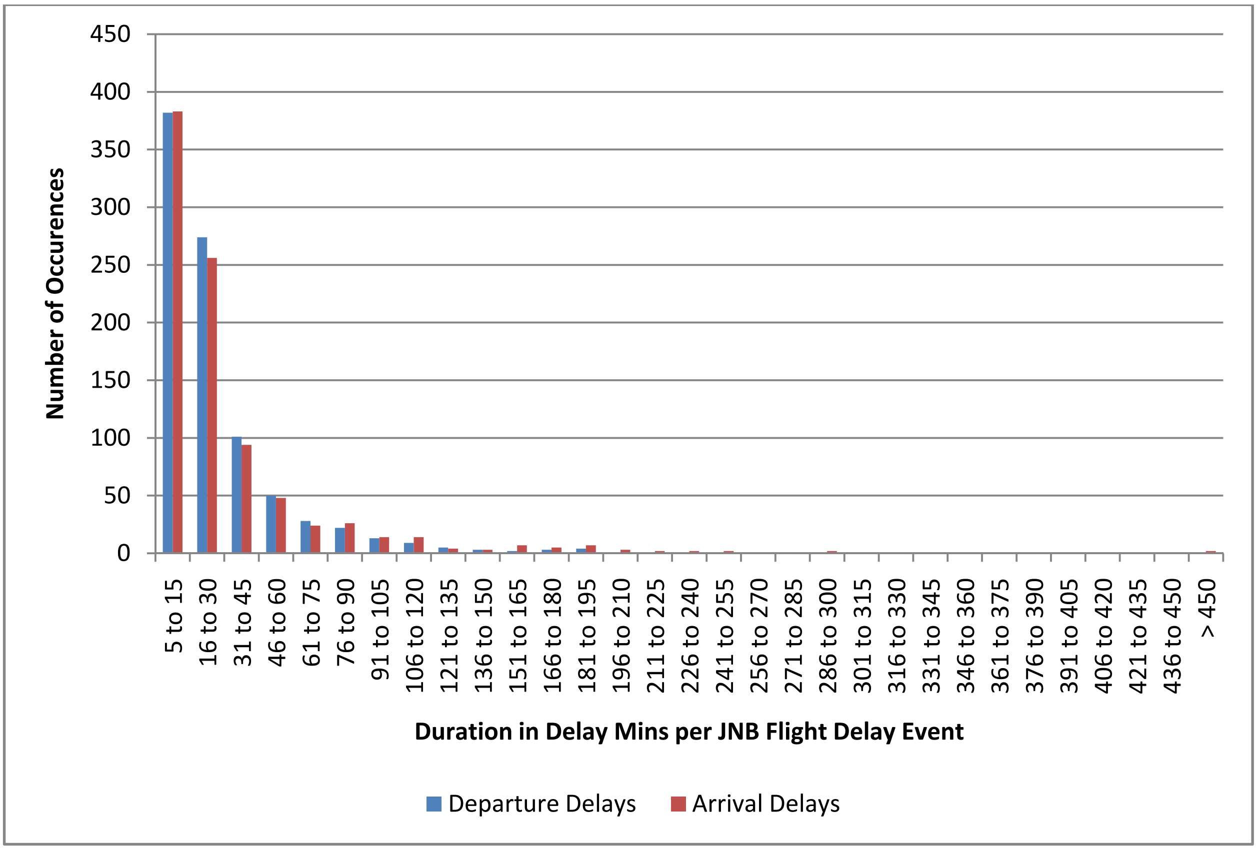


Figure 7 – Number of Delay Minutes per Delayed Flight at the Case Organisation's Main Base for the Period 01 January 2011 to 30 June 2011

Figures 5 through 7 provide useful data profiles that can be compared to equivalent theoretical probability distributions such as the Poisson and Gamma distributions (see Subsection 4.2.2). It is noteworthy that the data in Figure 6 is essentially a normalised representation of the data shown in Figure 5. In this regard, the application of a percentage value for delayed departures and arrivals per day normalises the incidence rates of these delays to a common baseline of 'per 100 flights'. Figure 6 is a more appropriate means of representing flight delay incidence rates than Figure 5 as the number of flight departures and arrivals per day at the case organisation's main base can vary significantly according to variations in the organisation's flight schedule by weekday and season. For example, between 01 January 2011 and 30 June 2011 the count of aircraft arrivals into ORTIA per day varied from a minimum count of 17 arrivals up to a maximum count of 48 arrivals. Figure 6 has therefore been used instead of Figure 5 in order to compare the observed incidence rate profiles of flight delays in the case setting to the probability density distributions of relevant and appropriately-matched theoretical functions.

To enable more detailed scrutiny of the data profiles that are displayed in Figures 5 through 7, a MS Excel spreadsheet that shows the supporting calculations for these figures has been included as an appendix to this study. In this regard, refer to Spreadsheet 9 in Appendix I, titled '*Analysis of Airlink Flight Delay Records, 01 Jan to 30 Jun 2011.xlsx*'.

4.2.2 Comparison of the Measured Flight Delay Incident Rate and Duration Profiles to Selected Theoretical Probability Distributions

Referring to Subsection 2.3.4 of this study, a number of research works have been published in which the incidence rates or durations of airline flight delays are compared to theoretical probability distribution functions (e.g. the Normal distribution) that can be described mathematically and which can be readily reproduced. A similar exercise has been carried out in this study in an attempt to accurately model the observed incidence rate profiles of departure and arrival delays in the case setting (see Figure 6), as well as the profiles of the time duration of these delays (see Figure 7). Based on the contents of the supporting literature review, the following theoretical distributions have been selected for comparison against the flight delay data from the case organisation:

- Normal distribution
- Poisson distribution
- Exponential distribution
- Gamma distribution
- Weibull distribution
- Lognormal distribution

In order to compare the case-specific data to the various theoretical distribution functions, the first step that has been followed is to 'match' each theoretical function to the affected case data profile by setting its shape and scale parameters (as applicable) to coincide with the mean, variance and standard deviation values (as applicable) for the case data. Note that this matching process is described in detail per theoretical function in Appendix K. After matching each theoretical function to the case data profile under consideration, the two profiles have then been overlaid graphically in order to assess the 'goodness of fit' of the theoretical data to the case data. When doing so, the theoretical functions have been profiled using the same horizontal axis data ranges that are shown in Figures 6 and 7. Thereafter, the 'goodness of fit' of each overlay has been quantified using the 'CORREL' function in MS Excel to calculate a correlation coefficient (R) between the two data arrays, which is then squared to obtain an R^2 value. The theoretical functions have then been ranked from largest to smallest in terms of their R^2 value in relation to the associated case data profile. In this regard, the overlay with the highest R^2 value has been identified as the best initial fit to the corresponding case data profile.

Adapting from the work of Mueller and Chatterji (2002), additional calculations have then been performed to improve the 'initial fit' of the respective theoretical functions via a least squares method. In this regard, the theoretical profiles have been set to an initial shape and scale as described in the preceding paragraph. The relevant input parameters of each theoretical function have then been varied using the MS Excel Solver analysis tool in order to minimise the sum of the squared difference between the theoretical profile and the affected case data profile across each of the associated data range values on the horizontal axis. The parameter values corresponding to the minimum sum of squares calculation for each scenario have been selected as the modified 'best fit' parameter values for the theoretical distribution function that is being evaluated. As a final step, an additional R^2 calculation has been performed for each of the modified theoretical functions in relation to its associated case data profile. This calculation has enabled the selection of the best fitting function according to the highest R^2 value achieved.

Figures 8 and 9, reviewed in conjunction with Table 16, show the best fitting theoretical functions that have been determined for each case data profile that has been considered in this subsection. Some noteworthy outcomes have been extracted from these results, including the following points of observation:

- The modelling outcomes that have been achieved for both the departure and arrival delay characteristics in the case setting are reasonably consistent.

- For all four case data sets, high R^2 values of significantly above 90% have been achieved for the best fitting theoretical functions. These high R^2 values signify that the case data profile and that of the best fitting theoretical function are highly correlated in each instance. This outcome supports the assertion that probabilistic modelling is a viable means of accurately forecasting airline flight delay characteristics.

- With regards to the incidence rates of flight delays per day, Gamma and Weibull functions have been shown to be nearly equivalent in producing the best fits to both the departure and arrival delay profiles in the case setting. In addition, the Normal distribution has been shown to produce good fits to the case data where the least squares modification method is implemented. This observation is significant as the Normal distribution is able to generate positive probability outputs at an input value of zero and therefore has the ability to model occurrences of zero delays on a given day-of-operations. It should be noted in this regard that the case data includes a number of days where zero departure or arrival delays were recorded. The Gamma and Weibull distributions, on the other hand, are unable to generate non-zero outputs at an input value of zero and therefore cannot replicate occurrences of zero-delay days in their standalone form.

- Looking at the time durations recorded per delay event, the Lognormal distribution has been shown to produce very precise fits to the case data where least squares modification is applied, with R^2 values of close to 100% for both the departure and arrival delay profiles. Good fits have also been achieved with the Gamma and Weibull functions after applying the least squares method. Furthermore, the issue of generating positive probability values at an input value of zero is not relevant to these data sets as it is not possible for a delay occurrence of zero time duration to be registered in a real-life airline setting.

Table 16 – R^2 Values for the Mapping of Selected Theoretical Distribution Functions to the Case Data Profiles of Flight Delay Incidence Rates and Time Durations

(1) Data Mapping Results for '*% of Departing Flights per Day Delayed ≥ 5 Mins*'						
Correlation to Case Data	Theoretical Distribution Function					
	Normal	Poisson	Exponential	Gamma	Weibull	Lognormal
R^2 Value > Pre LSM	0.850	0.525	0.605	0.918	0.922	0.872
R^2 Value > Post LSM	0.939	0.504	0.665	0.937	0.945	0.901
(2) Data Mapping Results for '*% of Arriving Flights per Day Delayed ≥ 5 Mins*'						
Correlation to Case Data	Theoretical Distribution Function					
	Normal	Poisson	Exponential	Gamma	Weibull	Lognormal
R^2 Value > Pre LSM	0.793	0.686	0.479	0.891	0.888	0.906
R^2 Value > Post LSM	0.915	0.855	0.538	0.930	0.928	0.907
(3) Data Mapping Results for '*Time Duration of Departure Delays ≥ 5 Mins*'						
Correlation to Case Data	Theoretical Distribution Function					
	Normal	Poisson	Exponential	Gamma	Weibull	Lognormal
R^2 Value > Pre LSM	0.500	0.304	0.917	0.928	0.782	0.906
R^2 Value > Post LSM	0.973	0.307	0.996	0.997	0.997	0.999
(4) Data Mapping Results for '*Time Duration of Arrival Delays ≥ 5 Mins*'						
Correlation to Case Data	Theoretical Distribution Function					
	Normal	Poisson	Exponential	Gamma	Weibull	Lognormal
R^2 Value > Pre LSM	0.341	0.084	0.845	0.921	0.791	0.930
R^2 Value > Post LSM	0.964	0.272	0.991	0.995	0.996	0.998

Note:
(a) The acronym LSM stands for 'least squares modification'.
(b) The R^2 value for the best fitting theoretical function per case data profile is shaded in YELLOW.

Note 1: All theoretical functions are shown after least squares modification.

Note 2: In all the graphs below, the x-axis shows the percentage of flights delayed per day while the y-axis shows the count of occurrences for the various x-axis data ranges.

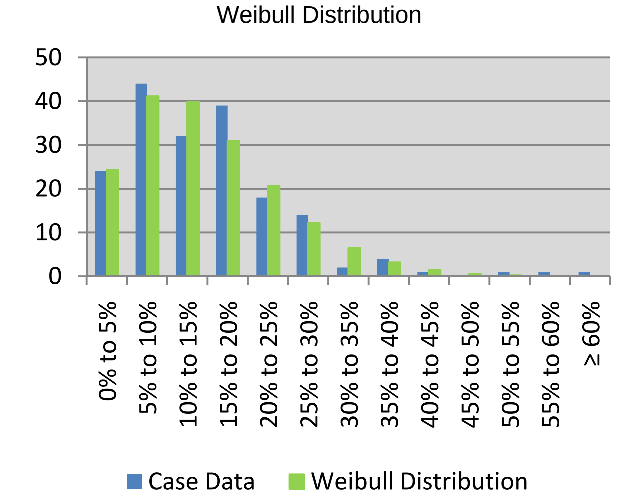
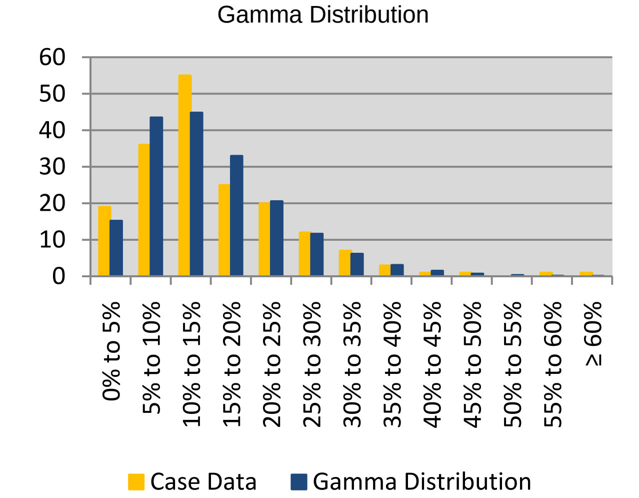
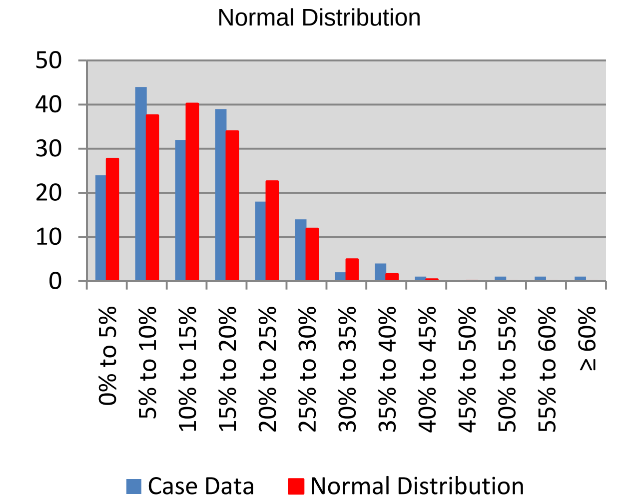
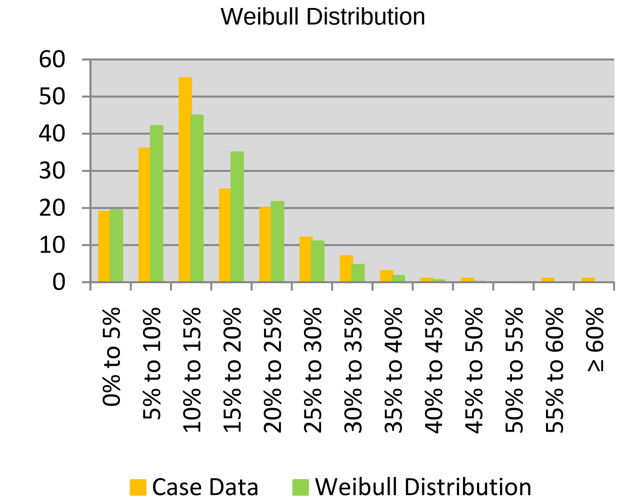
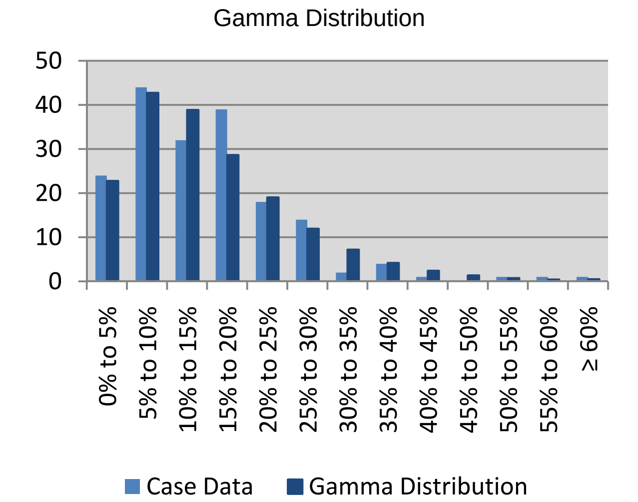
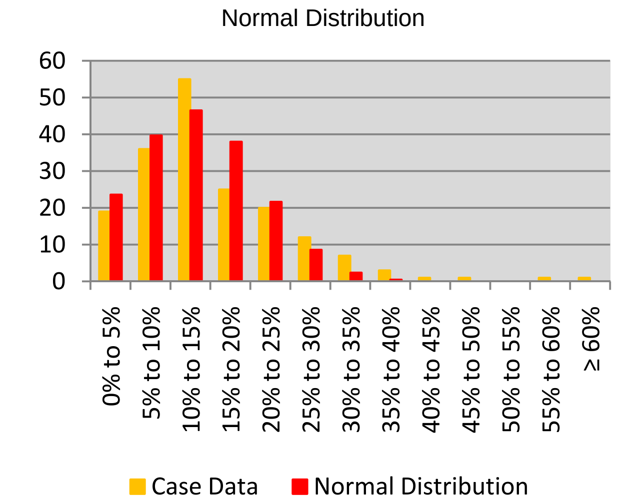
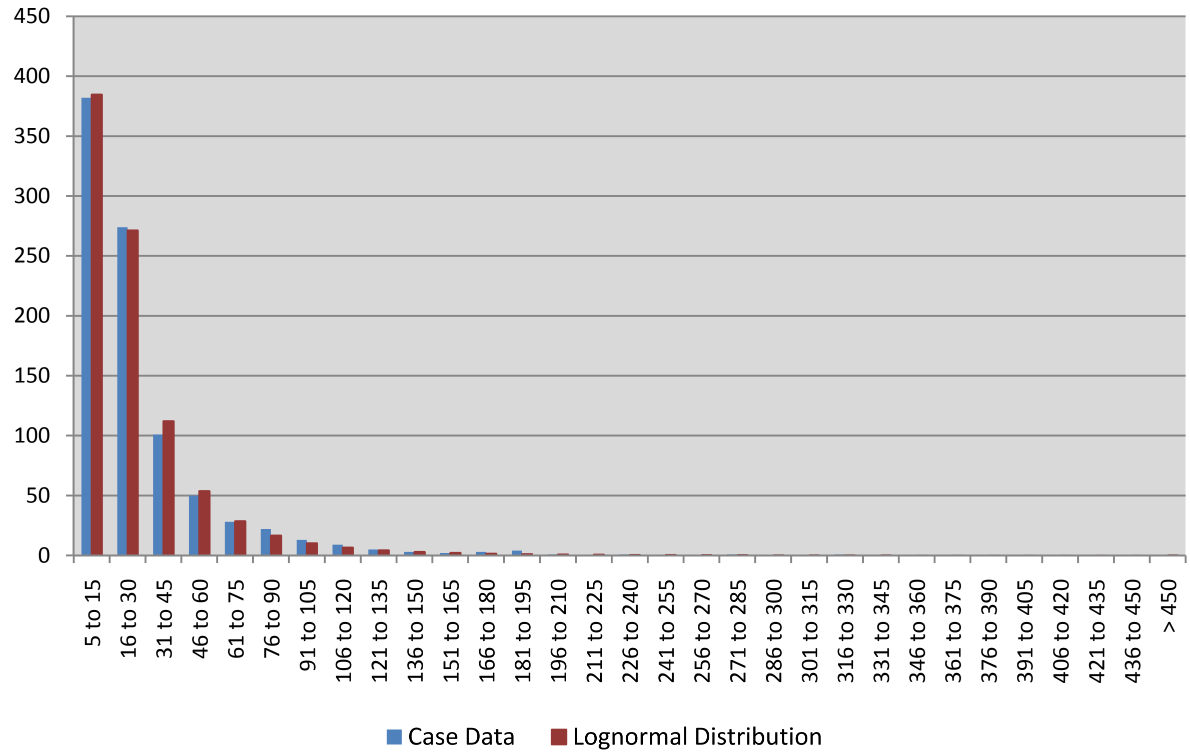
DEPARTING FLIGHTS	ARRIVING FLIGHTS
 R^2 = 0.945	 R^2 = 0.930
 R^2 = 0.939	 R^2 = 0.928
 R^2 = 0.937	 R^2 = 0.915

Figure 8 – Best Fitting Theoretical Functions to the Case Data Profiles of the Percentage of Flights Delayed per Operational Day, Ranked by R^2 Value

Note 1: Both theoretical functions are shown after least squares modification.

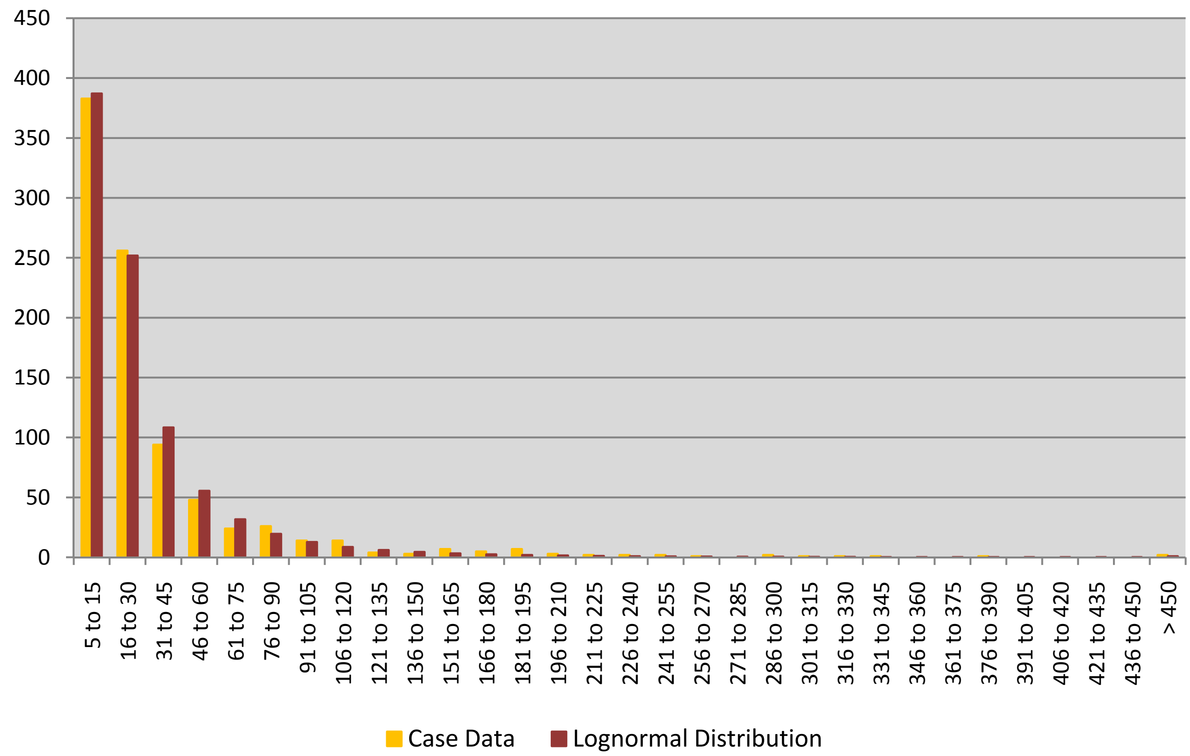
Note 2: In the two graphs below, the x-axis shows the time duration in minutes per flight delay while the y-axis shows the count of occurrences for the various x-axis data ranges.

Lognormal Distribution versus the Case Data Profile for Departure Delays



$R^2 = 0.999$

Lognormal Distribution versus the Case Data Profile for Arrival Delays



$R^2 = 0.998$

Figure 9 – Best Fitting Theoretical Function to the Case Data Profiles of the Number of Delay Minutes per Delayed Flight

For reference purposes, the detailed calculations that describe how the results in Table 16 as well as Figures 8 and 9 have been derived are contained in an appendix to this study. In this regard, refer to Spreadsheet 10 in Appendix I, titled '*Mapping of Theoretical Functions to Airlink Flight Delay Profiles, 01 Jan to 30 Jun 2011.xlsx*'.

4.2.3 Robustness Testing of the Experimental Labour Plan for STLM Activities under Disrupted Flight Schedule Conditions

4.2.3.1 Examining the Causality between Airline Flight Schedule Disruptions and Unplanned Variations to STLM Task Schedules

In order to subject the experimental labour plan for STLM activities in the case setting to tests for robustness against the effects of unplanned flight schedule disruptions, it is important to have a clear understanding of the causality that exists between airline flight schedule disruptions and the unplanned STLM task variations that can follow from these disruptions. These causal relationships are non-trivial in nature and add a significant degree of complexity to any attempt to model unplanned variations to STLM task schedules, even if the underlying flight schedule disruptions have been accurately modelled using mathematical or computational techniques. During this study, this causality has been investigated by scrutinising historical records of the operational decisions that the case organisation implemented in response to schedule disruption events over the period from 01 June 2011 to 20 June 2011. The analysis of these records has identified the following set of causal factors that are at play:

- Flight schedule disruptions have been separated into two distinct categories in this study based on their causality with regards to aircraft maintenance activities. In this regard, a disruption event may relate to one or more deficiencies in the technical or airworthiness status of the associated aircraft. This category of disruption is generally referred to as a 'technical disruption'. Technical disruptions may also be described using related terms such as 'technical delays', 'technical cancellations' or 'technical swaps'. These disruptions have been distinguished from disruptions that are unrelated to the technical status of the aircraft (e.g. delays relating to weather or air traffic control instructions). The reason for this distinction is that technical disruptions are more complex than non-technical disruptions in terms of the maintenance interventions and schedule recovery decisions that they invoke from an operations management perspective.

- Where schedule disruptions are unrelated to the technical or airworthiness status of the affected aircraft, the main area of focus is on arrival delays into a given base of operations. Where an arrival delay occurs, it will at the very least shift the timing window of the STLM task that is associated to that arrival (either a transit check or an after-flight check). This effect will be produced with no intervention by the affected airline operator. If the operator in question chooses to intervene to manage the effects of an inbound delay of this type, the action that may be implemented is to deploy a standby aircraft into service on the next outbound flight leg (if applicable and subject to availability of a standby aircraft). This type of intervention constitutes an aircraft swap event. Such a swap event may in turn give rise to changes in the scope of STLM tasks that are associated to the delayed arrival, such as adding a pre-flight check for the standby aircraft, as well as introducing new or modified timing windows for the one or more STLM tasks that are affected by the swap.

- Where non-technical disruptions occur on outbound flight legs, there is generally no direct impact on the STLM task schedule. Examples of such disruptions are flight delays relating to late boarding of passengers, or aircraft departure holds that are called due to severe weather either en-route or at the planned destination airport. In these cases, the STLM task that preceded the affected departure (either a pre-flight or a transit check) will have been performed on the assumption that the affected aircraft will not incur any new delay time on its next departure. Outbound delays of this type may result in 'knock on' delays on subsequent inbound flights for an affected aircraft, but the resulting delays will be logged directly against the associated inbound flights as propagated (or 'rotational') delay events. There is one possible scenario where an outbound non-technical disruption may impact directly on the STLM task schedule for an airline. This scenario is where the airline calls a cancellation on an outbound flight, e.g. due to persistent severe weather at the planned destination airport. This scenario may have multiple consequences depending on how the airline has planned to utilise the affected aircraft for the remainder of the day. One possible outcome is that the affected aircraft is vacated for a period of time and then reactivated for later planned flights. In such a case, airline policy may require that a fresh pre-flight check is carried out on the affected aircraft rather than the transit check that would have been performed had the aircraft completed its original sequence of planned flights.

- Where airline schedule disruptions are technical in nature, the recovery management of a given disruption must take into account the initial maintenance assessment of the aircraft's technical status and the maintenance actions that are then required for the troubleshooting, repair and release of the aircraft back to line operations. Depending on the nature of an airline's operational support structures, such unplanned maintenance actions may even include the transportation of AMEs and materials to other airports that do not have suitable local maintenance capabilities. It is practically impossible for airlines to predict precisely when technical disruption events will occur. As such, resourcing for these events from a maintenance perspective requires the application of methodologies such as fluctuation or permanence centred planning, rather than task-based planning from a predetermined work schedule as is typically the case for STLM activities. In addition to unplanned maintenance inputs that are introduced with regards to the technical deficiency (or deficiencies) at hand, technical disruptions also impact on STLM task schedules in the same ways as have already been described for non-technical disruption events.

- One additional causal factor is of relevance with regards to technical disruptions and their impacts on STLM task schedules. This factor is a temporal factor relating to the time at which aircraft technical deficiencies are identified and reported to the operations management structures at the affected airline. For example, a flight crew may radio in to report a technical fault on an aircraft whilst on an inbound flight leg into a given base of operations. Where the affected aircraft is scheduled to operate one or more subsequent outbound flights from this base, it may be possible to assess the information provided by the crew and make an early decision to implement an aircraft swap for the next flight leg (subject to availability of standby aircraft). In this case, the standby aircraft that is selected for deployment can be pre-flight checked in place of the transit check that was originally scheduled for the inbound aircraft. It may even be possible to implement this pre-flight check without delaying the next outbound flight. In contrast, a similar scenario may play out where an aircraft arrives into the same base of operations and is declared to be in an adequate technical condition by its flight crew. The aircraft is subjected to its routine transit check where the same conclusion is reached by an AME. The aircraft is then released to service and prepared for its next departure. However, during the start-up sequences for its next flight, a technical deficiency becomes apparent and the flight crew calls for an AME to assess the aircraft status. After investigating, the AME who responds to the crew call confirms the technical deficiency to be a hard fault that will require a number of hours of aircraft downtime. If the same standby aircraft is available at this point, the likely result is that a delay will be called on the affected flight number and an aircraft swap will be implemented from the faulty aircraft to the standby aircraft. It is now necessary to carry out an unplanned pre-flight check on the standby aircraft in addition to the transit check that has recently been performed on the faulty aircraft. Furthermore, the time that is needed to identify available manpower and then implement this pre-flight check will contribute to the duration of the associated flight delay.

Based on the causal factors that are presented in this subsection, it is reasonable to assume that all aircraft whose flight sequences are planned to commence from a given base of operations on a given day shall be maintained on the basis that they will depart on-time on their first departure of the day. These aircraft shall therefore be subjected to pre-flight checks in line with the STD of their first flight of the day, irrespective of whether or not this flight then becomes disrupted for any reason. Under this assumption, it is not possible for schedule disruptions to alter the timing of any of the predetermined pre-flight checks for a given day-of-operations. However, such disruptions may still introduce supplementary unplanned pre-flight checks into the STLM task schedule.

Now that the causality between flight schedule disruptions and unplanned variations to STLM task schedules has been examined from a generic perspective, it is logical to proceed in examining how schedule disruption impacts have been analysed in the case setting. Before continuing with this, however, it is important to confirm whether the investigation and rectification of unplanned aircraft defects and any other maintenance inputs relating to technical disruption events is to be included within the scope of STLM activities in this setting. With reference to Subsections 1.5 and 4.1.2.1, a simplifying assumption has been applied in this study whereby the case organisation's experimental FLM Team is protected from the most significant of the supplementary maintenance effects pertaining to technical disruptions. Under this assumption, the SVM Team is designated to meet all line maintenance actions that are beyond the scope of the checklist-based STLM tasks that are implemented in the case setting. This includes all troubleshooting and repair actions relating to aircraft technical disruptions. As such, all unplanned aircraft defect rectifications have been excluded from the definition of STLM activities in the case setting. Consequently, a significant portion of the complexity relating to the effects of technical disruptions (beyond those generally associated to all schedule disruption events) has been removed when looking from the perspective of the FLM Team.

In order to test the robustness of the experimental labour plan for the FLM Team, historical records of the planned and actual flight schedules that were operated at the case organisation over the 20 day period from 01 to 20 June 2011 have been analysed in conjunction with records of the flight schedule disruptions that were experienced over this date range. This analysis has mapped a STLM task profile for each day that incorporates the unplanned demand changes relating to any schedule disruptions that occurred. Task allocation processes have then been implemented in order to determine whether the optimised labour plan for the FLM Team, as detailed in Table 13 in Subsection 4.1.2.7, can accommodate the modified task demand profile on each day without any resource conflicts. Wherever resource conflicts have occurred, these have been scrutinised to determine the likely implications in terms of unplanned overtime or staff callouts in support of the on-duty workforce. In essence, the robustness testing process has examined how the outputs of the labour optimisation model react to unplanned input variations. These variations range from marginal changes to more extreme changes depending on the operational conditions of the day. As such, this testing can be described as a form of sensitivity analysis.

The robustness testing process detailed in the preceding paragraph has considered two sources of variation with regards to demand levels for STLM tasks when compared to the data on which the optimised labour plan for the FLM Team has been developed. Firstly, the process has identified differences in terms of the planned aircraft flight schedules by day for the date range 01 to 20 June 2011 in comparison to the flight schedules for the representative week of operations from 05 to 11 September 2011. In this way, the study has considered the effects on a fixed crew roster for STLM activities of seasonal or other adjustments to the planned flight schedule. Such adjustments may affect the quantity of aircraft movements for which STLM checks are required, as well as the departure and arrival times associated with these movements. Secondly, the process has mapped the aircraft roster changes that are introduced by flight schedule disruptions, or the recovery plans that are associated to these disruptions. These roster changes may in turn result in unplanned changes to the predetermined demand profile for STLM tasks on a given day-of-operations.

Figure 10 illustrates the finalised process flow for the robustness testing procedure that has been implemented in the study. This process model is an adaptation of the IPO model that has already been presented in Figure 2 in Subsection 3.4.1. In this regard, minor changes have been made in relation to the planned flight schedule input as well as the flight schedule variation inputs for the sensitivity analysis.

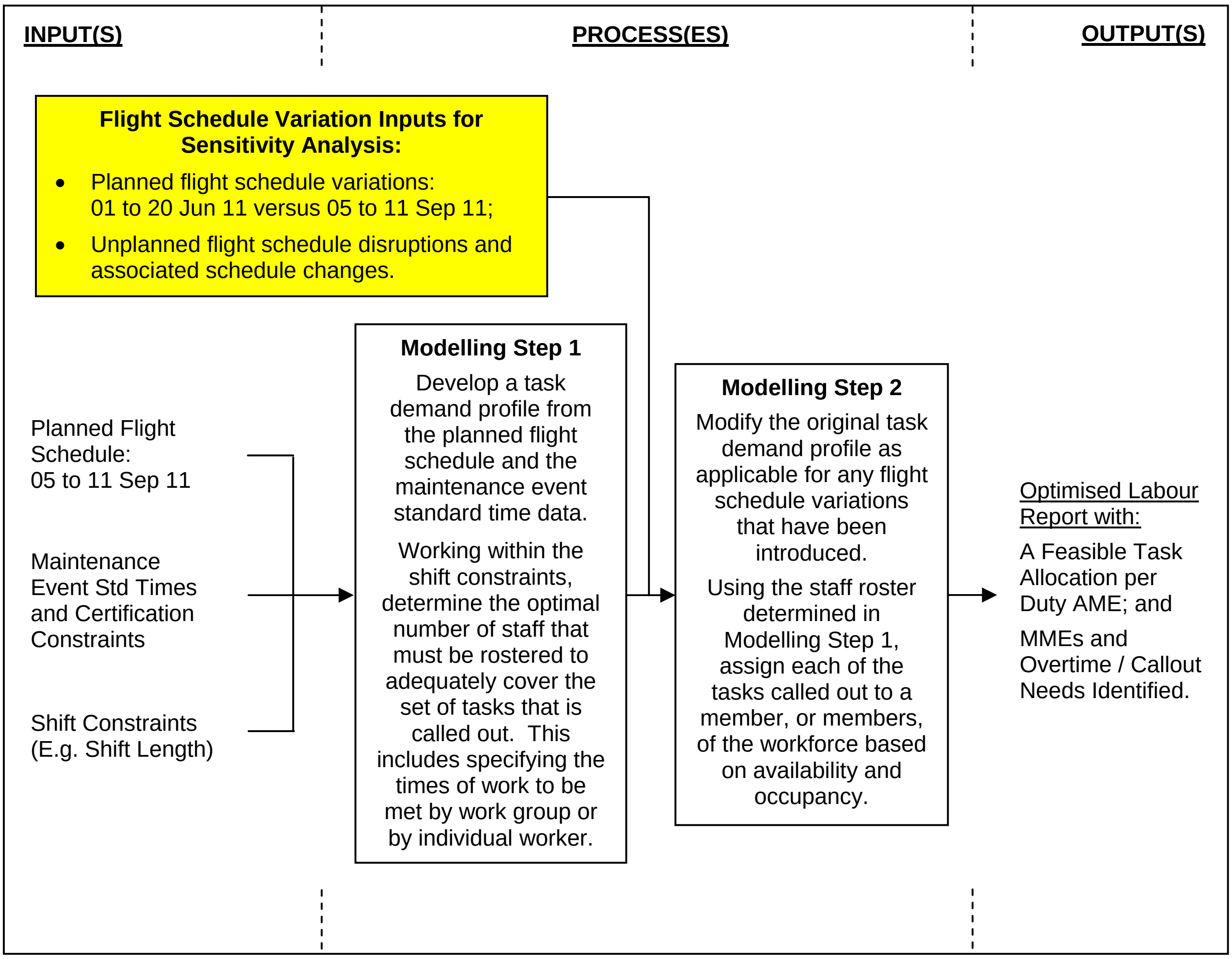


Figure 10 – Finalised Input-Process-Output (IPO) Model Representation of the Robustness Testing Process for the Experimental Personnel Scheduling Model

4.2.3.2 Flight Schedule Disruption Inputs for the Sensitivity Analysis

Working from records of the planned flight schedules at the case organisation, a simple exercise has been completed to scope the differences in planned STLM activity levels between the date range used in developing the FLM Team's optimised labour plan (i.e. 05 to 11 September 2011) and the date range used for the robustness testing exercise (i.e. 01 to 20 June 2011). In addition, differences between the planned flight schedules and the flights that were actually flown per day over the robustness testing date range have been measured. This has been done by comparing the planned flight schedule for each day against records of the flights that were ultimately logged for each day by aircraft tail number. Any differences have been mapped against corresponding records of the flight delays and other schedule disruptions that were recorded for the day in order to assess the underlying drivers of the unplanned schedule changes. Table 17 shows a summary of the schedule variation inputs that have been generated through this exercise.

Table 17 – Summary of the Flight Schedule Variation Inputs for the Sensitivity Analysis

		Model Development Data					Robustness Testing Data										
							Planned Differences			Unplanned Differences			All Differences				
Date	Weekday	Time Window >> Earliest to Latest Departure / Arrival	# of PF Checks Called Out	# of TCs Called Out	# of AF Checks Called Out	Total # of STLM Checks	Additional PF Checks Called Out	Additional TCs Called Out	Additional AF Checks Called Out	Additional PF Checks Called Out	Additional TCs Called Out	Additional AF Checks Called Out	Time Window >> Earliest to Latest Departure / Arrival	# of PF Checks Called Out	# of TCs Called Out	# of AF Checks Called Out	Total # of STLM Checks
1-Jun-11	Wed	14:20	13	25	13	51	2	-2	2	0	0	0	14:35	15	23	15	53
2-Jun-11	Thu	14:20	14	26	13	53	0	-3	1	1	-1	1	14:35	15	22	15	52
3-Jun-11	Fri	14:20	15	26	14	55	-1	-2	-1	1	1	0	17:35	15	25	13	53
4-Jun-11	Sat	11:05	11	9	12	32	1	0	0	0	0	1	11:30	12	9	13	34
5-Jun-11	Sun	11:35	14	12	14	40	-4	2	-3	2	-1	1	11:35	12	13	12	37
6-Jun-11	Mon	14:20	15	23	15	53	-1	1	-2	2	-1	2	14:20	16	23	15	54
7-Jun-11	Tue	14:20	14	23	14	51	0	0	0	0	0	0	14:20	14	23	14	51
8-Jun-11	Wed	14:20	13	25	13	51	1	0	1	3	-1	3	14:20	17	24	17	58
9-Jun-11	Thu	14:20	14	26	13	53	-1	-2	0	2	-1	1	14:20	15	23	14	52
10-Jun-11	Fri	14:20	15	26	14	55	-1	-2	-1	2	-2	2	14:20	16	22	15	53
11-Jun-11	Sat	11:05	11	9	12	32	0	1	0	1	-1	1	11:05	12	9	13	34
12-Jun-11	Sun	11:35	14	12	14	40	-2	2	-3	1	-1	1	11:35	13	13	12	38
13-Jun-11	Mon	14:20	15	23	15	53	-2	3	-2	2	-4	2	14:20	15	22	15	52
14-Jun-11	Tue	14:20	14	23	14	51	-1	0	-1	1	0	1	14:20	14	23	14	51
15-Jun-11	Wed	14:20	13	25	13	52	0	1	0	2	-2	2	14:20	15	24	15	54
16-Jun-11	Thu	14:20	14	26	13	53	-3	-9	-2	0	0	0	14:20	11	17	11	39
17-Jun-11	Fri	14:20	15	26	14	55	-1	-9	-1	2	-1	2	14:20	16	16	15	47
18-Jun-11	Sat	11:05	11	9	12	32	0	0	0	0	0	0	11:10	11	9	12	32
19-Jun-11	Sun	11:35	14	12	14	40	-2	2	-2	0	0	0	11:35	12	14	12	38
20-Jun-11	Mon	14:20	15	23	15	53	0	1	0	1	0	1	14:30	16	24	16	56

In order to demonstrate how the data in Table 17 has been developed, a detailed analysis of the schedule disruptions that affected operations at the case organisation's main base on the 08th of June 2011 has been provided in Spreadsheet 11 in Appendix I. The affected spreadsheet is titled '*Contributing Schedule Disruption Events and Related STLM Task Profile Variations at Airlink's Main Base on 08 June 2011.xlsx*'. This spreadsheet demonstrates just how significant the STLM task profile changes in relation to schedule disruptions may be on a given day-of-operations at a medium to large airline base. On this particular Wednesday, two additional STLM tasks in the form of a pre-flight check and an after-flight check were called out in the case setting as a result of planned schedule changes in comparison to the Wednesday from the representative operational week (i.e. the 07th of September 2011). However, STLM task profile variations relating to unplanned schedule disruptions were of far greater significance on this day. In this regard, the spreadsheet provides information on 39 aircraft movements at the case organisation's main base where STLM task profile changes were brought about, either in terms of the timing or scope of the associated tasks. Of these disrupted movements, 22 related to normal arrivals where flight delay implications were at play, whilst two related to abnormal arrivals in which outbound flights were forced to return to base due to inclement weather conditions at the planned destination airfield. Furthermore, STLM task variations were associated to 13 aircraft departures, six of which were influenced by aircraft technical faults or structural damage. The overall effect of these disrupted movements was that an additional five STLM tasks were called out at the case organisation's main base on the 08th of June 2011. This set of additional tasks included three supplementary pre-flight checks as well as three supplementary after-flight checks. These were offset by one transit check that was entirely removed from the STLM maintenance schedule for the day.

The set of disruption data for the 08th of June 2011 shows a comparatively high level of unplanned variations to the case organisation's flight schedule for the day. Out of a total of 108 flights that were planned across the case organisation's network, only 105 were flown as three flights were forced to turn back from their intended destination due to bad weather, resulting in cancellations of the return flights. Of the 105 flights operated, 60 flights were subject to inbound or outbound delays. In percentage terms, this equates to 57.1% of flights impacted by delays. 28 of these 60 delays were driven by initiating delay events, while the remaining 32 delays were attributed to rotational effects that propagated from an initiating delay. The drivers of the initiating delay events included factors such as air traffic control (ATC) start delays (relating to airfield congestion), poor weather, aircraft towing delays, aircraft technical faults and an aircraft lightning strike.

Looking specifically at main base operations at the case organisation on the 08th of June 2011, 78 aircraft movements (i.e. arrivals or departures) were handled throughout the operational day. This set of movements gave rise to 58 STLM tasks, 17 of which were aircraft pre-flight checks relating to first departure events. The remaining 41 tasks were associated to inbound flights for turnaround (i.e. transit check) or night stop (i.e. after-flight check). 49 of the 78 aircraft movements, or 62.8%, were subject to inbound or outbound flight delays. Of these 49 delayed movements, it has been identified that 39 were impacted by disruptions that in turn affected the execution of STLM tasks in the case setting, either in terms of the timing or scope of the associated tasks. It should be noted in this regard that disruptions to certain flights have been assessed to have had no impact on the associated STLM task requirements for the day. For example, an air traffic control delay on Flight Number SA8252 would have impacted the departure time of the flight after the affected aircraft had already been subjected to a pre-flight check on the assumption of an on-time departure.

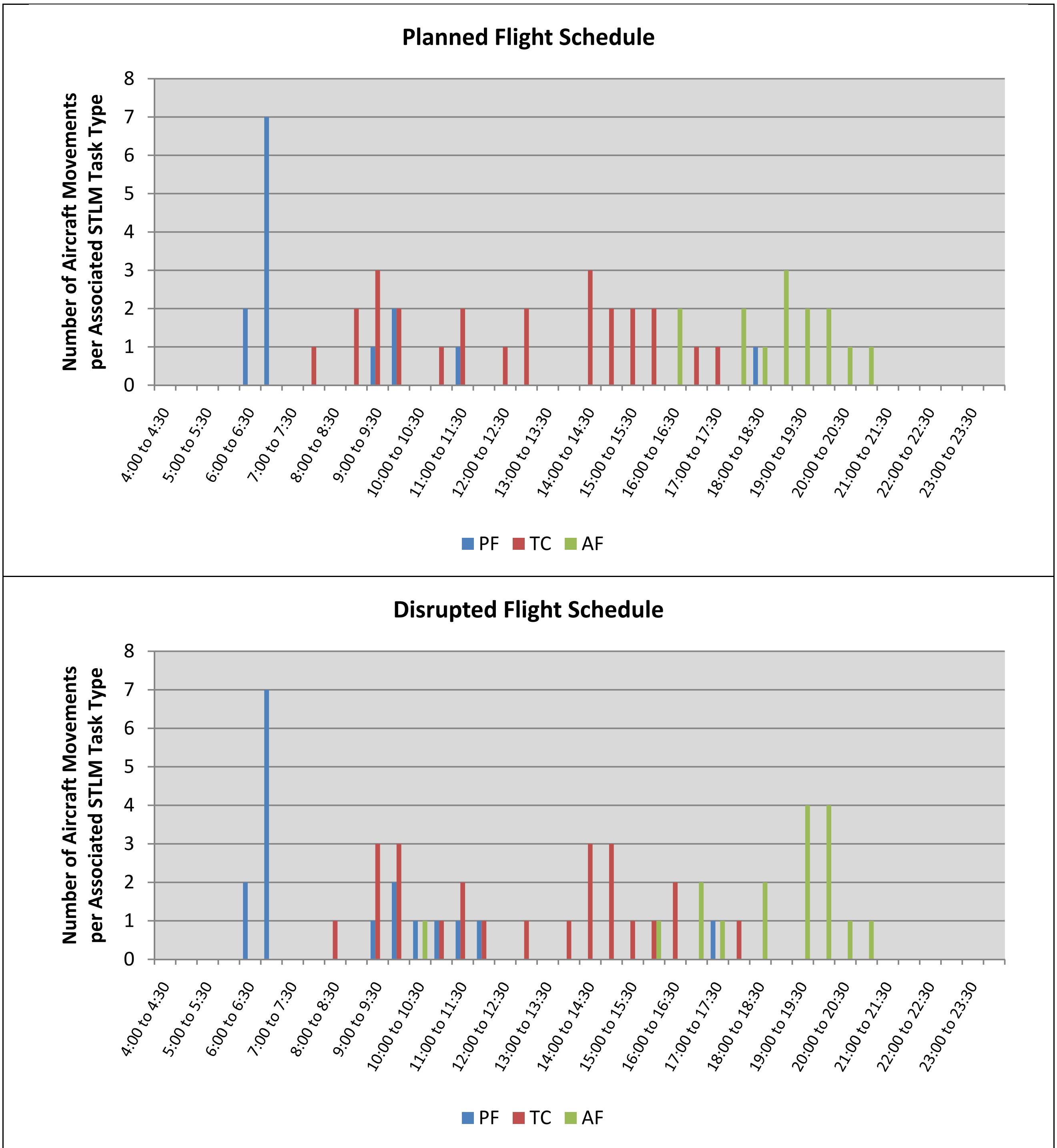


Figure 11 – Comparison of the Incidence Profiles of Planned and Actual Aircraft Movements that Triggered STLM Task Requirements on 08 June 2011

Figure 11 provides a graphical illustration of the impact that flight schedule disruptions had on the STLM task demand profile in the case setting on the 08th of June 2011. In this figure, the planned and actual demand profiles of STLM tasks for the day have been compared by counting the aircraft movements that triggered these tasks in 30 minute intervals. Each aircraft movement has been categorised according to the type of STLM task that it triggers, i.e. either a pre-flight (PF) check, a transit check (TC) or an after-flight (AF) check. While the planned and actual aircraft movements in the first and final hours of the day's operations are largely similar, the figure shows discernible differences in the nature of aircraft movements in almost all of the 30 minute intervals across the remainder of the operational day.

For clarity, a similar analysis to that presented in Appendix I for Wednesday the 08th of June 2011 has been carried out for each day-of-operations in the date range 01 to 20 June 2011. The data in Table 17 is essentially a summary of the outcomes of the analysis for each day in this date range. The 08th of June 2011 has been selected as a sample day for demonstration purposes as this day was found to be the most disrupted day within the testing date range in terms of the percentage of aircraft movements that were impacted by flight schedule disruptions.

4.2.3.3 Implementation of the Sensitivity Analysis by Testing the Sufficiency of the Predetermined Labour Force against the Adjusted Task Demand for STLM Activities

With reference to Figure 10 in Subsection 4.2.3.1, the implementation of the sensitivity analysis in this study has been achieved by assigning the set of STLM tasks for each test day to one or more available AMEs amongst the on-duty workforce. This assignment process has been implemented using the Solver functionality in MS Excel, but with manual adjustments applied after primary processing in order to ensure that reasonable break times are assigned to each on-duty AME over the course of the various duty shifts. The labour force that has been rostered for duty on each test day has been established according to the labour plan for the corresponding weekday as detailed in Table 13 in Subsection 4.1.2.7. The main objective of the sensitivity tests has been to ascertain whether any MMEs are incurred as a result of violations to the start time windows for the affected STLM tasks. Furthermore, the testing process has identified any requirements for unplanned overtime or AME callouts in order to complete the applicable set of STLM tasks on each test day.

Similarly to the previous subsection, the task assignment data relating to the day-of-operations on the 08th of June 2011 has been used as a sample data set for demonstration purposes. In this regard, a proposed STLM task assignment plan for the 08th of June 2011 has been presented in Table L1 in Appendix L. According to this table, the proposed labour deployment plan for the day is not able to meet all the required STLM tasks within the confines of the predetermined shift start and finish times for the on-duty work groups. As a result, the table identifies requirements for three AMEs to work beyond the finish time of their assigned shift on an overtime basis. The additional duty time that is associated to these overtime requirements amounts to 2 hours and 25 minutes. This overtime allocation is below the minimum time allocation that is applicable for an AME callout (i.e. 3 manhours). As such, the implementation of this overtime is a more economical option than calling a standby technician out to duty. Furthermore, the maximum individual shift length that is required by the modified task assignment plan is 12 hours and 25 minutes. This length of duty still allows for a sufficient rest period prior to the following day's shift for an affected AME, should he or she be rostered for duty the following day. It is also noteworthy that the task assignment profile on this day is not affected by any MMEs in the task assignment process. As such, it has not been necessary to ascertain any operational implications or costs relating to MME recovery plans on this test day (e.g. callouts of standby AMEs in response to induced aircraft delays).

A similar task assignment analysis to that presented for the 08th of June 2011 has been performed for each operational day in the date range 01 to 20 June 2011. The resulting data set has been used to assess how the coverage performance of the optimised STLM labour plan is impacted by variations between the flight schedules that are used for roster development and the flight profiles that are actually operated in the case setting. Of the 20 operational days that have been subjected to this analysis, three days show instances where the modified STLM task profile generates AME demand levels that exceed the available supply of on-duty workers. These three days are the 02nd, 08th and 20th of June respectively. In total, six STLM tasks have been identified on these three days where labour coverage violations are evident. The nature of each of these coverage violations has been summarised in the bullet points that follow. Note that one of these bullet points discusses a constraint violation in the case setting that has been deemed not to be a labour coverage violation on the grounds that a suitable contingency plan is available. Also note that overtime allocations have not been considered where AMEs work 10 minutes or less beyond the closing time of an affected shift in order to complete STLM tasks that were already in progress at the prescribed finish time of the shift.

- On the 01st, 02nd and 03rd of June 2011, Flight Number SA8747 reflects in the operating schedule as an early departure flight out of ORTIA at 06:00 on an RJ85 aircraft. When this flight is loaded into the experimental labour scheduling model, this combination of aircraft type and an early departure time results in a pre-flight check requirement with a start time window from 04:15 to 04:45. Given that the labour scheduling model does not allow for AMEs to commence a shift prior to 05:00, this requirement has been flagged in the task assignment process as a constraint violation. However, by assigning two AMEs to perform this pre-flight check from 05:00, it is possible to complete the check five minutes earlier than its maximum finish time limit of 05:30. This intervention has been assessed to be a suitable contingency plan. As such, this constraint violation has been removed from the list of task coverage violations that has resulted from the sensitivity testing process.

- On the 02nd of June 2011, two task violations have been identified in allocating the set of STLM tasks for the day against the optimised labour roster for the FLM Team. The first of these violations relates to the ERJ135 transit check requirement that is associated to the arrival of Flight Number SA7995 into ORTIA. The experimental model calls for a start time window on this check from 14:45 to 14:55, but competing STLM task requirements mean that the earliest time that this check can be allocated to an available AME is at 15:00. This violation thus constitutes a MME. Given that the next planned departure on the affected flight string falls at 15:15, this 15 minute check can only be completed at the STD for the next flight. It has therefore been assessed that a departure delay of five minutes will have been induced by this task start time violation in a real-life scenario. The short duration of the induced delay suggests that an AME callout will not have been practical as a means of reducing the delay impact, unless advance warning of the imminent violation was possible to allow for reasonable travel time in response to the callout. The experimental model also shows that the commencement of the after-flight check on the final arriving flight of the day, namely Flight Number SA8103 on an RJ85 aircraft, is constrained to a start time of 24:00 due to manpower demands in implementing after-flight checks on earlier night stop arrivals. Although this start time is within the allowable time window for the affected task, the completion of the task runs through to 00:55 with the maximum compliment of two available AMEs assigned. This finish time is 25 minutes beyond the planned shift closing time for the affected AMEs. As such, an overtime requirement of 25 minutes has been registered against each of these AMEs in order to ensure that the STLM task schedule for the day is completed. No flight schedule impact is associated to this particular rostering violation.

- Referring to Table L1 in Appendix L, operational data from the 08th of June 2011 shows that unplanned overtime allocations against three AMEs would be required in order to complete the after-flight checks on the final three night stop arrivals into ORTIA on this day using the optimised labour roster for the FLM Team. The affected flights are Flight Numbers SA8009 and SA8165, both on ERJ135 aircraft, as well as Flight Number SA8103 on an RJ85 aircraft. The start times of these after-flight checks all conform to the start time windows that are defined in the experimental model, but the tasks cannot be completed before the planned shift closing times for the assigned AMEs. In total, 145 overtime minutes have been allocated to complete the STLM task requirements for the day. This total comprises individual overtime allocations of 55 minutes, 40 minutes and 50 minutes respectively for the three affected AMEs. No flight schedule disruption impacts are associated to these particular rostering violations.

- Day-of-operations records for the 20th of June 2011 show that the commencement of the after-flight check on the final arriving flight of the day, namely Flight Number SA8103 on an

RJ85 aircraft, cannot be commenced by its latest (soft) start time limit of 24:00 using the optimised FLM Team labour roster. Similarly to the preceding two bullet points, this is due to manpower demands in implementing after-flight checks on earlier night stop arrivals. In this instance, the earliest time that this task can be commenced based on AME availability is at 00:20. Technically this constitutes a MME, although the fact that this MME occurs after the final arrival of the day into ORTIA means that there is no associated induced delay impact to the flight schedule (this is why the 24:00 time limit is a soft constraint only). The completion of this task runs to 01:15 with the maximum compliment of two available AMEs assigned, which is 15 minutes beyond the planned shift closing time for these technicians. As such, an overtime requirement of 15 minutes has been allocated against each of these AMEs to ensure that the STLM task schedule for the day can be completed.

In summary, only two MMEs have been identified across the 20 operational days that have been subjected to robustness testing in this study. Together, these two MMEs account for just a single induced flight delay with an associated duration of only five minutes. Considering that flight delays are generally only logged where a flight departs 15 minutes or more later than its planned time of departure, these MMEs should not have resulted in any official flight delays in a real-life operating scenario. Furthermore, no supplementary delay costs are predicted for the induced delay time as delay costs are only incurred for flight delays of 15 minutes duration or longer.

Looking at the predicted impact of AME callouts and overtime in the case setting, no requirements for callout support have been identified across the testing date range. Instead, modest allocations of overtime have been shown to be sufficient in managing the few instances where the modified demand profile for STLM tasks exceeds the available labour supply. In this regard, 225 minutes (or 3.75 hours) of overtime have been predicted across the 20 day testing period. Considering that the planned duty time for STLM activities over this period amounts to 1,383 AME manhours, this overtime adds just 0.41% to the labour costs for the FLM Team at an overtime rate of 1.5 times the normal hourly labour rate. It is even likely that this is a conservative calculation as the maximum normal working hours per AME per 28 day cycle on the FLM Team is 154 hours for AMEs that are allocated to the Afternoon Shift (see Table 13 in Subsection 4.1.2.7). Given that overtime is only paid where an AME works in excess of 168 hours per 28 day cycle, it is impossible that an AME on the FLM Team will exceed this threshold of hours worked in a given cycle based on the unplanned overtime levels that have been determined across the testing date range, unless supplementary AME duty time is allocated to administrative or training activities.

The data in Table 18 expands on the results from the preceding two paragraphs. This information has enabled conclusions to be drawn regarding the viability of the experimental labour scheduling methodology for STLM activities where task schedules disruptions are at play.

Table 18 – Summary of the Sensitivity Analysis Results for the Optimised STLM Labour Plan over the Testing Period 01 to 20 June 2011

Date / Weekday	# of STLM Maintenance Events Called Out	# of STLM Maintenance Events Planned For	Ratio of Actual STLM Events to Modeled Events	# of Contributing Disruptions	# of Contributing Delay Minutes	# of Flight Arrivals	# of Arrival Delays	# of Arrival Delay Minutes	# of Departure Disruptions	% of Total Events Disrupted	% of Inbound Flights Delayed	MMEs / Induced Delay Minutes	Overtime Manminutes Called Out	Status
1-Jun-11 Wed	53	51	103.9%	13	235	38	5	135	4	24.5%	13.2%	0 0	0	Robust
2-Jun-11 Thu	52	53	98.1%	13	225	37	9	225	2	25.0%	24.3%	**1** **5**	**50**	**Not Robust**
3-Jun-11 Fri	53	55	96.4%	12	445	38	5	375	3	22.6%	13.2%	0 0	0	Robust
4-Jun-11 Sat	34	32	106.3%	4	25	22	1	25	2	11.8%	4.5%	0 0	0	Robust
5-Jun-11 Sun	37	40	92.5%	4	75	25	2	75	2	10.8%	8.0%	0 0	0	Robust
6-Jun-11 Mon	54	53	101.9%	15	435	38	8	435	2	27.8%	21.1%	0 0	0	Robust
7-Jun-11 Tue	51	51	100.0%	10	145	37	4	145	2	19.6%	10.8%	0 0	0	Robust
8-Jun-11 Wed	58	51	113.7%	39	910	41	24	790	15	67.2%	58.5%	0 0	**145**	**Not Robust**
9-Jun-11 Thu	52	53	98.1%	20	660	37	10	475	10	38.5%	27.0%	0 0	0	Robust
10-Jun-11 Fri	53	55	96.4%	25	730	37	13	535	6	47.2%	35.1%	0 0	0	Robust
11-Jun-11 Sat	34	32	106.3%	3	0	22	0	0	2	8.8%	0.0%	0 0	0	Robust
12-Jun-11 Sun	38	40	95.0%	7	140	25	4	90	2	18.4%	16.0%	0 0	0	Robust
13-Jun-11 Mon	52	53	98.1%	10	340	37	7	340	3	19.2%	18.9%	0 0	0	Robust
14-Jun-11 Tue	51	51	100.0%	7	435	37	3	335	2	13.7%	8.1%	0 0	0	Robust
15-Jun-11 Wed	54	51	105.9%	12	130	39	8	110	3	22.2%	20.5%	0 0	0	Robust
16-Jun-11 Thu	39	53	73.6%	4	55	28	4	55	0	10.3%	14.3%	0 0	0	Robust
17-Jun-11 Fri	47	55	85.5%	13	165	31	7	145	2	27.7%	22.6%	0 0	0	Robust
18-Jun-11 Sat	32	32	100.0%	4	20	21	1	20	1	12.5%	4.8%	0 0	0	Robust
19-Jun-11 Sun	38	40	95.0%	8	110	26	5	110	1	21.1%	19.2%	0 0	0	Robust
20-Jun-11 Mon	56	53	105.7%	15	135	40	8	130	3	26.8%	20.0%	**1** **0**	**30**	**Not Robust**
Averages	46.9	47.7	98.3%	11.9	271	32.8	6.4	228	3.4	25.4%	19.5%	-	-	-
Totals	938	954	-	238	5415	656	128	4550	67	25.4%	19.5%	2 5	225	-

4.2.3.4 *Extending the Outcomes of the Sensitivity Analysis to the Broader Date Range of Flight Delay Data in the Case Setting*

The information provided in Subsection 4.2.3.3 indicates that the financial and operational impacts of unplanned labour roster changes for STLM activities in response to flight schedule disruptions are minor across the testing date range. These findings lend strong support to the assertion that the optimised labour plan for the FLM Team, as per Table 13 in Subsection 4.1.2.7, is sufficiently robust to the effects of flight schedule disruptions for use in real-life operations. As a final step in the process of robustness testing, an effort has been made to assess whether the findings across the testing date range can be extended to the broader date range across which flight delay statistics have been mapped in the case setting.

With reference to Subsection 4.2.1 and the contents of Table 18 in Subsection 4.2.3.3, an average of 19.5% of inbound flights to the case organisation's main maintenance base were delayed per day over the date range 01 to 20 June 2011. On average, 228 delay minutes were associated to these inbound delays per day over this period. These statistics compare to an average of 16.5% of inbound flights that were delayed per day, with an average level of associated delay time of 177 minutes per day, across the broader six month observation period for flight delays that has been considered in this study (i.e. 01 January to 30 June 2011). Thus, it can be concluded that the date range used in the sensitivity testing process spanned a period of comparatively higher levels of inbound flight delays in the case setting in comparison to the average levels for the full six month period over which flight delay data has been collected. On the basis that inbound flight delays account for the majority of the schedule disruptions that have been observed in the case setting across the robustness testing date range, it is considered likely that the results of the sensitivity analysis will remain valid for the broader date range of 01 January to 30 June 2011. This assertion is based on the lower levels of schedule disruptions that would be expected to have occurred across this expanded date range due to the generally lower levels of flight delays.

Table 19 illustrates the distribution of the data from the sensitivity analysis date range in relation to the full six month set of flight delay information that has been collected in the case setting, using the statistics relating to inbound flight delays as a basis of comparison. In this regard, the table uses a 2-dimensional distribution map that classifies each operational day from the six month observation period according to its level of inbound flight delays and associated delay minutes into the case organisation's main base. For example, the blue outline box shows that 63.0% of operational days from 01 January to 30 June 2011 had levels of inbound flight delays of 20% or less of the total number of inbound flights flown on the day, with associated delay minutes totalling 300 or less. Overlaid over this map is the distribution of data points from the sensitivity analysis. For test days where the optimised labour plan for STLM activities has been shown to deal robustly with the disrupted flight schedule without any MMEs or overtime requirements, green cell shading has been used. For days where MMEs or overtime requirements have been identified, red cell shading has been used.

Table 19 – Distribution Map of Flight Delay Characteristics for the Period 01 January 2011 to 30 June 2011, with Sensitivity Analysis Data Points Overlaid

Total Delay Minutes of Inbound Delays per Operational Day	% of Inbound Flights to the Main Base Delayed per Operational Day								
	0-10 %	10-20 %	20-30 %	30-40 %	40-50 %	50-60 %	60-70 %	70-80 %	80-100 %
0-50	16.0%	3.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
51-100	6.6%	14.4%	3.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
101-150	2.8%	8.8%	5.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
151-200	0.6%	4.4%	4.4%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%
201-250	0.0%	3.3%	1.7%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
251-300	0.6%	2.2%	0.6%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%
301-350	1.7%	1.1%	1.1%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
351-400	0.0%	2.2%	2.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
401-500	0.6%	0.0%	2.2%	0.6%	0.6%	0.0%	0.0%	0.0%	0.0%
501-600	0.6%	0.0%	0.6%	1.1%	0.6%	0.0%	0.0%	0.0%	0.0%
601-700	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
701-800	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%
801-900	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
901-1000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1001-1200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1201-1400	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1401-1600	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1601-1800	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
1801+	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

See Below for the Count of Test Data Points by Flight Delay Classification Region

Total Delay Minutes of Inbound Delays per Operational Day	% of Inbound Flights to the Main Base Delayed per Operational Day								
	0-10 %	10-20 %	20-30 %	30-40 %	40-50 %	50-60 %	60-70 %	70-80 %	80-100 %
0-50	3								
51-100	1	2							
101-150		3	2 / 1						
151-200									
201-250			1						
251-300									
301-350	1	1							
351-400		1							
401-500			2						
501-600				1					
601-700									
701-800						1			
801-900									
901-1000									
1001-1200									
1201-1400									
1401-1600									
1601-1800									
1801+									

Table 19 indicates that the flight delay conditions that led to overtime requirements being called out on the 08th of June 2011 are uncommon. On this day, flight delay characteristics were recorded by the case organisation that have only been matched or exceeded in 1.7% of the 181 operational days for which these characteristics have been assessed in the study. Therefore, similar or more severe flight delay conditions to those that were experienced on this day are only likely to occur approximately once every 60 days on average in the case setting. Accordingly, AME callouts or unplanned overtime relating to days of the same classification region or higher are unlikely to occur frequently and should not have a significant impact on the total labour cost of STLM activities. On the other hand, similar or more severe flight delay characteristics to those that produced MMEs and overtime requirements on the 02nd and the 20th of June 2011 respectively have been observed to occur far more frequently in the case setting. In this regard, the flight delay characteristics that were recorded for the 02nd of June 2011 have been shown to be matched or exceeded in 43.9% of the operational days that have been examined, whilst the corresponding figure for the 20th of June 2011 is as high as 59.7%. Similar or more severe flight delay conditions to those that were recorded for the 02nd of June 2011 are therefore likely to occur as often as once every 2.3 days on average in the case setting. The equivalent statistic for the 20th of June 2011 is once every 1.7 days on average.

These observations suggest that more analysis is needed to investigate whether the levels of flight delays that were recorded for the 02nd and the 20th of June 2011 respectively will repeatedly give rise to unplanned overtime requirements and MMEs in the case setting, or whether the rostering impacts on these test days related to the specific delay events of the day with low repeatability. If overtime requirements and MMEs are to be called out as often as once every 1.7 days on average at the case organisation, then there is an argument to consider extended hours of work on the FLM Team on a permanent basis in order to provide extended staff coverage to mitigate the effects of such frequent labour roster impacts.

It has already been mentioned in Subsection 4.2.3.3 that the levels of unplanned overtime that have been predicted across the robustness testing date range (i.e. 3.75 manhours) add 0.41% in supplementary labour charges to the FLM Team at an overtime rate of 1.5 times the normal AME labour rate. If this percentage is applied across a full 28 day cycle rotation in the case setting, the AME labour costs per cycle on the FLM Team increase from 344,552.40 ZAR to 345,953.78 ZAR. These labour costs are still nearly 22% less than the equivalent labour charges for STLM activities that are listed in Table 15 for the case organisation's existing line maintenance labour planning model. If this outcome is considered in conjunction with the finding of only five induced delay minutes in the case setting over the date range 01 to 20 June 2011, the robustness testing results that have been achieved to date in this study suggest that the impacts of unplanned flight schedule disruptions on the experimental labour planning model are largely insignificant.

4.3 Conclusions and Recommendations

4.3.1 Conclusions: Research Question 1

Looking at the first research question that has been posed for this study, a key issue has been to assess the extent to which the methodology used by the case organisation to develop its labour rosters for aircraft STLM activities conforms to the best or suggested practices for this type of staff scheduling that are described in contemporary operations research literature. It has been shown in Subsection 4.1.1.1 that the case organisation's incumbent labour planning methodology makes use of two alternating shift cycles to perform all line maintenance activities (including STLM work) in the case setting. Both of these shift cycles are manned by an equal complement of AMEs. This complement then subdivides into two work groups (i.e. a day shift and a night shift) on a rotational basis. The size of each shift team has been determined according to the resource planning model described in Subsection 4.1.1.2 that calculates the total AME complement that is needed to deliver the average number of manhours estimated for line maintenance activities across one 28 day cycle rotation. In this regard, each shift team is crewed by exactly half of this complement, rounded up to the nearest AME.

As detailed in the interview transcripts in Table F1 in Appendix F, experience has determined that a team of five AMEs supervised by a Crew Chief is sufficient to implement the case organisation's normal line maintenance requirements during day shift hours. In this regard, day shift activities focus predominantly on implementing pre-flight and transit checks on line operational aircraft, as well as rectifying minor technical defects that affect these assets. As of early 2013, however, the case organisation has started deploying a small number of additional day shift AMEs in a short visit maintenance role. At times when the aircraft fleet is operating well in terms of technical reliability, these SVM AMEs focus on implementing scheduled line maintenance tasks that are beyond the scope of STLM checks on aircraft that are on standby allocations or on maintenance downtime. However, at times when significant technical disruptions affect the running of the flight schedule, these AMEs switch roles to that of a rapid-response team. This response team then takes on the assessment and rectification of aircraft defects and damage occurrences that are not possible to resolve through routine transit check activities on the airport parking bays in between flights.

The remaining line maintenance AMEs in the case setting are assigned to night shift duties. These AMEs constitute the majority of the labour resources on each shift cycle due to the comparatively high levels of aircraft ground time that are available to the line maintenance function overnight. Night shift duties generally include both STLM activities (i.e. aircraft after-flight checks) as well as short visit maintenance activities. The types of short visit maintenance activities that are typically implemented in the case setting during the night shift include planned tasks such as scheduled engine replacements, or packages of planned tasks such as A-checks. Detailed investigations of aircraft system faults or component defects also fall within the scope of short visit maintenance activities that are commonly carried out overnight.

With reference to the contents of Table B2 in Appendix B, the current labour scheduling approach used by the case organisation for its line maintenance services has similarities to the permanence centred planning methods that are often employed in health care systems and emergency services operations. Staff members are assigned to this type of duty roster in a way that provides for permanence of the affected service. In the case setting, the incumbent line maintenance labour plan ensures that a permanent maintenance service is provided with no variation from one day to the next in terms of the number of rostered AMEs on the day shift and night shift workgroups, respectively. This approach therefore offers complete confidence to the operator that maintenance services shall always be available irrespective of the time or day in question. However, there are some significant deficiencies with this labour planning methodology and its application in the case setting that this study has identified. These deficiencies are presented and discussed in the bullet points that follow:

- While the case organisation has applied computational modelling to quantify the total staff complement that it requires to deliver its line maintenance services, no evidence has been found of an in-depth quantitative assessment by this organisation of possible fluctuations in demand levels for these services and the associated implications for AME rostering. If one looks at the nature of demand for the various components of line maintenance that are detailed in Appendix M, it is highly probable that significant variations in demand levels will be evident in real-life operations from one day to the next as well as by time of day. As a result, resource allocations for line maintenance in the case setting can be managed more efficiently by providing for a degree of flexibility in supply, thereby allowing for improved matching against prevailing demand levels. The variations in resource supply at the case organisation to cater for variations in line maintenance demand are fairly simplistic under the current regime. In this regard, the present AME supply profile only shows a variation between the numbers of AMEs that are rostered for the day shift (06:00 to 18:00) versus those that are allocated to the night shift (18:00 to 06:00). It is of note that no variations have been identified in the numbers of AMEs that are rostered for duty by weekday even though the study results have shown that levels of flight schedule activity vary significantly from one weekday to the next. In this regard, the most significant differences have been found when comparing levels of flight schedule activity between regular office days and weekend days in the case setting. Given that schedule activity levels in the case setting have a direct impact on the levels of STLM tasks that must be implemented, as well as probabilities for unscheduled aircraft technical faults and technical queries by flight crews, it is reasonable to expect that AME levels for these components of the line maintenance service should flex up and down in direct proportion to schedule activity levels to deliver optimal labour efficiencies.

- Expanding on the bullet point above, no evidence has been found to show that the case organisation has made an attempt to separate its line maintenance service into constituent maintenance components to allow for detailed analysis of the specific demand drivers of each component. Refer to Appendix M for a detailed assessment of the components that make up the line maintenance service in the case setting, or at a comparable aircraft or airline maintenance operation.

- On the basis that demand levels for line maintenance services in the case setting are variable (refer to the two preceding bullet points), it is deemed to be likely that the following working conditions will occur regularly at the case organisation:
  - Underutilisation of rostered AMEs at times of lower maintenance demand, and
  - Potentially excessive workloads and associated time pressures at other times where the on-duty AMEs must meet higher than average maintenance demand levels.

Note:
Although the interviewees were reluctant to admit that there are significant shortcomings with respect to labour demand and supply matching for the line maintenance function in the case setting, the interview transcripts in Table F2 in Appendix F do contain comments to support the assertion that such shortcomings exist. For example, the Chief Inspector of the Line and Base Maintenance function commented as follows in his interview:
"*From time to time, due to factors such as courses, leave constraints (including annual and sick leave) or unplanned defects (e.g. an engine change due to a birdstrike event), you may find that we run slim on manpower coverage.*"

- No evidence has been found that the case organisation has supported its line maintenance labour scheduling methodology with any specific measurements and statistical analysis of standard times for routine and common maintenance tasks. Rather, the organisation has applied standard times for these maintenance tasks based on recommendations that have been made by senior AMEs. The task time measurements made during the course of this study, as detailed in Appendix D, have shown that the case organisation's standard time specifications for after-flight checks are overly conservative. These conservative standard time figures have had a significant effect in overestimating the manhours that are needed to implement the three categories of STLM checks in the case setting that are the primary focus area of this study. Consequently, the case organisation has forecasted a higher number of total manhours per shift cycle rotation to deliver line maintenance services than what the measurements of this study suggest should be necessary.

The study has successfully benchmarked the performance characteristics of the labour planning model for line maintenance services that is currently in use in the case setting against those of an experimental simulation model for labour resource planning, using STLM activities as a test case. This experimental model has employed sophisticated computational processes, adapted from a relevant set of contemporary research works in the subject area of personnel scheduling, in order to optimise the outputs of the staff rostering process for these activities. The experimental model has been successfully implemented in the study using a commercially-available laptop computer running the Microsoft Excel software package. This combination of PC hardware and software is generally highly accessible to an operations manager or resource planner in a modern workplace. The benchmarking results presented in Subsection 4.1 of the study show that the sophisticated computational processes of the experimental model significantly outperform the comparatively crude planning model that is currently in use at the case organisation. In this regard, these computational processes have enabled the development of a labour schedule for STLM activities that is more efficient and potentially significantly cheaper to operate than the equivalent labour schedule based on the case organisation's incumbent planning model for line maintenance labour.

Upon close scrutiny, it is evident that the experimental computational model that has been used in this study has successfully addressed a number of the shortcomings that have been highlighted in relation to the case organisation's existing labour planning model for line maintenance services. The following discussion points have been identified in this regard:

- Firstly, the experimental model focuses on a single component (i.e. first line maintenance) of the broader line maintenance service, rather than on this service as a whole. By doing so, it has been possible to achieve a greater level of focus on the specific characteristics of first line maintenance, as have been described in Subsection 4.1.2.1, in an environment of reduced modelling complexity. In turn, this increased focus has enabled a more detailed and accurate analysis of the staff rostering problem than was likely to be achieved by incorporating first line maintenance into a single labour planning model encompassing all aspects of the line maintenance service.

- Secondly, the experimental model has been adapted from existing research works in which demand modelling is a key requirement in formulating demand inputs to subsequent crew scheduling and task assignment processes. Demand modelling is clearly specified as the first step of the generic labour scheduling process described by Ernst *et al.* (2004), which has been discussed in Subsection 2.2.1 as well as Table B3 in Appendix B. As a result, a detailed analysis of the demand drivers and incidence levels of STLM tasks in the case setting has been carried out as the initial phase of the implementation of the experimental model. This analysis has been made directly from a selection of historical flight schedules that were actually operated by the case organisation.

Note:
With further reference to the work of Ernst *et al.* (2004), the experimental labour scheduling model can be separated into a set of six distinct steps or modules. A detailed description of the modular nature of the experimental model is provided in Appendix N.

- Thirdly, the experimental crew scheduling model has been supported by a set of structured standard time specifications for the nine types of STLM tasks that are carried out by the case organisation. In this regard, the standard time for each applicable task type has been calculated according to a predetermined formula from a series of on-the-job measurements of the time taken to execute the affected task. To ensure consistency in the scope of work covered for each of these time measurements, the tasks have been implemented according to a standard checklist. This structured approach has ensured that realistic task execution times have been allocated per STLM task to improve modelling accuracy. Furthermore, the application of 80th percentile standard times rather than average or median standard times has ensured that task time allocations are reasonable for AMEs with a slower pace of work. In this way, the experimental model has avoided the imposition of excessive time pressures that can lead to errors or oversights in maintenance in a real-life operating environment.

- Fourthly, the experimental model has been used to test a vast number of feasible options in terms of possible task demand profiles and shift configurations in the case setting in order to find a near-optimal rostering solution. With reference to Subsection 2.2.1 of the study, this characteristic is congruent with the assertions of Ernst *et al.* (2004) that the principal purpose of staff scheduling processes is to develop good or optimal solutions in modelling environments that present vast numbers of feasible solutions.

By applying a more sophisticated analytical approach with closer ties to contemporary research and best practices in the area of personnel scheduling, the experimental optimisation model has been able to generate a labour plan for first line maintenance in the case setting that significantly outperforms the case organisation's existing line maintenance labour planning model. In terms of comparative performance characteristics, the results presented in Subsection 4.1.3 of the study show that the experimental model requires 33% fewer AMEs and 48% fewer rostered manhours to meet the STLM needs of the airline than the equivalent labour force specified by the organisation's current planning model. This finding represents a significant improvement in the labour resources that are needed to provide the STLM service. However, it has been noted that a considerable portion of this resource saving relates to conservative demand modelling by the case organisation, particularly with regards to the quantities and standard time inputs that have been imposed for after-flight checks in the current line maintenance labour planning model. If this model is modified according to the findings of the demand modelling processes that have been implemented in this study, resource savings through the application of the experimental model have been shown to be more modest. Under this scenario, the experimental model is able to provide a 22.0% reduction in rostered manhours and associated labour costs in comparison to the modified case organisation labour planning model, but with no reduction in the number of AMEs employed. Although not as substantial as the original finding, this more realistic outcome remains positive and potentially valuable from the viewpoint of the operations manager.

With reference to Subsection 2.2.5 of the study, the criteria proposed by Warner (1976) can be used to assess the relative benefits of the experimental labour scheduling modelling in comparison to the case organisation's incumbent line maintenance labour planning model. In this regard, the experimental model has been shown to provide significant cost savings in terms of the levels of human resource that are required to deliver the STLM service, while at the same time maintaining sufficient levels of AME coverage in line with associated service demand levels. Although the experimental model involves more complex computational processes, it has been shown that these can be performed using contemporary PC hardware and software tools that are typically readily available in most modern workplaces. However, there is a concern that higher levels of management time (and associated costs) will be needed to deliver the optimised solutions of the computational model, even where tools such as Microsoft Excel macros are used to eliminate or reduce manual processing requirements. In order to achieve more optimal outputs in terms of labour costs, it has also been necessary to reduce the stability of the labour roster that is delivered by the experimental model in comparison to the case organisation's existing line maintenance staff roster. However, these stability reductions have been deemed to be manageable provided that appropriate information sharing tools are made available to affected AMEs with respect to their upcoming work shifts.

The savings in direct maintenance manhours for first line AMEs that can be achieved through the application of the experimental model may be applied to reduce total aircraft maintenance costs. Alternatively, the manhours saved can be re-allocated to training activities or the support of other work teams that provide line maintenance or heavy maintenance services at the case organisation. In conclusion, the outcomes of the experimental modelling support the assertion that a significant knowledge gap exists between the case organisation's practical application of labour scheduling concepts and the state-of-the-art as detailed in contemporary literature on personnel scheduling in similar operational environments.

Despite the positive outcome discussed in the preceding paragraph, some areas of concern have been identified with regards to the study outcomes in respect of Research Question 1. These are discussed in the following bullet points:

- The experimental model has applied the assumption that all affected AMEs are authorised to the level of at least limited line release approval on the three Airlink aircraft types. By implication, this means that all AMEs working on the First Line Maintenance Team shall be LAMEs. Although this assumption reduces the modelling complexity, there is a concern that it may give rise to higher average salaries or wages on the FLM Team in comparison to a modelling scenario that enables the employment of an appropriate mix of licensed and unlicensed AMEs. This may, in turn, act to offset the projected improvements in overall labour costs.

- The mathematical programming spreadsheets that collectively constitute the experimental labour scheduling model have been developed exclusively in Microsoft Excel. This has been done deliberately as this software package is generally readily available to operations managers and resource planners in contemporary workplaces. Although successful results have been achieved using these Excel spreadsheets, the optimisation processes have had to be limited to the generation of near-optimal outputs rather than fully-optimised solutions. In this regard, the number of feasible solutions for the problems at hand has been found to be simply too great for the affected Excel models to test each feasible outcome. It has been observed that errors and memory constraints have occurred in Microsoft Excel for solutions that require modelling iterations of the order of 150,000 or more. The need to limit the number of feasible solutions to be tested has been most apparent for the demand modelling calculations. In this regard, the number of feasible configurations of the STLM task demand profile for each weekday of the representative operational week in the case setting has been shown to be an enormous number, e.g. 1.53×10^{50} configurations for the Monday flight schedule. It has also been noted that the Microsoft Excel Solver function is unreliable in terms of being able to accomplish optimisation calculations successfully for the integer-based linear programming problems that typify the demand modelling and crew scheduling processes that have been implemented in this study. Modelling in an Excel environment exclusively has thus been found to be cumbersome and iterative in this study and the spreadsheets that have been used are complex as a result.

- The Excel difficulties that are highlighted in the preceding bullet point support the use of more specialised modelling and calculation platforms that can handle integer-based as well as non-linear calculations and which are better suited to the scale of rostering problem that has been addressed in this study. In particular, it is recommended that use be made of software tools that can handle greater processing loads and numbers of feasible solutions. This may include the use of sophisticated search algorithms that enable the generation of near-optimal solutions in an efficient manner in integer-based modelling environments. However, it is strongly suspected that sophisticated computational modelling of this type is not yet likely to see widespread use at the majority of aircraft or airline maintenance organisations. This suspicion is based on the assertion that complex computational modelling techniques are likely to be beyond the capability and understanding of most of the operations managers and resource planners that are employed at such organisations, particularly where Microsoft Excel is used. This assertion is supported by the interview transcripts in Table F1 in Appendix F where the interviewees acknowledge that they have not attended training in generic operations management principles and they don’t recognise a range of computational modelling techniques that are commonly applied in operations research problems such as personnel scheduling. More realistically, complex personnel scheduling models could be implemented in the form of ‘black box’ software applications with user-friendly interfaces where the affected operations managers or resource planners need only enter the relevant task demand and shift modelling constraints at hand.

4.3.2 Conclusions: Research Question 2

The primary requirement in relation to Research Question 2 has been to assess whether a labour roster for STLM activities, optimised on the basis of an airline operator conforming precisely to its planned flight schedule, can be robustly applied in real-life operations where flight schedules are regularly disrupted. Such flight schedule disruptions will, in turn, introduce unplanned variations to associated STLM task schedules. In this study, an optimised labour roster has been developed for a proposed First Line Maintenance Team in the case setting on the basis that flight operations at the case organisation conform exactly to the published flight schedule. The outcomes of the study in respect of Research Question 1 have shown that this optimised roster offers significant labour efficiency improvements as well as cost savings over the existing personnel scheduling method that is in use at the case organisation for delivering the STLM services that are demanded of it. Furthermore, the results in respect of Research Question 2 have shown positive evidence that this optimised labour roster is reasonably robust to the effects of schedule disruptions that have been applied in a simulation environment based on historical data in the case setting.

Looking at the robustness testing process in greater detail, the FLM Team’s optimised labour plan has been deployed to implement STLM services in relation to a set of disrupted flight schedules over 20 consecutive test days. With reference to Subsection 4.2.3, the task demand profile for each test day has been constructed from historical records of actual flight schedule disruptions in the case setting, supported by an assessment of the associated schedule recovery decisions that were implemented by the case organisation’s operations control function. Over this testing period, the optimised labour plan for the FLM Team has been shown to require only 3.75 manhours of unplanned AME overtime, with no requirements for AME callouts, in order to manage the modified task demand profiles in relation to the schedule disruptions that were experienced. In addition, only two constraints (one hard and one soft) in terms of task start time limitations have been violated over the sensitivity testing period. The combined impact of these two constraint violations has been assessed to be very minor at only five minutes of 'induced' flight delay time. In this regard, it must be remembered that flight delays are only logged formally at airlines when a flight departs 15 minutes or more after its planned departure time. Furthermore, the set of constraints detailed in Appendix E specifies that delay-related costs are only incurred for delays that exceed 15 minutes in duration. As such, no formal induced flight delay events or associated flight delay costs have been predicted across the 20 day sensitivity testing period. The additional labour costs in relation to unplanned overtime inputs have been estimated at only 0.41% of the planned AME labour costs on the FLM Team.

Referring to the contents of Subsection 4.2.3.4 of the study, it is noteworthy that the sequence of test days that has been employed in the robustness testing process spanned a time period where delay incidence rates and levels of associated delay minutes on arriving flights were comparatively high in comparison to the corresponding six month average levels in the case setting for the period 01 January to 30 June 2011. On the understanding that inbound flight delays account for the majority of flight schedule disruptions that affect demand levels for STLM tasks, it has thus been deemed likely that the levels of STLM task variations that have been applied in the robustness testing process will exceed the average long-term levels of these variations that are encountered at the case organisation. It is a logical inference to expect that generally lower levels of flight schedule disruptions and associated STLM task variations, e.g. inbound delays that give rise to standby aircraft deployments, will lead to fewer MMEs as well as overtime or callout support requirements for the on-duty workers on the FLM Team. On this basis, it has been concluded that the robustness testing results that have been achieved in the study provide compelling evidence that the experimental model for optimised STLM labour scheduling is sufficiently robust in its present form for practical application in real-life airline operations. This conclusion is, however, conditional on appropriate allowances being made for occasional unplanned overtime to be worked by affected AMEs.

Despite the positive result that has been achieved through the sensitivity analysis, it is recognised that the span of the testing was fairly limited in covering only 20 operational days. In an attempt to assess whether the findings over this limited date range can be readily extended to operations on an ongoing basis in the case setting, the inbound flight delay characteristics of the test days have been mapped against equivalent flight delay characteristics for all operational days over the period 01 January to 30 June 2011 (refer to Table 19 in Subsection 4.2.3.4). In this regard, it has been noted that both of the operational days that produced MMEs during the robustness testing process (i.e. the 02nd of June 2011 and the 20th of June 2011 respectively) experienced levels of inbound flight delays and associated delay minutes that appear to be relatively common in the case setting. Table 19 shows that similar or more severe inbound flight delay characteristics have occurred as often as once every 1.7 days on average at the case organisation in the six month period over which flight delay records have been collected. It is thus an issue for further investigation to conduct more comprehensive robustness tests to examine how reliably these levels of flight delays (or more severe levels) will produce task conflicts that require callout or overtime support, as well as associated MMEs.

To support future extensions of the robustness testing that has been undertaken in this study, the results presented in Subsection 4.2.2 show that the occurrence rates of flight delays in the case setting, as well as the associated time durations per delay event, can be replicated to a reasonably high degree of accuracy using appropriate theoretical probability distributions. This is particularly so where the affected theoretical distributions have been modified via a least squares method so as to achieve the closest possible fit to the case data. For example, it has been found from the case data that the percentage of arriving flights per day that are subject to flight delays matches closely to a Gamma probability distribution whose parameter values have been modified using the least squares method to give the best possible fit (refer to Figure 8). Similarly, Figure 9 shows that histogram profiles of the recorded time durations of both inbound and outbound flight delays in the case setting correspond very closely to Lognormal distributions whose parameter values have also been modified using the LSM to give the best possible fit. It is thus plausible that such theoretical probability distributions could be applied in a stochastic model to simulate realistic profiles of flight delay occurrences and associated time durations for the case organisation or for a similar airline operation. In this regard, a significant advantage of a stochastic modelling approach is that it can be used to produce any number of flight delay profiles in an automated fashion without the need to collect additional raw airline data. This is a potentially valuable outcome where delay input data is required for an in-depth sensitivity analysis process where high numbers of tests or iterations are being performed.

Although the preceding paragraph supports the automated simulation of flight delay data through the application of stochastic modelling approaches, the sensitivity analysis that has been carried out in this study has identified that the causality by which a given flight delay event is linked to its associated schedule disruption effects can be complex. In this regard, the effects of flight delays on aircraft scheduling are frequently more involved than simple adjustments to the departure or arrival times of delayed flights. Operational records at the case organisation have shown that the airline routinely deploys standby aircraft into service (subject to availability), or adjusts the planned flight sequences for aircraft already in use, as a means of mitigating and controlling the duration of flight delays. Aircraft technical delays that required unplanned maintenance inputs, for instance, gave rise to a number of spare aircraft deployments and aircraft sequencing changes over the 20 day robustness testing period. Where aircraft changes are made in response to flight delays, it has been shown that more significant variations to the demand profile for STLM events may be introduced than simple timing changes. A good example that has been observed in this study is where a standby aircraft is deployed into service at the case organisation's main base in response to a significant inbound flight delay in order to prevent propagated delays on subsequent flights on the affected flight string. In such a case, the maintenance demand changes from a scheduled transit check on the inbound aircraft to a pre-flight check on the standby aircraft and either a transit check or an after-flight check on the inbound aircraft upon its eventual delayed arrival.

Thus, while the study outcomes confirm that realistic profiles of flight delays can be modelled using probabilistic modelling techniques, it is uncertain whether it is possible to accurately model the effects of flight delay occurrences on the timing and scope of STLM tasks at a given aircraft or airline maintenance operation. Modelling of these effects will require additional operating factors to be considered, e.g. the availability of standby aircraft as well as organisational decision criteria for recovering from flight schedule disruptions. Furthermore, a probabilistic device for modelling flight delay characteristics must give adequate consideration to delay propagation impacts. These relate to the tendency of an initial flight delay occurrence on a given flight to produce additional delays on subsequent flights (if these are applicable) where the airline is not able to 'catch up' the delay time on the initial delay. Delay propagation effects may also be complex in nature, requiring factors such as aircraft turnaround times in between flights as well as the availability of standby aircraft to be considered. It has not been examined in this study whether these additional factors can be suitably encompassed in a computational model to enable the automatic generation of disrupted STLM task demand profiles under delayed flight conditions. At this point, supporting operations control data from the affected airline is needed to accurately model the maintenance task demand changes that are associated to flight delay events.

4.3.3 Recommendations for Further Research

The outcomes of this study have highlighted a number of issues and areas where further research is recommended. These are detailed in bullet point form as follows:

- There is an opportunity to explore further refinements to the experimental labour scheduling model using techniques such as labour supply flexibility and optimised days off scheduling that have not been explored in this study. It is also recommended that efforts be made to explore the use of more specialised solver software than Microsoft Excel for finding optimal or near-optimal solutions to the large multiple-criteria linear programming formulations that are incorporated within this model. Such software products should be better equipped than Excel to handle the scale of these formulations in terms of numbers of feasible solutions.

- Following on from the preceding bullet point and with reference to the contents of Table B3 in Appendix B, it will be useful to benchmark the optimisation capabilities of a suitable metaheuristic approach or constraint programming model against the rostering solution that has been achieved in this study using mathematical programming. In this regard, the large integer linear programming formulations of the experimental labour scheduling model, particularly in terms of the task demand optimisation process, have meant that techniques such as random number generation have had to be used to limit the number of feasible solutions that have been considered. Such techniques may affect the optimality of the final solution that is established for a given linear programming formulation. As such, there is a distinct possibility that alternative modelling techniques may yield more optimal outputs for the labour scheduling problem at hand.

- Further refinements to the experimental labour scheduling model may also be possible through the application of variable inspection times for STLM tasks as a modelling input. The set of physical STLM task time measurements contained in Table G1 in Appendix G, read together with the summary information in Table 8 in Subsection 4.1.2.3, shows that significant levels of variation have been observed in the case setting in terms of times taken by AMEs to implement STLM tasks according to a standard checklist. The result of these high levels of variability is that reasonably conservative standard times have been used to model the case organisation's STLM operations. This issue may lead to the prediction of higher levels of AME inputs, occupancy levels and associated manpower costs than are true in reality. In turn, this may impact negatively on the levels of optimisation that are deemed to be possible through the computational labour scheduling model that has been implemented. Referring to the contents of Subsection 2.3.3 of the literature review, this recommendation can be linked to the work of Higle and Johnson (2005) whereby random times may be registered for short inspections (i.e. short-term layover maintenance tasks) on aircraft. These authors have therefore proposed that use be made of a stochastic linear programming approach with associated randomness factors to model repair times for short inspections. It would be useful to explore whether this type of modelling could improve on the outcomes that have been achieved in this study using the experimental STLM labour scheduling model.

- Due to its application of a single case method, this study lacks validation in terms of tests to assess the transferability of research outcomes from the case site to the broader research population under consideration. As a result, additional research is recommended to test the transferability of the findings in the case setting to other African-based aircraft or airline maintenance organisations that perform STLM services. Alternatively, the transferability of these findings could be tested in similar operational settings in other industries.

- Expanding on the preceding bullet point, a specific recommendation is to conduct a survey into the application of contemporary labour scheduling principles similar to those that were adapted and applied in this study amongst other aircraft or airline maintenance companies based on the African continent. The purpose of this survey will be to assess the current level of application of contemporary scheduling principles within these organisations, as well as the knowledge base of incumbent operations managers to make productive use of such principles to optimise operational efficiencies and improve running costs. It is further proposed that the survey report should, if applicable, consider appropriate means by which to transfer the methods that have been applied in this study to other organisations in order to achieve similar operational benefits to those that have been quantified for the case organisation (e.g. 'black box' software). As an additional point, it is of interest to establish whether there are significant differences in the levels of application of contemporary labour scheduling methods between airline maintenance organisations and the airline operators to which they are associated. In this regard, it may be found that sophisticated scheduling techniques are already in active use for flight crew planning purposes but have not yet been transferred into maintenance operations.

- It is recommended that more comprehensive sensitivity testing of the experimental labour scheduling model be carried out over a wider range of test days where disruptions to the planned flight schedule are at play. This recommendation has been made on the basis that additional physical evidence is needed to improve confidence that the model is sufficiently robust to the effects of airline flight schedule disruptions and associated changes to STLM task demands in its present form for deployment in real-life operations.

- Linked to the preceding bullet point, uncertainty factors with regards to the labour supply for STLM activities (i.e. issues such as employee absenteeism and instances of sick leave) should be considered at an appropriate point in further research efforts. The incorporation of these factors as an input to the experimental model, possibly as a component of ongoing sensitivity tests, is a step forward in developing a more comprehensive formulation of the personnel scheduling problem at hand.

- It is expected that improvements in the optimisation capability of the personnel scheduling model (e.g. through the application of flexible labour planning strategies) will increase the degree to which the resulting staff rosters are susceptible to the adverse effects of flight schedule disruptions, i.e. MMEs and requirements for AME overtime or callout support. As a result of this expectation, it is recommended that increasingly thorough sensitivity testing against schedule disruption effects be carried out in conjunction with ongoing refinements to the model.

- It is proposed that further research be conducted to explore the causal chain by which flight schedule delays and cancellations at the case organisation, or a similar airline operation, translate into changes in the demand profile for STLM tasks. It has been noted in the study that flight delays do not always translate into equivalent timing adjustments for the next due STLM task on the affected aircraft. In certain scenarios, the scope, quantity and timing of upcoming STLM tasks can be modified as a result of a delay event. For example, a flight delay caused by an aircraft technical fault or breakdown may result in the affected aircraft being withdrawn from operational service for maintenance investigations and replaced by a standby aircraft. In such a scenario, the standby aircraft that is deployed into service will require an unplanned pre-flight check prior to its first flight of the day and an unplanned after-flight check after its operations for the day are completed. In addition, the timing window of the planned after-flight check on the faulty aircraft may be shifted. It is of interest to investigate whether these changes to the maintenance task demand profile follow a predictable pattern of decision-making and resource allocation from the originating flight delay event. Following on from this investigation, there is an open research question as to whether it is possible to model the relationship between flight delays or cancellations and associated STLM task demand changes computationally, without the need to build modified task demand profiles manually from airline day-of-operations and maintenance records as has been done in this study. This investigation should also consider delay propagation effects where an initial delay event on an aircraft may affect the on-time performance of subsequent flights that are allocated against this aircraft.

- Appendix N describes the modular labour scheduling process that has been adapted from generic personnel scheduling literature and used as an analysis tool in this study. It is recommended that this modular process be further explored to determine its applicability to labour resource planning across the full range of line maintenance components that are detailed in Appendix M. In this regard, it is of interest to investigate whether the application of this structured resource planning process to the various aspects of the line maintenance service can produce significantly more efficient and cost-effective labour plans for the line maintenance operation as a whole at affected aircraft or airline maintenance organisations. This investigation should include personnel planning for maintenance services relating to unscheduled aircraft defects and equipment breakdowns where analysis techniques such as random arrivals may need to be incorporated as part of the demand modelling process. It should be noted that this aspect of an aircraft line maintenance service links back to the research work of Belien *et al.* (2010), as referenced in Subsection 1.2.2 of the study, that discusses how the task demand for routine aircraft maintenance services is inherently uncertain due to the potential for unscheduled defects or breakdowns to manifest during line operations.

With reference to the second bullet point in this subsection, two key factors have been identified that may influence the capability of the experimental labour scheduling model to deliver similar levels of optimisation as have been achieved in this study at other aircraft or airline maintenance organisations. These factors are as follows:

- Other organisations may not have 'limited' certification allowances that enable all rostered AMEs to be certified to release STLM tasks. In such a scenario, additional resources may be required to ensure that sufficient certified personnel are rostered along with non-certified personnel to enable all tasks to be implemented and released appropriately. In mitigation, non-certified resources are likely to be cheaper than their certified counterparts, particularly where unlicensed AMEs are used, so total labour costs may be lower despite higher staff numbers. The labour model developed by Ip *et al.* (2010), which caters for variable license holdings and associated certification authorisations within a given AME work or shift group, is a useful reference in this regard.

- Additionally, other organisations may have access to more flexible labour planning methods than were available at the case organisation, which currently only uses full-time AMEs for its line maintenance services (8 to 12 working hours per AME per day). For example, the use of half-time workers as has been explored by Yang *et al.* (2003) could allow for even more optimised labour plans by allowing for closer matching of AME supply levels to the associated demand levels for these workers. In particular, it has been noted in this study that the third and fourth AMEs allocated to the morning shift work group on the FLM Team are only used sporadically to cover short-duration peaks in the demand for STLM services over the course of their assigned shift. The most notable demand peak that has been identified in this regard in the case setting is that relating to the first wave of departures on normal office days (i.e. Monday through Friday). After this first departure wave, these two AMEs are generally underutilised for the remainder of the shift for first line maintenance purposes. It is thus a worthwhile issue to investigate whether half-time workers could be used as more efficient alternatives to these two full-time workers.

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6 Appendices

The following appendices have been included to support the research results that are presented in Section 4 of this study:

Appendix A: Basic Hierarchy of Airliner Maintenance Checks

The table below expands on the discussion in Subsection 1.2.1.1 of this study by providing a more detailed description of the hierarchy of airliner maintenance checks:

Table A1 – Basic Hierarchy of Airliner Maintenance Checks, Adapted from Hessburg (2000)

Check Type	Check Requirements and Characteristics
Daily Checks	These checks are carried out under several common names, e.g. post-flight check, maintenance pre-flight check, service check, transit check and overnight check. These checks constitute the lowest level of scheduled maintenance checks on an aircraft. It should be noted that the walk-around inspections that flight crews carry out prior to flight are not normally listed as part of an aircraft maintenance program. Daily checks are a cursory inspection of the aircraft to look for obvious damage and deterioration. They check for 'general condition and security' and also review the aircraft flight log for discrepancies (or defects) and subsequent corrective actions taken. The accomplishment of daily checks generally requires little in the way of diagnostic equipment, tools or facilities. A basic goal of daily checks is to ensure that the aircraft concerned remains airworthy over periods between significant maintenance checks. In this regard, daily checks are generally accomplished at least once every 24 to 60 hours of accumulated flight time on a given aircraft. Examples of tasks that could be incorporated in a daily check include: • Check oil and other fluid levels. • Check general security and cleanliness of the flight deck. • Check that emergency equipment is installed.
'A' Check (or Check 'A') (or A-Check)	An 'A' check is the next level of scheduled maintenance above the daily checks that are carried out on an aircraft. 'A' checks are normally implemented at flying hour intervals of between 350 and 750 hours at suitably-equipped maintenance stations in the route structure of an airline. These checks generally include requirements for access panels to be opened for inspection, testing or servicing requirements. In addition, some special tooling, as well as servicing and diagnostic equipment, may be required to perform 'A' check activities. 'A' checks generally include the lower level tasks that are incorporated in daily checks. In addition, examples of specific 'A' check tasks are as follows: • Carry out a general external visual inspection of the aircraft structure for evidence of damage, deformation, corrosion and missing parts. • Check the pressure level of the crew oxygen system. • Operationally check the emergency lights system. • Lubricate the nose landing gear retraction actuator. • Perform a Built-In Test Equipment (BITE) test of the Flap Electronic Control Unit (FECU).
'B' Check (or Check 'B') (or B-Check)	'B' checks involve slightly more detailed checks of components and systems than 'A' checks, for which special equipment and tests may be required. In general, however, 'B' checks do not involve detailed disassembly or removal of components. Contemporary maintenance programs do not use the 'B' check interval. For various reasons, the tasks formerly defined for the 'B' check interval have been distributed between the 'A' and 'C' check packages for most modern aircraft types.

Table continued on next page.

Table A1 – Basic Hierarchy of Airliner Maintenance Checks, Adapted from Hessburg (2000) (Continued)

<table>
<tr><th>Check Type</th><th>Check Requirements and Characteristics</th></tr>
<tr><td>Heavy Checks</td><td>
The following two aircraft check types are traditionally known as ‘heavy checks’. Heavy checks are normally accomplished at the main maintenance base of an airline where specialised manpower, materials, tooling and hangar facilities are available. Intervals between heavy checks can be as high as three to ten years.
'C' check (also referred to as a check ‘C’ or a C-check):

This is an extensive check of individual systems and components for serviceability and function, requiring a thorough visual inspection of specified areas, components and systems, as well as operational or functional checks.
It is a high-level check that involves extensive tooling, test equipment and special skill levels.
‘C’ checks remove an airliner from revenue operations for at least three to five days and possibly considerably longer.
'C' checks generally include the lower level tasks that are incorporated in ‘A’ checks, ‘B’ checks and daily checks.
In addition, examples of specific 'C' check tasks are as follows:

Check the operation of the DC bus tie control unit.
Carry out a leak check on the pitot-static system.
Inspect the engine inlet ducting for cracks.

‘D’ check (also referred to as a check ‘D’ or a D-check):

This level of check may also be referred to as a ‘structural check’.
‘D’ checks include detailed visual and non-destructive testing inspections of the aircraft structure. These checks involve an intense inspection of the structure for evidence of corrosion, structural deformation, cracking and other signs of deterioration or distress. In this regard, ‘D’ check work packages generally involve extensive disassembly to gain access for inspections.
Special equipment and techniques are used in ‘D’ checks.
‘D’ checks are manpower intensive and generally remove an airliner from revenue service for 20 or more days.
'D' checks generally include the lower level tasks that are incorporated in ‘A’ checks, ‘B’ checks and ‘C’ checks, as well as daily checks items.
In addition, examples of specific 'D' check tasks are as follows:

Inspect the stabiliser attachment bolts.
Carry out a detailed inspection of the wing box structure.

</td></tr>
</table>

Appendix B: Labour Scheduling Processes – Characteristics, Classifications and Modelling Methods

With reference to Subsection 2.2.1 of this study, the six modules or phases of the generic labour resource scheduling process that have been identified by Ernst *et al.* (2004) are as follows:

Table B1 – The Six Modules of the Personnel Scheduling Process as per Ernst *et al.* (2004)

Module Name	Description of Module
Demand Modelling	Demand modelling is the process by which a predicted pattern of incidents is translated into an associated pattern of duties from which a demand for labour resources can be derived. There are three basic incident categories on which staff demand can be based, namely task-based demand, flexible demand and shift-based demand: • <u>Task-Based Demand:</u> This category applies where demand is obtained from lists of individual tasks that are to be performed. These tasks are usually defined in terms of a starting time and duration, or a time window within which the task must be completed. If required, the skills or qualifications that are needed to perform the task are considered, as well as the location at which the task must be performed. • <u>Flexible Demand:</u> In this category, the occurrence of future incidents is not explicitly known and must be modelled using forecasting methods. Requests for service may have random arrival rates and possibly also random service times. As such, the matching of requests for service and staffing levels is often achieved by applying a service standard to a queuing analysis based on an estimated or predicted distribution of incidents or arrivals. The outcome is normally a specification of the numbers of staff members that are required at different times of day for each of the days in the rostering forecast window. • <u>Shift-Based Demand:</u> Shift-based demand is obtained directly from a specification of the number of staff members that are needed on duty during different shifts. This demand type is frequently used in areas such as nurse scheduling and ambulance services where staff levels are determined by the need to maintain service delivery standards, e.g. ratios of nurses-to-patients or response times to incident callouts. Shift-based demand may also be applied as a simplification to the more complex problem of rostering to task-based or flexible demand profiles.
Days Off Scheduling	This module encompasses the processes that determine how rest days are to be inserted between work days in a given roster for different lines of work. This requirement arises more frequently when rostering to flexible or shift-based demand than for rosters pertaining to task-based demand conditions.
Shift Scheduling	Shift scheduling addresses the problem of selecting the shifts that are to be worked from a given (and potentially large) pool of candidates in order to meet an associated workload demand. For rosters relating to flexible incident demand profiles, the timing of work and meal breaks within the limits allowed by workplace regulations and company rules also needs to be considered. When rostering to task-based demand, shift scheduling is often referred to as crew scheduling, or crew pairing optimisation, where the main goal is to select a good set of feasible duties, shifts or pairings to cover all the required tasks.
Table continued on next page.	

Table B1 – The Six Modules of the Personnel Scheduling Process as per Ernst *et al.* (2004) (Continued)

Module Name	Description of Module
Line of Work Construction	The process of constructing a line of work depends on the basic building blocks that are used in a given roster. These building blocks are typically shifts, duties or stints. For example, if the basic building blocks used are shifts, then one shift can be assigned to each working day for a given staff member, providing of course for relevant workplace constraints such as the fact that it might not be possible or practical to immediately follow a sequence of night shifts with a day shift. This module involves careful consideration and matching of the workplace or regulatory rules that relate to lines of work, as well as the associated demand pattern. Line of work construction is generally referred to as 'tour scheduling' when dealing with flexible demand scenarios, or as 'crew rostering' when addressing crew pairings.
Task Assignment	Depending on the rostering scenario, it may be necessary to assign one or more tasks to be carried out during each shift. These tasks may require particular staff skills, qualifications or levels of seniority. As such, task assignment processes may need to be associated with particular lines of work.
Staff Assignment	This module involves the assignment of individual staff members against the associated lines of work for a given rostering scenario. This is often done during the construction of these lines of work.

In addition, as discussed in Subsection 2.2.2 of this study, the ten organisational application areas for labour scheduling problems as proposed by Ernst *et al.* (2004) are presented in Table B2. This table includes a cross-reference to the classification system of De Causmaecker *et al.* (2004), with supporting notes:

Table B2 – Classification of Labour Scheduling Problems by Organisational Application Area, Adapted from Ernst *et al.* (2004) and De Causmaecker *et al.* (2004)

Classification A Ernst *et al.* (2004)	**Classification B** De Causmaecker *et al.* (2004)	**Notes**
Transportation systems	Mobility centred planning	• Staff scheduling and rostering is known as crew scheduling and rostering in the transportation business. This business sector includes airlines, railways, mass transit and buses. • Both temporal and spatial features are involved, i.e. each task is characterised by its start time and location, as well as its finish time and location. • All tasks to be performed by employees are determined from a given timetable. • Tasks are the smallest elements and are obtained from decompositions of flight, train or bus journeys. • A task may be an airline flight leg, a trip by train between two or more consecutive stops on a rail line, or a trip between two or more consecutive stops on a bus line. • Mobility centred planning includes transportation companies, as well as other businesses such as home health care where staff duties involve transportation to different locations.
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Table B2 – Classification of Labour Scheduling Problems by Organisational Application Area, Adapted from Ernst *et al.* (2004) and De Causmaecker *et al.* (2004) (Continued)

Classification A **Ernst *et al.* (2004)**	**Classification B** **De Causmaecker *et al.* (2004)**	**Notes**
Call centres	Fluctuation centred planning	• Personnel rostering in call centres does not involve a geographical (i.e. spatial) feature. • The exact nature and number of tasks to be performed is not known in advance. • All that is known is that a workforce requirements pattern exists for the entire planning horizon. • Call centre workforce requirements are necessarily variable from day to day and from week to week. • Shift start times and shift lengths need to vary in order to obtain good, low-cost rosters that cover the workforce requirements adequately. • Rosters may need to over-staff for demand at certain times and under-staff at other times. • Examples of organisations that typically apply fluctuation centred planning methods are fast food restaurants, distribution centres and call centres.
Health care systems	Permanence centred planning Mobility centred planning	• Nurse scheduling has been the major rostering focus in health care systems, usually in high care or intensive care hospital wards. • Both clinical and cost imperatives are associated with providing appropriate levels of staff in the different medical wards in a hospital. • Rosters must provide qualified nurses to cover the demands that arise from the numbers of patients in the wards, while also accommodating factors such as work regulations, distinguishing between casual and permanent staff members, ensuring that night and weekend shifts are distributed fairly, etc. • Rostering problems are mostly over-constrained. • Police services and hospitals face the problem of permanence centred planning where the number of personnel needed is defined in advance. • Mobility centred planning is linked to aspects of health care systems, e.g. home health care.
Protection and emergency services	Fluctuation centred planning Mobility centred planning Permanence centred planning	• An important aspect of staffing police, fire, security and ambulance services is the need to maintain service standards such as incident response times or the ability to dispatch suitable numbers of trained officers to particular incidents. • Given the nature of duties, most emergency services have very tightly controlled regulations that specify acceptable patterns of shift work. • The frequency of incidents that require emergency services officers will typically vary at different times of a day, a week or even a season (e.g. demand for ambulances may be higher on Friday nights). • If service standards are to be met, changes in the frequency of incidents require corresponding changes to the numbers of on-duty officers. • Except for emergency cases, staff numbers in police services and at hospitals are defined in advance and are permanence centred.

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Table B2 – Classification of Labour Scheduling Problems by Organisational Application Area, Adapted from Ernst *et al.* (2004) and De Causmaecker *et al.* (2004) (Continued)

Classification A **Ernst *et al.* (2004)**	**Classification B** **De Causmaecker *et al.* (2004)**	**Notes**
Civic services and utilities	Fluctuation centred planning Permanence centred planning Mobility centred planning	• From local to national levels, governments operate many labour intensive services. • Optimised staff rostering for these public services can improve the services that are provided while at the same time containing costs. • These application areas present unique challenges as government employees tend to have more generous employment conditions that can severely restrict the flexibility of rosters. • Labour scheduling literature has addressed the types of claims processing that might occur in government agencies dealing with pension claims and other social security entitlements, where large fluctuations in the workload must be managed. • Toll collection is another personnel scheduling problem in civic services and utilities that has been extensively covered in a host of literature sources. • Rostering of shift workers and operators in public service utilities and related services is becoming an important area of application. • An example of mobility centred planning in a civic services application is a health and safety board.
Venue management	Not applicable	• There are many different types of operations that involve completing tasks with a variety of skills requirements all at the same location (or venue). • Venue management problems include operations at sporting venues and airport ground operations. • A significant amount of published research in this category relates to staff scheduling at airports, e.g. customs staff, aircraft refuelling staff and general ground staff such as baggage handlers. • These airport staffing problems are characterised by service demands that are relatively well known as they are driven by regular airline timetables. • The scheduling of aircraft maintenance personnel is a somewhat different rostering problem where the main difficulty is to allocate a variety of small tasks to shifts in the presence of skill constraints.
Financial services	Fluctuation centred planning Project centred planning Mobility centred planning	• Rostering is important for banks in the staffing of tellers as well as some back office staff. • Teller staffing has similar characteristics to other customer service applications where the main difficulty is variability of demand over the day. • Another quite different problem is noted in the scheduling of audit staff. Here, the main source of complexity is the inconsistent nature of demand with a variety of audit projects that have a mix of skills requirements and working locations. • A consultancy service is another good example of an application area for project centred planning where different groups of employees are assigned to accomplish different projects.

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Table B2 – Classification of Labour Scheduling Problems by Organisational Application Area, Adapted from Ernst *et al.* (2004) and De Causmaecker *et al.* (2004) (Continued)

Classification A **Ernst *et al.* (2004)**	**Classification B** **De Causmaecker *et al.* (2004)**	**Notes**
Hospitality and tourism	Fluctuation centred planning Project centred planning	• Hotels normally employ staff with many different skills such as catering, housekeeping, reception, accounting, reservations and maintenance. • Staff members at hotels may be required to be rostered around the clock in some areas, such as room service. • Some hotel staff may be multi-skilled and others will have training needs written into workplace agreements. • The demand for services is not generally known with certainty in advance and management often relies on a combination of intuition and software systems, as well as local knowledge of marketing campaigns, events and attractions. • The provision of tailored tour services and events planning are examples of hospitality and tourism applications where project centred planning approaches may be applied.
Retail	Fluctuation centred planning Mobility centred planning	• Important criteria for generating high quality labour schedules in the retail environment include total cost and the service quality that is required. • Retail applications can be dealt with in a similar manner to the scheduling of call centre operators because shopping customers can be modelled as callers and sales clerks as call takers. • Certain retail activities such as product delivery services and the activities of sales representatives involve mobility centred planning.
Manufacturing	Fluctuation centred planning Project centred planning Mobility centred planning	• Decisions must be made in dynamic production environments in order to establish production levels for many different items such that product demands over a given period are met whilst adequate inventory levels are maintained. • The determination of manpower requirements for each production period is a critical problem that is associated to the balance between demand and supply. • In certain manufacturing applications, e.g. building construction and shipbuilding, labour scheduling may be project centred. Other manufacturing applications may include aspects where mobility centred planning is important, such as highly skilled or specialised mobile teams that support a number of dispersed manufacturing sites.

Furthermore, Subsection 2.2.3 of this study includes a discussion on the categories of modelling techniques or methodologies that are applicable to personnel scheduling problems. In this regard, Ernst *et al.* (2004) have identified five main categories of modelling approaches from the body of associated literature on staff planning and scheduling. These approaches are described in detail in Table B3.

Table B3 – The Five Principal Categories of Modelling Techniques that are Applicable to Personnel Scheduling Problems as Proposed by Ernst *et al.* (2004)

Category Name	**Category Description and Applicability**
Demand Modelling	This is the process by which customer arrivals during different time intervals and their associated service requests are translated into the staffing levels that are needed to maintain required or desired service standards. Queuing theory and simulation modelling are the two approaches that are most commonly applied in this regard. A number of numerical modelling approaches may be used for incident forecasting purposes, e.g. simple averaging, exponential smoothing, regression and seasonal or non-seasonal moving averages. Furthermore, theoretical probability distributions such as the Poisson distribution may be utilised where these distributions are found to be comparable to real-world observations. Traditional demand modelling methods are applied in situations where task demands are not explicitly known, such as customer arrivals in a supermarket checkout queue or incoming telephone calls to a customer service call centre. These modelling methods have not been widely applied in environments such as scheduled airline services or commuter bussing operations where the task demands are based on known timetables.
Artificial Intelligence Approaches	When examining artificial intelligence approaches, it should be noted that constraint programming (CP) and, to a lesser extent, metaheuristic methods have linkages to research in the field of artificial intelligence. However, these approaches are considered as individual modelling categories in this table and are therefore not covered under this category heading. Apart from CP, several other artificial intelligence techniques have been applied to personnel rostering problems, including techniques such as fuzzy set theory and intelligent search techniques. In this regard, fuzzy set theory has already been applied to solve air crew rostering problems. Within this category, researchers have discussed the use of decision support systems that are intended to assist rostering clerks and operations managers in their role. These systems apply techniques like intelligent search algorithms to improve solutions with a user-selectable degree of automation that provides a range of options from full manual rostering to a completely automated process. The decision support approach to rostering can be particularly useful where there are a host of human factors that cannot be coded in software and must be left to the discretion of the person(s) in charge of a given rostering scenario. Partially automated approaches can also be beneficial where these are applied as a first step in upgrading from a fully manual system at organisations where there is a significant lack of trust in 'black box' rostering systems. The affected researchers indicate that many metaheuristic approaches, as described later in this table, can also be modified for use in partially automated decision support systems for staff rostering problems.
Constraint Programming	Constraint programming (CP) can be a powerful tool for finding feasible solutions to staff rostering problems, particularly where a given problem is highly constrained or when any feasible solution is acceptable even if it is not optimal. However, CP techniques are less likely to generate good solutions for problems where there are a vast number of feasible solutions and the primary challenge is to determine an optimal, or near-optimal, solution. Powerful and flexible constraint logic programming languages are available to assist researchers or practitioners in this area. The use of these languages offers the notable advantage to the user that even complex constraints can be expressed relatively easily in a computational modelling environment.
Table continued on next page.	

Table B3 – The Five Main Categories of Modelling Techniques that are Applicable to Personnel Scheduling Problems as Proposed by Ernst *et al.* (2004) (Continued)

Category Name	Category Description and Applicability
Metaheuristics	Metaheuristics form a class of methods that may be used to solve complex problems such as combinatorial or discrete optimisation. Metaheuristics are typically hybrids of heuristic algorithms and are applied to problems that cannot be solved by traditional heuristics. Such algorithms combine different base methods under one high-level framework, with the different base methods being drawn from a potentially wide range of areas such as classical heuristics, artificial intelligence, biological evolution, neural engineering and statistical mechanics. Examples of metaheuristics are techniques such as 'simulated annealing', 'neural networks' and 'ant colony optimisation'. Heuristics and metaheuristics have been used frequently in solving staff scheduling problems, where their popularity is attributed to factors such as: • While they cannot be guaranteed to produce an optimal solution, they tend to be relatively robust and can usually produce a reasonably good and feasible solution for a wide input data range in a limited amount of running time. By comparison, many integer programming approaches carry the risk of not returning any feasible solutions unless a lengthy period of running time is allowed. • Most metaheuristics are relatively simple to implement and are adaptable to allow for problem-specific information to be incorporated and exploited. • Heuristic approaches allow for complex objectives to be dealt with comparatively easily. Based on the above factors, heuristics have generally been the method of choice for rostering software that is designed to deal with complex real-world objectives and constraints that do not solve easily within a mathematical programming formulation. However, they are generally less effective if the rostering problem is highly constrained, unless the constraints can be built directly into the heuristic. As such, CP approaches are reported to work better for more highly constrained problems.
Mathematical Programming	In mathematical programming approaches, scheduling and rostering problems are formulated either as linear programs, linear integer programs or general mathematical programs. Days-off scheduling, shift scheduling, tour scheduling, crew scheduling and crew rostering are all examples of labour scheduling problems that have been addressed using mathematical programming methods. Algorithms that are based on mathematical programming approaches have an advantage in that they generally achieve the most optimal solutions. However, there are a number of difficulties with such approaches that prevent them from being universally applied, such as: • Mathematical programming formulations are limited in terms of the constraints and objectives that can be expressed easily. These approaches are thus more commonly applied to simplified versions of real-world rostering problems, or in scenarios where there are few complications or constraints in the original problem. • Implementing an effective integer programming method for a particular crew scheduling and rostering problem has been found to be relatively difficult and time consuming. Such an approach is therefore only recommended when the cost benefit of the solution is significant and when the rostering constraints and rules are relatively static over time. • Even with current computational technology, it is still a formidable task to efficiently solve large linear integer programs to optimality with millions or even billions of feasible solutions. To mitigate this issue, methods can be applied to reduce the formulation size, e.g. generating limited numbers of columns either randomly or by using some intuitive criteria (although this may affect solution optimality).

Appendix C: Terminology and Illustrative Devices for Describing Shift Rosters

The terminology and illustrative devices that have been used in this study to describe shift rosters have been modified from the work of Belien *et al.* (2010). In this regard, a shift roster is composed of shift teams that are arranged according to so-called ‘shift cycles’. A ‘shift cycle’ is a pattern of on-duty and off-duty days (or shifts) for a shift team that loops repeatedly to describe the ongoing duty requirements for the affected team. By combining sequences of configurable shift cycles into a consolidated shift roster it is possible to optimise the coverage profile of on-duty staff members to best meet the demands of a shift-based operation such as an airport ground handling company or a manufacturing plant. Staff coverage at different times of day, such as morning, afternoon and night shifts, can be specified directly through the shift cycle definition. Alternatively, a shift cycle may only specify the duty days for an affected shift team, with the team being further subdivided into a number of work groups that are rostered for duty at different times of day. In either case, shift rosters can provide staff coverage characteristics that significantly exceed the coverage that is provided by typical office hours in a business or organisational setting.

Table C1 shows two illustrative examples of shift roster descriptions using different combinations of shift cycles. This table employs the same shorthand format for depicting a shift roster as was used by Belien *et al.* (2010) in their study on staff scheduling for airline line maintenance activities. Using this format, a shift roster can be depicted as a series of ‘shift blocks’. The number of shift blocks tells the reader how many cycles (equal to the number of shift teams) are included in the roster. Furthermore, by combining the shift blocks in sequence according to the cycle number under consideration, one can build the profile of duty days or shifts for each associated shift team. For example, in Scenario 2 shown in Table C1 there are three cycles which corresponds to three shift teams. In a single cycle rotation in this scenario, each shift team is rostered as follows:

- Cycle A (Team A): Shift Block 1, then Shift Block 2, then Shift Block 3
- Cycle B (Team B): Shift Block 2, then Shift Block 3, then Shift Block 1
- Cycle C (Team C): Shift Block 3, then Shift Block 1, then Shift Block 2

It should be noted that Belien *et al.* (2010) have made use of a fixed shift block length of one week in their study. This assumption is a limitation in that it prevents the generation of shift cycles that are not multiples of one week. The only limitation on shift block length that has been imposed in this study is that this variable must be a positive integer number. The concept is essentially the same as that used by Belien *et al.* (2010), but with the advantage of additional flexibility in terms of potential roster configurations.

Table C1 – Sample Shift Rosters Based on a 'Shift Cycle' Construction Concept, Adapted from Belien *et al.* (2010)

<u>SCENARIO 1:</u>

A shift roster employing an 8-day cycle length composed of 2 x 4-day shift blocks, i.e. 2 x cycles:

<< Note: O = a day with a rostered duty shift >>

O	O	O	O	<< Shift Block 1
				<< Shift Block 2

Expanding the above shorthand roster notation to show 3 x consecutive 8-day cycles for the two affected shift teams:

Team A	O	O	O	O					O	O	O	O					O	O	O	O				
Team B					O	O	O	O					O	O	O	O					O	O	O	O
	Cycle Repetition 1								Cycle Repetition 2								Cycle Repetition 3							

<u>SCENARIO 2:</u>

A shift roster employing a 21-day cycle length composed of 3 x 7-day shift blocks, i.e. 3 x cycles:

<< Note: D = a day shift allocation; N = a night shift allocation >>

D	D	D	D	D	D	D	<< Shift Block 1
			N	N	N	N	<< Shift Block 2
N	N	N					<< Shift Block 3

Expanding the above shorthand roster notation to show 1 x 21-day cycle for the three affected shift teams:

Team A	D	D	D	D	D	D	D				N	N	N	N	N	N	N				
Team B				N	N	N	N	N	N	N					D	D	D	D	D	D	D
Team C	N	N	N					D	D	D	D	D	D	D				N	N	N	N

Appendix D: Structured Interview Layouts

INTERVIEW 1:

Exploration of the Existing Methodology or Approach for STLM Labour Scheduling that is Applied at the Case Organisation

Overview:

This interview template probes the existing methodology that is applied at the case organisation to develop its STLM labour schedules. Interviews conducted according to this template are intended to be accomplished within a time period of 90 minutes or less. Two one-on-one interviews shall be conducted using this template, each with a senior manager who is involved in the oversight of line maintenance activities at the case organisation. The managers concerned are the head of the Airlink maintenance division, i.e. the AMO Accountable Manager, as well as the Chief Inspector who is directly responsible for the line maintenance function.

Each interview shall be carried out in the business environment. Furthermore, audio recordings shall be made of each interview and these recordings shall be transcribed into typed interview records. When interviewing, a brief overview of the interview structure and the research context may be presented before commencing with the set of interview questions that follow.

Interview Questions:

a) What is your role within the organisation?

b) What formal training or other exposure have you had to theoretical principles in the field of operations management?

c) What knowledge do you have of the following concepts that may be applied to operations management problems: (1) ‘linear programming’, (2) ‘constraint programming’, (3) ‘discrete event simulation’ and (4) ‘heuristics’?

d) What tools (e.g. computer software) does the organisation employ when developing labour rosters for aircraft maintenance activities?

e) Has the organisation employed any specialists in the field of operations management to assist in the development of these labour rosters?

f) Can you describe the current process or model by which staff rosters for STLM activities are developed at the organisation? Focus on how this process or model provides staff coverage to meet the demand for maintenance services across the operational hours of the day and the operational days of the week. Is sufficient coverage always provided?

g) To what extent does this rostering process incorporate demand planning that is tied directly to the published flight schedules that must be met by the organisation?

h) Do you acknowledge that planned flight schedules at the organisation vary significantly in capacity according to factors such as seasonality in demand, as well as fluctuations in demand by weekday? If yes, does the staff roster for STLM activities adjust accordingly to efficiently match labour supply levels to the prevailing demand levels?

i) Does the existing rostering process make use of numerical or computational techniques such as ‘iteration’ or ‘search’ to find optimal or near-optimal solutions?

j) How have accomplishment times (or standard times) for STLM events been determined in the existing rostering process? For clarity, have these times been determined through some form of measurement and supporting statistical analysis? If yes, provide details on the approach that has been followed. If no, do you feel that the approach that has been followed is sufficient to provide high quality rostering solutions?

k) Comment on the adequacy of the staff coverage that is provided by the existing rostering process. Is this coverage conducive to a smooth and orderly pace of work throughout the operational day? Is it necessary to supply additional unplanned labour resources during periods of high maintenance demand? Are there periods of significant idle time where the on-duty labour force is underutilised?

<< END OF INTERVIEW 1 >>

INTERVIEW 2:

A Review of the Validity and Viability of the Modelling Constraints that have been Established for Optimised STLM Labour Scheduling at the Case Organisation

Overview:

This interview template assesses a provisional set of modelling constraints in relation to STLM activities in the case setting. This set of modelling constraints has been established in order to support the implementation of a computational model for optimising the case organisation's STLM labour schedules. The main goal of the interview is to contemplate the validity and viability of each affected modelling constraint. Interviews conducted according to this template are intended to be accomplished within a time period of 60 minutes or less.

As with Interview 1, the following requirements are applicable to Interview 2:

- Two one-on-one interviews shall be carried out using this template, one with the head of the Airlink maintenance division (i.e. the AMO Accountable Manager) and the other with the Chief Inspector who is directly responsible for the line maintenance function.
- Each interview shall be carried out in the business environment.
- Audio recordings shall be made of each interview and these recordings shall be transcribed into typed interview records.
- When interviewing, a brief overview of the interview structure and the research context may be presented before commencing with the set of interview questions that follow.

Interview Questions:

With reference to the list of modelling constraints that has been provided (refer to Appendix E), assess the relevance and scope of each individual constraint in relation to the organisation's STLM operations. Make comments or recommend changes as you deem appropriate. In this regard, consider the following aspects:

a) The appropriateness of each constraint with regards to implementing personnel rosters that provide ample staff coverage at an acceptable cost for the needs of the operation.

b) The adequacy of each constraint in facilitating high quality staff rosters that are sufficiently stable, flexible and fair to the human resources to which they are applicable.

<< END OF INTERVIEW 2 >>

Appendix E: Constraints for the Experimental STLM Labour Scheduling Model

Note:
The modelling constraints in this appendix are in their provisional form where they are formatted as 'normal text'. Where comments or editions to a provisional constraint have been inserted based on the interview transcripts in Table F2 in Appendix F, these have been formatted in italics. The use of this approach has avoided unnecessary duplication in presenting the provisional and finalised list of modelling constraints.

The modelling constraints that have been established are as follows:

a) Shift starting times for work groups shall not fall outside the following time bounds:
   - '*Morning shifts*' (M) shall not commence earlier than 05:00 in the morning with an upper bound at 08:00.
   - '*Afternoon shifts*' (A) shall commence no earlier than 08:00 and no later than 18:00.
   - '*Night shifts*' (N) shall not commence later than 21:00 at night, with a lower bound at the midday mark (i.e. 12:00).
   - Shift starting times shall fall either on the hour or at an intermediate half hour mark.

b) The planned duration of each shift for a given work group shall be no less than 8 x hours and no more than 12 x hours, incrementing in half hour steps.

c) With reference to Subsection 4.1.1.1 of the study, the current duty cycle in the case setting of five days on, five days off, four days on, five days off, five days on, four days off shall be retained. This is due to its favourable provisioning of two weekends off per staff member in any consecutive four week period in addition to its structure whereby each staff member is given adequate rest days in between any consecutive sequence of on-duty days. This shift cycle structure is also well accepted amongst the current compliment of line maintenance AMEs and other technical staff that work the cycle. Although the basic shift cycle structure with its two associated shift teams shall be retained, the breakdown of work groups within the two shift teams may be varied according to constraints (a) and (b).

   Note:
   Applying a similar approach to that presented in Appendix C for describing duty cycles, the current line maintenance duty cycle in the case setting can be described in its most basic form as shown in Table E1. Note that this table depicts the same basic cycle as shown in Table 4 in Subsection 4.1.1.1. The structure of the cycle is such that each affected worker is allocated two on-duty and two off-duty days for each weekday in any 28 day period.

d) Read together, constraints (b) and (c) imply that all AMEs deployed to STLM activities by the case organisation shall be full-time workers. As such, the use of half-time or short-time workers as a flexible strategy for optimising STLM labour efficiencies is precluded for the case setting at hand.

e) A common start time shall apply for all AMEs assigned to a particular shift or work group on a given day. This constraint precludes the allocation of staggered start times amongst the individual workers that are assigned to a given shift or work group on a given day.

f) The start times of equivalent shifts on consecutive days should be equal as far as possible, but shall not differ by more than 120 minutes as a hard constraint. Note that this constraint is consistent with the work of Herbers (2005). In addition, each AME shall be assigned to the same work group, e.g. the morning shift, for each sequence of consecutive on-duty days for which he / she is rostered.

g) If more than one duty shift is necessary to cover the hours of operation on a given day, the second (or subsequent) duty shift shall commence no later than the planned finish time of the preceding duty shift. This constraint ensures continuity of STLM services throughout each operational day. In this regard, continuity is deemed to be necessary as the timing and scope of STLM events may vary from the stipulations of the published flights timetable due to uncertainties such as unforeseen schedule disruptions.

Comment:

Looking at the contents of Table F2 in Appendix F, both interviewees who evaluated the modelling constraints in this study have recommended an overlap of consecutive shifts in order to facilitate an accurate handover of work. These interviewees have suggested that a handover period of approximately 30 minutes should be applied. This recommendation has not been adopted in this study for two reasons. Firstly, the researcher has been deemed that it is more relevant for handovers to be mandated between consecutive duty shifts of the supervisory staff (i.e. the Crew Chiefs) who oversee the FLM Team than for this to be applied for all incoming and outgoing AMEs on the team. It should be noted in this regard that supervisory manhours have not been specifically quantified in the study results. Secondly, constraint (o) prohibits the handover of individual STLM checks between AMEs on consecutive shift groups. This, in turn, means that shift handovers need only cater for the upcoming sequences of tasks that must be met by the incoming shift group as all STLM checks that are in progress are required to be completed by the affected members of the outgoing shift group prior to them vacating the shift.

h) Overtime shall be paid at a rate of 1.5 times the standard hourly labour rate for any AME on the FLM Team who works in excess of 168 duty hours in a 28-day cycle. However, it is not permissible for overtime to be used as a means to provide coverage for planned STLM events that are associated to on-time aircraft movements.

i) Based on constraints (b), (c) and (h), the average number of rostered working hours per AME per week, inclusive of break or meal times, shall not exceed 42 hours.

j) The average number of working hours per AME per week, inclusive of break or meal times, should not fall below 35 hours (soft constraint). By virtue of constraints (b) and (c), it is noted that this average cannot fall below a minimum level of 28 hours.

k) With regards to constraints (f), (i) and (j), work group allocations shall rotate periodically at the discontinuities between sets of consecutive on-duty days. This shall ensure that all AMEs on the shift system are, in the medium to long term, equally exposed to the various work groups and associated duty times on their assigned shift team.

l) Prior to releasing an affected aircraft for flight, each STLM task that has been performed shall be inspected and certified by a suitably-authorised LAME on the given aircraft type. In this regard, Category W LAMEs are not required for the performance or certification of any aspect of the STLM checks on any Airlink aircraft type. Only Category A and Category C LAMEs are needed to certify these tasks.

m) Following on from constraint (l), it is a common practice in the airline industry for LAMEs with a general line maintenance orientation to be dual-rated as Category A and Category C licence holders. All LAMEs deployed by the case organisation to its STLM function shall therefore be assumed to be qualified as so-called ‘A and C’ license holders.

n) Although STLM events can, in theory, be split amongst any number of AMEs, practical limits shall be applied in this study as indicated in Table E2.

Comment:
During the evaluation of this list of modelling constraints, one of the interviewees suggested that it is feasible to allocate up to three AMEs to perform an after-flight check on an RJ85 aircraft, which is the largest of the aircraft types that Airlink operates. This maximum allocation would consist of two AMEs in the airframe and engine maintenance categories, along with a specialist avionics technician. This suggestion has not been applied in the study as it has been assumed that there is no specific requirement for a specialist avionics technician to participate in the after-flight check work scope on any Airlink aircraft type. As

such, the use of avionics technicians to assist in performing routine after-flight checks has been deemed to be an inefficient deployment of these specialised resources. In addition, the other interviewee recommended that a fixed allocation of one AME is sufficient for implementing the pre-flight check requirement on each Airlink aircraft type. However, it has been decided to retain the flexibility of allocating up to two AMEs to maintenance pre-flight checks based on preliminary testing results for the optimisation modelling processes that have been implemented.

o) AMEs shall not be permitted to contribute to a STLM event for less than the full duration of the event. As such, each AME assigned to a given maintenance task must work from the start time to the finish time of the task. This constraint is applied due to the potential for oversights and miscommunications in maintenance where AMEs can arrive to assist on a check after it has commenced or vacate a check before it has been completed. Where a STLM check is commenced towards the end of a particular duty shift, this constraint may require affected AMEs to work overtime or extended hours beyond the published finish time of their shift.

p) The performance of STLM events shall be constrained by the time windows presented in Table E3. These time windows have been defined on the premise that the STLM event applicable to an aircraft during a given period of ground time at a maintenance station must be carried out within the time period between the aircraft's most recent arrival and its next planned departure. However, additional practical considerations have also been included with regards to these time windows. For example, a maximum start time for after-flight checks has been imposed, as well as a restriction to ensure that pre-flight checks do not finish earlier than 60 minutes before an associated flight. As a representative example, the maximum start time constraint for after-flight checks has been imposed in order to ensure that sufficient time is available before the next planned departure of an affected aircraft to assess and correct any unforeseen defects that may be identified through the completion of the after-flight check work scope.

Comment:

In evaluating the modelling constraints that have been applied in this study, one of the interviewees has suggested that a constraint on after-flight check start times of 30 minutes post-arrival is overly conservative. In this regard, the affected interviewee has expressed his opinion that after-flight checks can be commenced as soon as the crew and passengers have vacated the aircraft. This typically occurs within 15 minutes after the arrival of an affected aircraft at its assigned parking bay. Under this constraint, however, routine ground handling functions such as after-flight cabin cleaning and servicing of toilets may need to be implemented after AMEs have already completed the required after-flight check. It has *been considered prudent in this study to retain a sufficient time lag after an aircraft's final arrival on a given day-of-operations to enable such ground handling functions to be completed before the commencement of the after-flight check. In this way, opportunities for an aircraft to be disturbed after its final maintenance check of the day are minimised.*

q) AMEs on the FLM Team shall be compensated for a minimum time period worked of three hours for any instance where they are called out to duty on a reactive basis to support the needs of the operation. This callout labour charge shall be supplemented by a claim for the transportation costs incurred by each affected technician. A fixed average transportation cost claim of 131.20 ZAR per callout has been assumed. This cost has been calculated on the basis of an average distance travelled per callout event of 40 kilometres at a total cost of 3.28 ZAR per kilometre (i.e. Airlink's standard rate for vehicle expense claims).

r) Wherever a flight delay is induced by a lack of sufficient on-duty AMEs to meet the STLM requirements for dispatching an aircraft, flight delay costs shall be incurred. These costs shall be calculated according to the average delay costs specified by Eurocontrol (2009), cited in Cook and Tanner (2009: p. 7). According to this source, delay costs of 79 EUR per minute on average are applicable to flight delays of 15 minutes or longer after the planned departure time of a given flight. For delays of less than 15 minutes in duration, delay costs are approximated to zero. An average exchange rate for the 2012 calendar year of 10.56 ZAR per EUR shall be applied for currency conversions in this regard.

Table E1 – Basic Format of the Staff Duty Cycle that is Applied within the Line Maintenance Department of Airlink's Maintenance Division, Adapted from Belien *et al.* (2010)

The shift roster employs a 28-day cycle length composed of 2 x 14-day shift blocks (O = a day with a rostered duty shift):

<< Note: O = a day with a rostered duty shift >>

O	O	O	O	O						O	O	O	O	<< Shift Block 1
					O	O	O	O	O					<< Shift Block 2

Expanding the above shorthand roster notation to show 1 x 28 day cycle for the two affected shift teams:

<< Note: The shift teams are denoted as the Yellow Shift and Green Shift respectively >>

Yellow Shift	O	O	O	O	O						O	O	O	O						O	O	O	O	O				
Green Shift						O	O	O	O	O					O	O	O	O	O						O	O	O	O
	Week 1							Week 2							Week 3							Week 4						

Table E2 – Manpower Constraints and Certification Requirements per STLM Event at the Case Organisation

Description of STLM Event	AMEs Allocated per Event		Certifying LAMEs Required per Event
	Minimum	Maximum	
J41 After-Flight Check	1	2	1
J41 Pre-Flight Check	1	2	1
J41 Transit Check	1	1	1
ERJ135 After-Flight Check	1	2	1
ERJ135 Pre-Flight Check	1	2	1
ERJ135 Transit Check	1	1	1
RJ85 After-Flight Check	1	2	1
RJ85 Pre-Flight Check	1	2	1
RJ85 Transit Check	1	1	1

Note: For a description of each aircraft type (i.e. J41, ERJ135 or RJ85) listed in the table, refer to Subsection 3.3.1.

Table E3 – Time Windows Imposed at the Case Organisation for the Completion of STLM Work Scopes

Event	Time Window Limit(s)	Notes
After-Flight Check	**Lower Bound** Start time >= arrival time + 30 mins (hard constraint) Start time >= arrival time + 40 mins (soft constraint) **Upper Bound** Start time <= 24:00 (soft constraint) Start time <= 02:00 (hard constraint)	The lower bound is needed to allow time for passengers to vacate the aircraft and for ground services to complete certain routine tasks after an arrival. This time period also allows the aircraft to be relocated to a maintenance area if needed. The upper bound is a practical constraint to ensure that a recovery time window is available after completing an after-flight should a significant defect or technical issue be identified. There is a further soft constraint on the lower bound in that it is recommended that after-flight checks commence no earlier than 15:00 for aircraft finishing their operational day early. This stipulation avoids duplication of work should an affected aircraft need to be redeployed to service for unplanned reasons, such as a significant arrival delay on another aircraft.
Pre-Flight Check	**Lower Bound** Finish time >= departure time less 60 mins (soft constraint) **Upper Bound** Finish time <= departure time less 30 mins (hard constraint)	The lower bound is a practical consideration to prevent pre-flight checks from being accomplished too early where there is still a significant time window for an aircraft's technical condition to change before the flight crew arrive at the aircraft to prepare for the upcoming operational day. The upper bound is a hard constraint to ensure that pre-flight maintenance is completed in good time to prevent interference with flight crew preparations, ground servicing activities and passenger boarding in the critical 30 minutes prior to departure. **Note:** The pre-flight check start time limits in this study are based on the assumption that 1 x AME is generally assigned to such checks.
Transit Check	**Lower Bound** Start time >= arrival time (hard constraint) **Upper Bound** Start time >= arrival time + 10 mins (hard constraint)	Transit checks are initiated within 10 minutes after an associated arrival. This constraint supports quick turnarounds and allows for maximum recovery time should such a check uncover a significant defect or technical issue on an affected aircraft. There is a minor area of concern with the practice of initiating transit checks shortly after an arrival where the affected aircraft has a significant period of ground time prior to its next flight. In such a case, the flight crew will generally vacate the aircraft and leave it unsupervised for a period of time. In this scenario, there is a potential for the aircraft technical condition to change before the flight crew return to the aircraft to prepare for the next flight.

Appendix F: Interview Transcripts

Table F1 – Transcripts for Interview 1

Question	**Response** >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(a)	**AM:** My role within the organisation of Airlink Maintenance is to coordinate all maintenance functions of the airline to ensure that the aircraft, which are our means of making money, are supplied to the flight line for operations timeously and in a fit-for-flight condition. This involves management of the workforce to ensure that all associated maintenance work is completed. **MC:** As Chief Inspector for the line maintenance function at Airlink, my day normally starts by reviewing the maintenance work that has been carried out the previous night and ensuring that the rostered shift team has attended to the rectification of all unplanned defects in the proper manner. This is necessary because, at times, an AME on the hangar floor understands a defect in a completely wrong way which then results in incorrect or inadequate rectification actions. I am also involved in the drafting of policies and procedures that company AMEs have to work with. Furthermore, I research ongoing defects within the fleet to try and give guidance or recommendations on corrective actions. In this regard, I also look at preventative maintenance actions to avoid such defects from manifesting during line operations. In short, I deal with the day-to-day technical issues on the operational aircraft fleet. Our AMEs assigned to line maintenance duties work a shift system and I am involved in the management of the affected personnel. This includes interviewing and placing the Crew Chiefs (i.e. supervisors) that are employed. It also includes the management of leave and training for line maintenance AMEs, as well as deciding on the allocation of AMEs to shift teams. To a certain extent I am involved in the allocation of maintenance work to the on-duty shift team. Even though this is the supervisor's responsibility primarily, there are times when I will step in to make decisions on the prioritisation of work. Whenever we have to deal with an aircraft breakdown away from base, I will also get involved in setting up a crew for a recovery process. On the recruitment and staffing side, I look at bringing in appropriate levels of AMEs to suit the workload. The day-to-day running of the on-duty work shift is really a direct responsibility of the active supervisors, but any discipline issues as well as any workmanship issues fall under my accountability as well.
(b)	**AM:** I have completed a basic management course through the Dale Carnegie Institute. I have also completed an aircraft planning and maintenance course in New Orleans which went about the scheduling of maintenance into an aircraft hangar, the workflow of aircraft while in the hangar, as well as the basic quality control process for hangar maintenance. **MC:** I have had no formal training in operations management principles.
(c)	**AM:** To be absolutely honest, I have never been involved in any of the four items listed. **MC:** None whatsoever to all of the listed concepts. I have never even heard of the word 'heuristics'.
(d)	**AM:** Airlink per se does not have any (dedicated) tool or computer software to be able to roster manpower for maintenance activities. The best that we have done is to make use of Microsoft Excel spreadsheets. Many years ago we always used to use a whiteboard for organising and rostering manpower in a manual fashion. Come to think of it, we still this method today on our flight line. For overnight maintenance, a Crew Chief will typically write down the work for the night on a whiteboard so the staff members on duty are aware of what they have to do. We have also used the Microsoft Project package on a limited basis. We have not used this tool an awful lot, but it is a tool we have employed. However, we have not yet perfected the use of this tool. **MC:** I know that they make use of dedicated software for this purpose in the flight operations department, but I am not aware of any computer software for such activities in the maintenance department.
(e)	**AM:** No, we have not employed specialists or consultants in this regard. **MC:** None that I know of.

Continued on next page.

Table F1 – Transcripts for Interview 1 (Continued)

Question	**Response** >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(f)	**AM:** At present, and we have actually used this for several years now, we have a Microsoft Excel spreadsheet that lists the two crews for our short-term line maintenance work. We refer to these crews as the Green Shift and the Yellow Shift respectively. On each of these shift crews, we have licensed and unlicensed AMEs, including avionics technicians, as well as unskilled labour in the form of technical assistants. Each of the crews incorporates a total of around about 30 AMEs, which should be sufficient for the operation. However, in times of high levels of sickness and training, we do end up with brief periods of staff shortages where we have insufficient coverage for our needs. The shift structure as it is with its total number of people is actually divided into various work groups. In this regard, the Crew Chief on each crew divides the crew into a day shift work group and a night shift work group. During the day, the manpower that is available for the shift, which is about five people, provides sufficient coverage to perform all of the maintenance activities on the aircraft that come and go during the day. The majority of the staff members on each crew are rostered to work the night shift, on a four day on, four day off rotation basis. To enable us to get to the figure of approximately 30 AMEs per shift, we did work in the past to list all the tasks which we feel are required to run the line maintenance function. The number of AMEs we determined using this method came out to around about 59. What we have done as a result of the four on, four off system is to settle on about 30 AMEs per shift crew. **MC:** We have a shift system at work, which is composed of sequences of four days on / four days off and five days on / five days off duty rotations. This system utilises 12 hour shifts. The bulk of the AMEs on the shift system will come in at night and about five AMEs run the day shift where the main requirement is the implementation of aircraft transit checks. In this regard, most of the line maintenance activities are done at night when the aircraft have returned to base upon completion of their daily operations. This includes scheduled maintenance items as well as the rectification of aircraft defects that have been logged during the course of the day by the flight crews. A few AMEs could be on leave or could call in sick, but under normal conditions there is sufficient manpower to accommodate whatever work is out there. From time to time, due to factors such as courses, leave constraints (including annual and sick leave) or unplanned defects (e.g. an engine change due to a birdstrike event), you may find that we run slim on manpower coverage. On the whole, however, there is sufficient coverage to meet the demand for maintenance services across the hours of the day.
(g)	**AM:** To be absolutely honest with this, we have actually used historical data to determine the number of men that we should roster per shift. However, this approach does not always take into consideration the peak demand levels that we are required to meet as well as the low periods that are demanded of us. In that respect, we sometimes end up with an ineffective workforce and this could be a lot better organised with a suitable planning tool. **MC:** The AMEs that are allocated to the day shift crew are focused on meeting the pre-flight check and transit check requirements of the airline. At times, these AMEs also attend to any quick turnaround defects that the flight crews may have logged. Generally, at the beginning of the day, all the required activities in terms of aircraft movements (and associated STLM checks) will be listed and this has given us an idea of how many AMEs are needed to effectively run the flight line, which has turned out to be about four or five AMEs during the day. In addition, we have also recently set up a SVM Team so that if any unplanned maintenance work comes up that is going to require significant maintenance downtime, the affected aircraft is pulled off the flight line and taken to a dedicated maintenance area where it can be attended to by this team which supplements the manpower allocated to flight line duties. We also use forecasting of upcoming scheduled maintenance events, such as A-checks or major component changes such as landing gear or engine changes, in order to make decisions on moving the shifts around to get the work done effectively. In this way, we can act to avoid the occasional instances where surplus numbers of AMEs sit idle because there isn't sufficient work currently in progress. This includes decisions such as directing AMEs to report for duty earlier than the specifications of their predefined shift roster. We do get ups and downs in the demand levels for aircraft maintenance services, but in general the AMEs deployed to line maintenance activities are kept busy.
Continued on next page.	

Table F1 – Transcripts for Interview 1 (Continued)

Question	**Response** >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(h)	**AM:** Our flight schedule does actually vary quite a bit, particularly over weekends. However, for consistency and continuity, our shift system provides for a certain number of people during the night and through the day. This does not vary unless AMEs are off sick or on training. **MC:** Yes, I agree that the planned flight schedules do vary in capacity according to the day of the week. From Monday to Friday, and on Fridays especially, the schedule is at its busiest. On Saturday, the day ends quite early. On Sunday, the day starts late but once underway it ends up being quite busy and similar to a normal office day. In general, however, the operation slows down over weekends. We keep the same manpower levels over both weekends and normal office days, but we use the weekends to get other work done and we don't deploy the full shift to the flight line. In this regard, we can have additional AMEs in the hangar attending to an engine change or a landing gear change over weekends when the schedule is less active. Alternatively, we can also use surplus day shift AMEs on weekends to start the after-flight checks early as the active aircraft complete their daily operations, thus reducing the after-flight check workload that must be met by the night shift. This then enables the night shift to focus on implementing planned maintenance tasks that have been issued out by the Maintenance Planning Department. So our operation is quite flexible in that respect.
(i)	**AM:** No. **MC:** We are a company built more on experience. We have grown over the years, diversified the fleet and the number of staff members employed has grown steadily in conjunction. We have used our experience to assess the growth in planned maintenance tasks and aircraft defects that has accompanied the growth in our fleet and we have used this assessment to determine the AME numbers that are required to meet the maintenance demand. We haven't done any scientific research or applied scientific methods to come up with our rostering processes and staff numbers.
(j)	**AM:** We have varying skills within the organisation. We have some highly competent AMEs who have been in the organisation for quite some time and who have built up some very good skills. On the other hand, we also have AMEs who have a mediocre work ethic and we have those who are just coming out of their (qualification) time or are still apprentices. As such, we don't have consistency amongst all members of the workforce where we could determine a set standard of times. We have tried to measure times of these various classes of AMEs, from the highest to the lowest, and to use an average. The difficulty we have had with this approach relates to the varying conditions of work on the airport. To clarify, aircraft are parked overnight with varying proximity to the maintenance hangar and other facilities. There is a lot of time wastage when comparing an aircraft parked out on the flight line with one parked close by the hangar and the stores facility. As such, the manpower management and the planning of the various maintenance tasks can be quite difficult. In this regard, it is difficult to get accuracy because of the challenges in determining the time wastage in getting to and from each aircraft and to and from the stores. Where we have made measurements to try to determine standard times, we have basically taken an average of a group of people. However, these measurements have not considered real-world factors such as where the aircraft are parked, the current weather conditions and working a 24 hour day. We work 365 days a year, with extremely cold conditions on certain winter nights and thunderstorm activity in the evenings in summer. So it is very difficult to determine accurate times for performing SLTM events as we are discussing today. **MC:** Again, I would say that this has been based on experience. For standard tasks such as carrying out an aircraft pre-flight or after-flight check where the affected AME works according to a checklist, we do see a degree of variation in task times from individual to individual. In this regard, although they are working to the same checklist, some AMEs are a lot more thorough than others in the way they execute tasks. But I would say that the times for implementing these routine tasks are still reasonably uniform from AME to AME. The times that have been recommended for these tasks are based on the assessments of senior AMEs. Because these senior AMEs are heavily involved in on-the-job training of more junior AMEs, it is my belief that their recommendations are generally reasonably standard amongst the line maintenance crews. For example, if the time specified for an after-flight check is one hour, then this is the standard that will be trained and passed on to the other members of a work crew by the senior AMEs on the crew.
Continued on next page.	

Table F1 – Transcripts for Interview 1 (Continued)

Question	**Response** >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(k)	**AM:** In theory, the staff coverage should be more than adequate to perform the work that is at hand. I think the weak area that we have in our organisation is lack of supervision because of aircraft being parked all over the airfield. They can be hundreds of metres apart. As a result, our supervisors (i.e. Crew Chiefs) struggle to adequately oversee the work that is being done. I think the skill that we have not been able to impart on our supervisors is delegation skills and, in particular, the ability for those supervisors to hold staff members to account for the work that has been delegated to them according to set performance parameters. I do feel that we could run the organisation on more lean principles with better management skills. I do not believe at this point that it is necessary to supply additional unplanned labour resources during periods of high maintenance demand, but in saying that we do have a number of maintenance departments within the organisation. As such, we have been able to draw down on other parts of our labour force to compensate for peak schedule times and other instances of heavy workloads. Because we run a scheduled airline, we have peaks and troughs of work that must be handled. For example, from 06:00 through to 08:00 on weekday mornings, where a high number of departures are happening and aircraft are being towed around, there will be high activity levels. But in the period from 08:00 to between 09:00 and 09:30 when the aircraft start to some back from their first flight rotations, there will be periods of definite idleness with people having to wait for the work to come in. There are generally two or three peak and trough periods during any given day. **MC:** Adequate staff levels are provided by the existing staff rostering process. However, challenges come at times when AMEs are attending courses, where high levels of leave are applied for, where staff call in sick and, of course, where unplanned events such as lightning strikes or birdstrikes occur that result in significant unplanned maintenance inputs such as engine changes. Occasionally these factors will result in manpower constraints, but in general there is adequate staff coverage. Also, no day of the week is the same in terms of the aircraft defects that the crew identify during the course of operations. For example, in reviewing the aircraft technical logs for the previous day, you may find that the aircraft experienced no defects or only very minor items such as light bulb changes that would not have required any significant AME inputs to troubleshoot and rectify. In such a case, the number of AMEs rostered would have included a surplus and the on-duty AMEs would have had significant levels of idle time. They may have finished their work early and possibly even vacated the shift early. The opposite may happen as well. Even with a full complement of AMEs with nobody on annual or sick leave, you may have a day when the aircraft experience a high number of unplanned defects. In such a case, the workloads that are needed to investigate and rectify the aircraft defects may stretch the available workforce. This scenario may be further compounded where there is also scheduled maintenance work such as a landing gear change that must be performed overnight and which cannot be deferred to a later date. For cases such as this, we do not have a formalised standby system. However, during such high demand periods such a system is necessary. What we generally do in such scenarios is to call on AMEs who are on off-duty allocations to come in and assist on an overtime basis. So yes, we do occasionally call in supplementary labour resources on an unplanned basis in high-demand scenarios.

Table F2 – Transcripts for Interview 2

Constraint	**Response** >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(a)	**AM Comments:** Nil. **MC Comments:** Nil
(b)	**AM Comments:** Nil. **MC Comments:** A shift length of 8 x hours is ideal but I have noted that the 12 x hour shift does occasionally bring about issues of fatigue. While this is often based on the rest that an individual AME gets prior to a shift, I have noted that the 12 x hour shift can be taxing at times.
Continued on next page.	

Table F2 – Transcripts for Interview 2 (Continued)

Constraint	Response >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(c)	**AM Comments:** Nil. **MC Comments:** Nil.
(d)	**AM Comments:** Nil. **MC Comments:** Nil.
(e)	**AM Comments:** Nil. **MC Comments:** Nil.
(f)	**AM Comments:** Nil. **MC Comments:** Nil.
(g)	**AM Comments:** Where you have put down that the latest time for a shift transition is the end of one shift and the start of another, I believe that there should be an adequate handover period of at least half an hour between the affected shifts. **MC Comments:** For a smooth transition and handover, I would strongly recommend an overlap of at least 30 minutes with regards to the incoming and outgoing shifts.
(h)	**AM Comments:** Nil. **MC Comments:** Nil.
(i)	**AM Comments:** Nil. **MC Comments:** Nil.
(j)	**AM Comments:** I believe that giving less than optimum working hours, i.e. dropping down to 35 hours or 28 hours per AME per week, is disadvantageous where personnel work on a monthly fixed-based salary. This regime will be far better suited to personnel on an hourly salary. **MC Comments:** Nil.
(k)	**AM Comments:** Nil. **MC Comments:** Nil.
(l)	**AM Comments:** Nil. **MC Comments:** Nil.
Continued on next page.	

Table F2 – Transcripts for Interview 2 (Continued)

Constraint	Response >> AM = Andy Mace, AMO Accountable Manager (08 Feb 2013) >> MC = Morgan Chikurunhe, AMO Chief Inspector: Line and Base Maintenance (15 Feb 2013)
(m)	**AM Comments:** Nil. **MC Comments:** Nil.
(n)	**AM Comments:** With regards to the minimum and maximum manpower allocations per task, it is noteworthy that these numbers only include A and C Category AMEs and do not make any allowances for different trades, i.e. avionics technicians. I do feel that on a larger aircraft, such as the RJ85, you could go to a maximum number of three persons for an after-flight check, that being two A and C Category AMEs together with a specialist avionics technician. **MC Comments:** With regards to Table E2, for all three aircraft types I would recommend that a maximum of one AME for the pre-flight check will suffice.
(o)	**AM Comments:** Nil. **MC Comments:** Nil.
(p)	**AM Comments:** Nil. **MC Comments:** With regards to the after-flight check start time constraint of 30 minutes post-arrival, I feel that in many cases the after-flight ground handling functions such as aircraft cleaning only commence significantly after the aircraft's arrival on its last flight of the day. For me, as soon as the crew and passengers have vacated the aircraft, i.e. within 15 minutes or so after arrival, an AME should be able to commence the aircraft's after-flight check. Of course, I would recommend that the aircraft is given a final check after the cleaners have been on it to confirm that the aircraft has not been unduly tampered with or damaged as a result of the after-flight cleaning process.
(q)	**AM Comments:** Nil. **MC Comments:** Nil.
(r)	**AM Comments:** Nil. **MC Comments:** Nil.

Appendix G: Time Measurements for the Accomplishment of STLM Tasks in the Case Setting

Table G1 contains details of the time measurements that have been taken at the case organisation in order to establish standard times for the nine distinct STLM task scopes that are implemented in the case setting. In order to ensure consistency in the scope of work that has been covered per STLM task, each time measurement has been taken according to a standard checklist of required inspection and / or servicing actions for the associated task. Note that these time measurements exclude supplementary actions to rectify non-routine defects and technical findings that may result from the implementation of the affected STLM tasks.

Table G1 – Time Measurements in the Case Setting for the Accomplishment of STLM Tasks

Date	**Aircraft Registration** > NS = Not Specified	**Aircraft Type**	**Inspection Type** > AF = After-Flight Check > PF = Pre-Flight Check > TC = Transit Check	**Location** > See the Airport Code Key	**Number of AMEs**	**Person(s) Observed** > NS = Not Specified	**Start Time** > NS = Not Specified	**Finish Time** > NS = Not Specified	**Task Time (hh:mm)**	**Total Manminutes**
14-Jan-12	ZS-NRH	J41	TC	JNB	1	B. Froneman	12:08	12:23	0:15	15.0
14-Jan-12	ZS-SUV	ERJ135	TC	JNB	1	D. van Wyk	12:29	12:35	0:06	6.0
14-Jan-12	ZS-NRG	J41	AF	JNB	1	T. Chibanda	14:14	15:05	0:51	51.0
14-Jan-12	ZS-SSI	RJ85	AF	JNB	2	D. van Wyk W. Krog	14:54	15:35	0:41	92.0
19-Jan-12	NS	J41	AF	JNB	1	NS	NS	NS	1:25	85.0
19-Jan-12	NS	J41	AF	JNB	1	NS	NS	NS	1:30	90.0
19-Jan-12	NS	ERJ135	AF	JNB	1	NS	NS	NS	1:30	90.0
19-Jan-12	NS	RJ85	AF	JNB	1	NS	NS	NS	1:50	110.0
20-Jan-12	ZS-NRE	J41	TC	JNB	1	D. van Wyk	14:09	14:20	0:11	11.0
20-Jan-12	ZS-SSI	RJ85	AF	JNB	1	R. Bamberger	19:00	21:00	2:00	120.0
20-Jan-12	ZS-NRK	J41	AF	JNB	1	S. Mathabela	18:30	20:00	1:30	90.0
20-Jan-12	ZS-SNW	ERJ135	AF	JNB	1	T. Chibanda	18:20	20:03	1:43	103.0
21-Jan-12	ZS-SNW	ERJ135	AF	JNB	1	T. Chibanda	22:00	23:19	1:19	79.0
22-Jan-12	ZS-ASY	RJ85	AF	JNB	1	T. Chibanda	18:15	20:30	2:15	135.0
22-Jan-12	ZS-ASX	RJ85	AF	JNB	1	A. van Niekerk	19:00	20:45	1:45	105.0
22-Jan-12	ZS-OTM	ERJ135	AF	JNB	1	C. Barnard	18:30	20:15	1:45	105.0
28-Jan-12	ZS-NRL	J41	TC	JNB	1	R. Bamberger	10:16	10:26	0:10	10.0
28-Jan-12	ZS-SUV	ERJ135	TC	JNB	1	B. Froneman	10:50	11:05	0:15	15.0
28-Jan-12	ZS-SNX	ERJ135	TC	JNB	1	A. Shumba	11:55	12:06	0:11	11.0
28-Jan-12	ZS-OTM	ERJ135	TC	JNB	1	B. Froneman	12:07	12:23	0:16	16.0
28-Jan-12	ZS-OTM	ERJ135	TC	JNB	1	R. Bamberger	14:47	14:55	0:08	8.0
30-Jan-12	ZS-SSK	RJ85	TC	JNB	1	R. Bamberger	10:15	10:25	0:10	10.0
30-Jan-12	ZS-OTN	ERJ135	TC	JNB	1	R. Bamberger	12:34	12:46	0:12	12.0
30-Jan-12	ZS-OTM	ERJ135	TC	JNB	1	R. Bamberger	15:00	15:10	0:10	10.0
30-Jan-12	ZS-SNX	ERJ135	TC	JNB	1	S. Zaayman	15:05	15:15	0:10	10.0
31-Jan-12	ZS-OTN	ERJ135	TC	JNB	1	S. Zaayman	NS	NS	0:10	10.0
31-Jan-12	ZS-SNX	ERJ135	TC	JNB	1	S. Mathabela	11:43	11:55	0:12	12.0
23-Jan-12	ZS-OTN	ERJ135	TC	DUR	1	NS	16:10	16:25	0:15	15.0
23-Jan-12	ZS-OTN	ERJ135	AF	DUR	1	NS	18:45	19:30	0:45	45.0
24-Jan-12	ZS-OTN	ERJ135	PF	DUR	1	NS	5:45	6:30	0:45	45.0

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Table G1 – Time Measurements in the Case Setting for the Accomplishment of STLM Tasks (Continued)

Date	Aircraft Registration > NS = Not Specified	Aircraft Type	Inspection Type > AF = After-Flight Check > PF = Pre-Flight Check > TC = Transit Check	Location > See the Airport Code Key	Number of AMEs	Person(s) Observed > NS = Not Specified	Start Time > NS = Not Specified	Finish Time > NS = Not Specified	Task Time (hh:mm)	Total Manminutes
24-Jan-12	ZS-OTN	ERJ135	TC	DUR	1	NS	9:00	9:15	0:15	15.0
24-Jan-12	ZS-OTN	ERJ135	TC	DUR	1	NS	14:10	14:25	0:15	15.0
24-Jan-12	ZS-OTN	ERJ135	AF	DUR	1	NS	19:00	19:45	0:45	45.0
24-Jan-12	ZS-SNV	ERJ135	TC	GRJ	1	NS	8:10	8:20	0:10	10.0
24-Jan-12	ZS-OTN	ERJ135	TC	GRJ	1	NS	11:30	11:45	0:15	15.0
24-Jan-12	ZS-ASZ	RJ85	TC	GRJ	1	NS	17:35	17:50	0:15	15.0
24-Jan-12	ZS-NRG	J41	TC	PZB	1	NS	16:50	17:15	0:25	25.0
24-Jan-12	ZS-ASW	RJ85	AF	PZB	1	NS	18:45	19:35	0:50	50.0
24-Jan-12	ZS-ASZ	RJ85	AF	CPT	2	NS	19:20	20:10	0:50	100.0
24-Jan-12	ZS-SNV	ERJ135	AF	CPT	2	NS	20:20	21:20	1:00	120.0
25-Jan-12	ZS-OTN	ERJ135	PF	DUR	1	NS	5:45	6:30	0:45	45.0
25-Jan-12	ZS-OTN	ERJ135	TC	DUR	1	NS	9:10	9:40	0:30	30.0
25-Jan-12	ZS-OTN	ERJ135	TC	DUR	1	NS	13:00	13:30	0:30	30.0
25-Jan-12	ZS-NRF	J41	PF	DUR	1	NS	7:00	7:30	0:30	30.0
25-Jan-12	ZS-ASZ	RJ85	PF	CPT	1	NS	9:00	9:30	0:30	30.0
25-Jan-12	ZS-SNV	ERJ135	PF	CPT	1	NS	6:00	6:20	0:20	20.0
25-Jan-12	ZS-SNV	ERJ135	TC	CPT	1	NS	9:40	9:50	0:10	10.0
25-Jan-12	ZS-ASZ	RJ85	TC	CPT	1	NS	16:10	16:25	0:15	15.0
26-Jan-12	ZS-SSI	RJ85	PF	PZB	1	NS	5:30	6:05	0:35	35.0
26-Jan-12	ZS-NRH	J41	TC	PZB	1	NS	8:25	8:45	0:20	20.0
26-Jan-12	ZS-NRL	J41	TC	PZB	1	NS	11:05	11:35	0:30	30.0
13-Feb-12	ZS-NRH	J41	AF	DUR	1	NS	12:55	13:30	0:35	35.0
13-Feb-12	ZS-SNX	ERJ135	PF	CPT	1	NS	6:00	6:20	0:20	20.0
14-Feb-12	ZS-SSK	RJ85	PF	PZB	1	NS	5:30	6:15	0:45	45.0
14-Feb-12	ZS-NRK	J41	TC	PZB	1	NS	8:30	8:45	0:15	15.0
14-Feb-12	ZS-NRG	J41	TC	PZB	1	NS	10:50	11:10	0:20	20.0
14-Feb-12	ZS-NRH	J41	PF	DUR	1	NS	6:00	6:28	0:28	28.0
14-Feb-12	ZS-NRH	J41	AF	DUR	1	NS	13:00	13:35	0:35	35.0
14-Feb-12	ZS-SNX	ERJ135	PF	CPT	1	NS	6:00	6:20	0:20	20.0
15-Feb-12	ZS-NRH	J41	PF	DUR	1	NS	6:00	6:25	0:25	25.0
15-Feb-12	ZS-SNX	ERJ135	PF	CPT	1	NS	6:00	6:20	0:20	20.0
22-Feb-12	ZS-ASX	RJ85	PF	JNB	1	A. Shumba	8:50	9:15	0:25	25.0
22-Feb-12	ZS-OTM	ERJ135	TC	JNB	1	A. Shumba	9:20	9:31	0:11	11.0
22-Feb-12	ZS-SNZ	ERJ135	TC	JNB	1	A. Shumba	11:50	12:00	0:10	10.0
22-Feb-12	ZS-SNZ	ERJ135	TC	JNB	1	A. Shumba	14:30	14:39	0:09	9.0
22-Feb-12	ZS-SNW	ERJ135	TC	JNB	1	A. Shumba	15:40	15:50	0:10	10.0
22-Feb-12	ZS-ASZ	RJ85	PF	JNB	1	R. Bamberger	7:30	8:15	0:45	45.0
22-Feb-12	ZS-SNZ	ERJ135	PF	JNB	1	R. Bamberger	8:35	8:50	0:15	15.0
22-Feb-12	ZS-NRL	J41	TC	JNB	1	R. Bamberger	9:30	9:43	0:13	13.0
22-Feb-12	ZS-NRH	J41	TC	JNB	1	R. Bamberger	11:50	12:05	0:15	15.0
22-Feb-12	ZS-NRL	J41	TC	JNB	1	R. Bamberger	14:10	14:25	0:15	15.0
22-Feb-12	ZS-NRI	J41	TC	JNB	1	R. Bamberger	16:25	16:33	0:08	8.0
23-Feb-12	ZS-NRL	J41	PF	JNB	1	A. Shumba	10:50	11:10	0:20	20.0
23-Feb-12	ZS-SJX	ERJ135	PF	JNB	1	A. Shumba	8:55	9:06	0:11	11.0
23-Feb-12	ZS-NRH	J41	TC	JNB	1	A. Shumba	9:35	9:42	0:07	7.0
23-Feb-12	ZS-NRG	J41	TC	JNB	1	A. Shumba	10:40	10:48	0:08	8.0
23-Feb-12	ZS-OTM	ERJ135	TC	JNB	1	A. Shumba	12:10	12:17	0:07	7.0

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Table G1 – Time Measurements in the Case Setting for the Accomplishment of STLM Tasks (Continued)

Date	Aircraft Registration > NS = Not Specified	Aircraft Type	Inspection Type > AF = After-Flight Check > PF = Pre-Flight Check > TC = Transit Check	Location > See the Airport Code Key	Number of AMEs	Person(s) Observed > NS = Not Specified	Start Time > NS = Not Specified	Finish Time > NS = Not Specified	Task Time (hh:mm)	Total Manminutes
23-Feb-12	ZS-SSJ	RJ85	TC	JNB	1	A. Shumba	14:30	14:40	0:10	10.0
23-Feb-12	ZS-OTN	ERJ135	TC	JNB	1	A. Shumba	15:55	16:10	0:15	15.0
23-Feb-12	ZS-ASX	RJ85	PF	JNB	1	D. Allen	7:28	8:16	0:48	48.0
23-Feb-12	ZS-SNZ	ERJ135	TC	JNB	1	D. Allen	11:10	11:22	0:12	12.0
23-Feb-12	ZS-SNX	ERJ135	TC	JNB	1	D. Allen	13:48	14:03	0:15	15.0
23-Feb-12	ZS-SNZ	ERJ135	TC	JNB	1	D. Allen	15:22	15:33	0:11	11.0
23-Feb-12	ZS-SSK	RJ85	TC	JNB	1	D. Allen	16:00	16:14	0:14	14.0
23-Feb-12	ZS-OTN	ERJ135	TC	JNB	1	R. Bamberger	9:05	9:20	0:15	15.0
23-Feb-12	ZS-SSK	RJ85	TC	JNB	1	R. Bamberger	10:00	10:15	0:15	15.0
23-Feb-12	ZS-SNX	ERJ135	TC	JNB	1	R. Bamberger	11:05	11:20	0:15	15.0
23-Feb-12	ZS-OTN	ERJ135	TC	JNB	1	R. Bamberger	12:25	12:40	0:15	15.0
23-Feb-12	ZS-NRK	J41	AF	JNB	1	R. Bamberger	15:40	17:05	1:25	85.0
21-Mar-12	ZS-ASZ	RJ85	PF	JNB	1	D. Viljoen	7:20	7:50	0:30	30.0
21-Mar-12	ZS-ASW	RJ85	PF	JNB	1	G. Scanlen	9:55	10:20	0:25	25.0
21-Mar-12	ZS-SSJ	RJ85	PF	JNB	1	D. Viljoen	9:00	9:35	0:35	35.0
21-Mar-12	ZS-OTM	ERJ135	PF	JNB	1	T. Manyakara	NS	NS	0:20	20.0
21-Mar-12	ZS-SNZ	ERJ135	PF	JNB	1	T. Manyakara	NS	NS	0:20	20.0
21-Mar-12	ZS-OTN	ERJ135	PF	JNB	1	E. Moerane	NS	NS	0:20	20.0
21-Mar-12	ZS-NRF	J41	PF	JNB	1	E. Moerane	7:45	8:00	0:15	15.0
21-Mar-12	ZS-NRH	J41	PF	JNB	1	E. Moerane	8:45	9:00	0:15	15.0
21-Mar-12	ZS-SSI	RJ85	PF	JNB	1	D. Viljoen	8:00	8:30	0:30	30.0
21-Mar-12	ZS-ASX	RJ85	PF	JNB	1	D. Viljoen	9:00	9:35	0:35	35.0
25-Mar-12	ZS-NRK	J41	AF	JNB	1	V. Nxumalo	NS	NS	1:20	80.0
25-Mar-12	ZS-NRJ	J41	AF	JNB	1	M. Masite	NS	NS	1:25	85.0
25-Mar-12	ZS-NRF	J41	AF	JNB	1	S. Mpofu	NS	NS	1:00	60.0
25-Mar-12	ZS-SNZ	ERJ135	AF	JNB	1	A. Ndlovu	NS	NS	1:30	90.0
25-Mar-12	ZS-SNV	ERJ135	AF	JNB	1	T. Brewer	NS	NS	1:30	90.0
25-Mar-12	ZS-SJX	ERJ135	AF	JNB	1	M. Brookes	NS	NS	1:40	100.0
25-Mar-12	ZS-ASZ	RJ85	AF	JNB	1	D. Wasserman	NS	NS	1:45	105.0
25-Mar-12	ZS-SSI	RJ85	AF	JNB	1	J. Rademeyer	NS	NS	1:35	95.0
25-Mar-12	ZS-ASX	RJ85	AF	JNB	1	A. Nel	NS	NS	1:35	95.0
27-Mar-12	ZS-NRJ	J41	PF	JNB	1	R. Bamberger	5:30	5:50	0:20	20.0
27-Mar-12	ZS-NRK	J41	PF	JNB	1	R. Bamberger	6:00	6:15	0:15	15.0
27-Mar-12	ZS-NRF	J41	PF	JNB	1	S. Mutesva	5:20	5:40	0:20	20.0
27-Mar-12	ZS-SSJ	RJ85	TC	JNB	1	A. Ndlovu	8:10	8:25	0:15	15.0
27-Mar-12	ZS-ASW	RJ85	TC	JNB	1	B. Froneman	14:20	14:32	0:12	12.0
27-Mar-12	ZS-SSI	RJ85	TC	JNB	1	C. Nortje	16:15	16:27	0:12	12.0
29-Mar-12	ZS-NRK	J41	PF	JNB	1	M. Maramwidze	5:05	5:30	0:25	25.0
29-Mar-12	ZS-ASW	RJ85	TC	JNB	1	W. Krog	16:25	16:40	0:15	15.0

Airport Code Key (Location):
> CPT = Cape Town International Airport
> DUR = King Shaka International Airport (Durban)
> GRJ = George Airport
> JNB = OR Tambo International Airport (Johannesburg)
> PZB = Oribi Airport (Pietermaritzburg)

Appendix H: Archival Records and Physical Artefacts Used in Support of the Study

A large quantity of data from archival records and physical artefacts has been accessed and used in this study. As a result, a compact disc (CD) has been employed as a bulk data storage medium for these instruments. The use of this CD, titled 'Bulk Databases', has eliminated the requirement to insert large and cumbersome data tables into this appendix. The arrangement of research instruments on the 'Bulk Databases' CD is described in Table H1. This table also lists the data source that is applicable to each individual data set.

Table H1 – Index of Archival Records and Physical Artefacts on the 'Bulk Databases' CD

#	Instrument Type	Description of Instrument	**Associated File Name(s)** Note: data sources are shown in italics for the various instruments that have been accessed
1	Archival records	Details of the planned flight schedule at Airlink by historical day-of-operations	Airlink Day-of-Ops Schedule, 05 to 11 Sep 2011.pdf Airlink Day-of-Ops Schedule, 01 to 20 Jun 2011.pdf *Data source = flight schedule records extracted from the Geneva Airline Performance Software used at the Operations Control Centre (OCC) at Airlink* Standard Schedule S11 V4.xlsx (Distribution date = 28 June 2011) *Data source = schedule information published by the Flight Scheduling Department at Airlink*
2	Archival records	Records of the flights that were actually operated by Airlink per historical day-of-operations	Airlink Flights Operated, 01 Jan to 30 Jun 2011.xlsx Airlink Flights Operated, 05 to 11 Sep 2011.xlsx *Data source = the 'Monthly Stats Report' compiled and distributed by the Maintenance Logistics, Costs and Contracts Manager at Airlink; this report is compiled in the first week of each month from the Airlink flight records that were logged for the preceding month*
3	Archival records	Occurrences of flight delays or flight cancellations at Airlink	Airlink Flight Delays, 01 Jan to 30 Jun 2011.xlsx *Data source = flight delay records extracted from the Geneva Airline Performance Software used at the Operations Control Centre (OCC) at Airlink*
4	Archival records	Occurrences of aircraft technical faults or equipment breakdowns that resulted in flight delays or cancellations at Airlink	Airlink Technical Delays and Cancellations, 01 Jan to 30 Jun 2011.xlsx *Data source = technical delay reports compiled and distributed weekly by the technicians manning the Maintenance Control Centre (MCC) at Airlink*
5	Physical artefact	The existing labour scheduling model used by Airlink for line maintenance crew planning	Airlink Line Maintenance Labour Scheduling Model (Updated 2012).xlsx *Data source = resource planning records of the Line Maintenance Department at Airlink*
6	Physical artefact	The internal company procedure at Airlink that prescribes the qualifications, experience levels and limitations for company AMEs to perform and certify maintenance work, including STLM tasks	Procedure P-18-02 Certificates of Authority.pdf *Data source = Volume 2 of the internal Manual of Procedure for Airlink's AMO*

Appendix I: Selected Processed Data Sets that are Relevant to the Study Results

A number of large spreadsheets of processed data have been generated in developing the results of this study. In order to avoid the need to insert a set of cumbersome data tables in this appendix, a relevant selection of these spreadsheets has been added to the 'Bulk Databases' CD as referred to in Appendix H. Table I1 lists the arrangement of processed data spreadsheets that have been uploaded onto this CD.

Table I1 – Index of Processed Data Spreadsheets on the 'Bulk Databases' CD

#	Spreadsheet Description	Associated File Name(s)
1	Planned flight movements and associated STLM check requirements at Airlink's main base for the date range 05 to 11 September 2011	Planned Flights and STLM Check Requirements at Airlink's Main Base, 05 to 11 Sep 2011.xlsx
2	Approximate minimum shift coverage specifications for the FLM Team; these have been determined according to task profiles for STLM activities that have been generated from the planned flight schedules at Airlink's main base for the date range 05 to 11 September 2011	Minimum Hours of Coverage for the FLM Team by Weekday, 05 to 11 Sep 2011.xlsx
3	A specification of the number of unique STLM task demand profiles that are possible for each day in the date range 05 to 11 September 2011 based on allowable timing flexibilities for the planned set of STLM tasks for each day and applying a time interval base of 5 minutes for calculation purposes	Number of Feasible Task Demand Profiles by Weekday, 05 to 11 Sep 2011.xlsx
4	A quantification of the potential benefits of a demand modelling process that uses flexible task timing to generate an optimal or near-optimal arrangement of tasks to maximise the occupancy levels of the on-duty labour force	Best Case and Worst Case STLM Task Demand Profiles using Task Timing Flexibility, 05 to 11 Sep 2011.xlsx
5	A description of the demand modelling calculations by weekday for the date range 05 to 11 September 2011 to show how the most optimal task demand profile has been developed for each day	Optimised Task Demand Profiles by Weekday, 05 to 11 Sep 2011.xlsx
6	A comparison of the AME supply and demand profiles for the date range 05 to 11 September 2011 to verify that sufficient AMEs are made available via the labour force optimisation processes to meet the prevailing demand levels for STLM services	AME Supply vs Demand Comparisons by Weekday, 05 to 11 Sep 2011.xlsx
7	A description of the STLM task allocations by weekday for the date range 05 to 11 September 2011 to show how the STLM tasks and SVM Team support periods have been determined for each member of the on-duty workforce	Finalised Task Allocation Profiles by AME and Shift Group, 05 to 11 Sep 2011.xlsx
8	Calculations showing the AME manhours supplied and the occupancy levels achievable using the optimised manpower roster for the FLM Team	Performance Characteristics of Output Shift Roster for the FLM Team.xlsx
9	An analysis of Airlink departure and arrival delays at ORTIA for the period 01 January to 30 June 2011, showing profiles of the delay incidence rates per operational day and the duration in minutes per delay event	Analysis of Airlink Flight Delay Records, 01 Jan to 30 Jun 2011.xlsx
10	Mapping of theoretical distribution functions against the various case data profiles of flight delay characteristics (i.e. delay incidence rates per day and the duration in minutes per delay event) for the period 01 January to 30 June 2011 in order to find the best fit	Mapping of Theoretical Functions to Airlink Flight Delay Profiles, 01 Jan to 30 Jun 2011.xlsx
11	An examination of the schedule disruption events and associated schedule recovery decisions at the case organisation's main base on 08 June 2011, together with a description of the associated changes in the timing and scope of STLM tasks	Contributing Schedule Disruption Events and Related STLM Task Profile Variations at Airlink's Main Base on 08 June 2011.xlsx

Appendix J: Expanded Descriptions of the Supplementary Discussion Points for Refining the Computational Model

The discussion points in this appendix expand on the summarised points that are listed in Table 7 in Subsection 4.1.2.3 of the study. These discussion points supplement the assumptions that are listed in Subsection 1.7 and the modelling constraints that are described in Appendix E.

- **Discussion Point Number 1:**
  Although a Category A and C LAME is generally required to hold a license endorsement on a given aircraft and associated engine type (i.e. a type rating) as a prerequisite in order to certify maintenance work on that type, Airlink's maintenance division has implemented an internal procedure that allows for this requirement to be circumvented under a special set of circumstances referred to as 'limited line release'. This internal procedure has been approved by the SACAA and allows for a Category A and C LAME with a licence rating on any aircraft type to be granted limited certification powers on one or more Airlink aircraft types subject to completing a basic systems overview and maintenance course per type. Such 'limited line maintenance' courses range between three and five days in duration depending on the aircraft type under consideration. Furthermore, only six months prior logged experience on a given aircraft type, or a type of similar characteristics, is required for this approval to be issued. These requirements are significantly less onerous than the on-type training and experience requirements that are specified for comprehensive line release certification at the case organisation. The company procedure on which the limited line release approval is based, namely *Procedure P-18-02 Certificates of Authority*, has been included in PDF format in Appendix H for reference purposes.

- **Discussion Point Number 2:**
  Following on from the preceding point, a valuable characteristic of the limited line release approval in relation to this study is that it allows the holder to perform and certify all of the STLM checks on a given aircraft type. This characteristic has been used to simplify the modelling of certification authorisations on the FLM Team by applying the assumption that all AMEs on this team are Category A and C license holders on at least one aircraft and associated engine type and have been trained and authorised to the level of at least limited line release approval on all three Airlink aircraft types. Thus, all AMEs on the FLM Team are assumed to be competent and authorised to perform and certify all STLM task scopes that are called out by the Airlink operating schedule. In this respect, the computational modelling that has been implemented in this study is a simplification of the model applied by Ip *et al.* (2010) which caters for variable license holdings and associated certification authorisations within a given AME work group or shift team.

- **Discussion Point Number 3:**
  Referring to the contents of Subsection 3.6.1 and Appendix G, standard times for the nine distinct STLM events that are applicable at the case organisation have been established as shown in Table 8 in Subsection 4.1.2.3. In this regard, it should be remembered that the standard time for each task type listed in Table 8 is based on an 80th percentile rank value of the related time measurements that have been taken, rounded up to the nearest multiple of five minutes.

- **Discussion Point Number 4:**
  Where more than one AME is assigned to a given STLM task, it has been assumed that the time for the task to be completed is determined by dividing the standard time for the task by the number of AMEs assigned to it and then rounding the resulting output up to the nearest multiple of five minutes. For example, the accomplishment time for a J41 after-flight check performed by one AME is the standard time for the task, i.e. 85 manminutes, divided by one, giving a total task time of 85 minutes. The accomplishment time for a J41 after-flight check carried out by two AMEs is the standard time for the task, i.e. 85 manminutes, divided by two, giving a total task time of 42.5 minutes. Rounding this output value up to the nearest multiple of five minutes yields a final task accomplishment time of 45 minutes.

- **Discussion Point Number 5:**
  With reference to Subsection 1.7, it has been assumed that on-duty AMEs assigned to the FLM Team can transit between work locations at the main base for any two successive STLM tasks within a time window of five minutes.

- **Discussion Point Number 6:**
  It has been assumed that meal and tea breaks for on-duty AMEs shall be provided for adequately by the inherent lulls in activity in the work roster for the FLM Team. As such, break times have not been modelled as a hard constraint in the labour optimisation model. Where necessary, however, the model outputs have been adjusted manually to ensure that adequate break times are provided for on-duty AMEs. In this regard, it has been assumed that AMEs assigned to the FLM Team are agreeable in working to flexible break times based on the work demands of a given day.

- **Discussion Point Number 7:**
  In quantifying the study outcomes, it has been assumed that all AMEs deployed within the Line Maintenance Department of Airlink's maintenance division are paid a fixed and equal hourly wage. The study has also considered the implications of paying these AMEs a fixed and equal monthly salary. The assumption of a fixed hourly wage, or alternatively a fixed

monthly salary, is seen to be congruent with the current human resources management practices at the case organisation in the sense that the shift cycle and employee rotation policies that the company applies are designed to ensure that all AMEs within the Line Maintenance Department work equivalent allocations of normal weekdays and weekends, as well as day and night shifts, in the medium to long term. These policies have enabled pay increments for weekend and night shift work to be addressed via fixed shift allowances. However, the assumption of equal pay amongst the AMEs that are deployed to the line maintenance function does not hold in reality in the sense that significant pay variations do exist amongst these AMEs due to factors such as total post-qualification experience levels, years of tenure within the company, aircraft type license holdings and company-issued aircraft release authorisations. Nonetheless, the assumption of a fixed wage rate or monthly salary has been deemed to be reasonable in this study on the basis of finding ways to more optimally deploy the current labour resources that are employed within the Line Maintenance Department. Note that wage rate or salary inputs for the labour cost calculations in this study have been specified according to the average pay level for line maintenance AMEs for the 2012 financial year. This pay level has been calculated by the Human Resources Department at Airlink based on actual payroll records for this financial year period.

- **Discussion Point Number 8:**
  With reference to Table 4 in Subsection 4.1.1.1, the nature of the present line maintenance duty cycle at the case organisation is such that each shift team shall be rostered to work two duty shifts on each day of the week (i.e. Monday through Sunday) in any four week period. Given that this duty cycle structure has been retained in the experimental model, the FLM Team has had to cater for two associated constraints. Firstly, each shift team has had to be allocated an equal quantity of AMEs. Secondly, the allocation of AMEs per shift team has had to provide sufficient personnel coverage to meet the worst-case maintenance demand condition on any weekday. Looking at the STLM check requirements in Table 6 in Subsection 4.1.2.2, it is apparent that demand levels in the case setting are considerably lower on weekends (Saturdays in particular) than on normal office days. The retention of the present duty cycle may therefore lead to sub-optimal labour allocations on weekdays of lower STLM task demand levels in order to ensure that sufficient resources are provided for the weekday on which the highest STLM task demand levels are prevalent.

- **Discussion Point Number 9:**
  In order to mitigate the potential for inefficiencies relating to the preceding point, it has been noted that the maintenance facilities in the case setting are such that the contrasting levels of aircraft maintenance work (i.e. first line tasks up to aircraft heavy maintenance checks)

are all carried out within a reasonably localised radius of operations. On this basis, and as applicable, it has been assumed that AMEs on the FLM Team can provide support to the SVM Team, or even teams assigned to heavy maintenance checks, during periods of idle time in their working schedule that exceed a defined threshold of time between consecutive STLM tasks. In this study, only idle time periods of 90 minutes or longer between tasks have been allocated to this type of cross-functional support, factoring in a 10 minute setup window each time an AME switches between maintenance functions. It should also be noted that any on-duty AME on the FLM Team who is deemed to be surplus to operational requirements on a given workday can be allocated to work on the SVM Team for the full duration of the affected working shift.

Appendix K: Matching of Selected Theoretical Probability Distribution Functions to the Observed Case Data Profiles of Flight Delay Incidence Rates and Time Durations

Table K1 describes the numerical processes that have been implemented in this study in order to match a selection of theoretical probability distribution functions to real-life profiles of airline flight delay characteristics that have been observed in the case setting. The table is arranged according to the theoretical distribution function under consideration, as follows:

Table K1 – Matching of Theoretical Probability Distribution Functions to Real-Life Profiles of Flight Delay Characteristics in the Case Setting

Theoretical Function	Process of Matching to Observed Case Data
Normal Distribution	Calculate the arithmetic mean of the case data profile. Calculate the standard deviation of the case data profile. Using these parameter values of mean and standard deviation, apply the Excel 'NORMDIST' formula to calculate the difference in the cumulative distribution function between the start and end point of each data range shown on the x-axis of the associated case data profile. If applicable, exclude positive probability values of the Normal Distribution function at x-values that are less than that of the first data point on the x-axis. This is done by dividing each of the difference values by 1 minus the value of the cumulative probability function of the Normal Distribution at the first x-axis data point. Multiply the output value for each x-axis data range by the total number of events or occurrences in the data set in order to obtain the equivalent number of events or occurrences for the theoretical function.
Poisson Distribution	Calculate the arithmetic mean of the case data profile. Using this parameter value of mean, apply the Excel 'POISSON' formula to calculate the difference in the cumulative distribution function between the start and end point of each data range shown on the x-axis of the associated case data profile. If applicable, exclude positive probability values of the Poisson Distribution function at x-values that are less than that of the first data point on the x-axis. This is done by dividing each of the difference values by 1 minus the value of the cumulative probability function of the Poisson Distribution at the first x-axis data point. Multiply the output value for each x-axis data range by the total number of events or occurrences in the data set in order to obtain the equivalent number of events or occurrences for the theoretical function.
Exponential Distribution	Calculate the arithmetic mean of the case data profile. Invert the arithmetic mean of the case data profile to obtain the parameter 'lambda'. Using this parameter value of lambda, apply the Excel 'EXPONDIST' formula to calculate the difference in the cumulative distribution function between the start and end point of each data range shown on the x-axis of the associated case data profile. If applicable, exclude positive probability values of the Exponential Distribution function at x-values that are less than that of the first data point on the x-axis. This is done by dividing each of the difference values by 1 minus the value of the cumulative probability function of the Exponential Distribution at the first x-axis data point. Multiply the output value for each x-axis data range by the total number of events or occurrences in the data set in order to obtain the equivalent number of events or occurrences for the theoretical function.
Continued on next page.	

Table K1 – Matching of Theoretical Probability Distribution Functions to Real-Life Profiles of Flight Delay Characteristics in the Case Setting (Continued)

Theoretical Function	Process of Matching to Observed Case Data
Gamma Distribution	Calculate the arithmetic mean of the case data profile. Calculate the variance of the case data profile. Calculate the parameter 'alpha' by dividing the square of the arithmetic mean by the variance. Calculate the parameter 'beta' by dividing the variance by the arithmetic mean. Using these parameter values of alpha and beta, apply the Excel 'GAMMADIST' formula to calculate the difference in the cumulative distribution function between the start and end point of each data range shown on the x-axis of the associated case data profile. If applicable, exclude positive probability values of the Gamma Distribution function at x-values that are less than that of the first data point on the x-axis. This is done by dividing each of the difference values by 1 minus the value of the cumulative probability function of the Gamma Distribution at the first x-axis data point. Multiply the output value for each x-axis data range by the total number of events or occurrences in the data set in order to obtain the equivalent number of events or occurrences for the theoretical function.
Weibull Distribution	Follow the approach described by Dorner (1999) to calculate the 'shape' and 'characteristic life' parameters for a Weibull analysis using MS Excel. Dorner's approach involves the use of median ranks and regression analysis. Note that Dorner's approach requires that zero values (if applicable) in the case data profile are excluded from the Weibull parameter calculations as it is not possible to obtain a natural logarithm of zero. Using these parameter values of shape (i.e. alpha) and characteristic life (i.e. beta), apply the Excel 'WEIBULL' formula to calculate the difference in the cumulative distribution function between the start and end point of each data range shown on the x-axis of the associated case data profile. If applicable, exclude positive probability values of the Weibull Distribution function at x-values that are less than that of the first data point on the x-axis. This is done by dividing each of the difference values by 1 minus the value of the cumulative probability function of the Weibull Distribution at the first x-axis data point. Multiply the output value for each x-axis data range by the total number of events or occurrences in the data set in order to obtain the equivalent number of events or occurrences for the theoretical function.
Lognormal Distribution	Modify the case data profile by taking the natural logarithm of each data point. Note that this approach requires that zero values (if applicable) in the case data profile are excluded as it is not possible to obtain a natural logarithm of zero. Calculate the arithmetic mean of the modified case data profile. Calculate the standard deviation of the modified case data profile. Using these parameter values of mean and standard deviation, apply the Excel 'LOGNORMDIST' formula to calculate the difference in the cumulative distribution function between the start and end point of each data range shown on the x-axis of the associated case data profile. If applicable, exclude positive probability values of the Lognormal Distribution function at x-values that are less than that of the first data point on the x-axis. This is done by dividing each of the difference values by 1 minus the value of the cumulative probability function of the Lognormal Distribution at the first x-axis data point. Multiply the output value for each x-axis data range by the total number of events or occurrences in the data set in order to obtain the equivalent number of events or occurrences for the theoretical function.

Appendix L: Sample STLM Task Execution Plan for a Disrupted Day-of-Operations in the Case Setting

With reference to Subsection 4.2.3.3 of the study, the STLM task allocation plan that has been developed for the day-of-operations on the 08th of June 2011 has been presented in this appendix as an example of how the sensitivity testing process has been implemented in the study. In this regard, Table L1 shows a potential deployment plan for the rostered labour force on the FLM Team in response to the disrupted STLM task demand profile on this day. It must be remembered that certain manual adjustments have been made in the task allocation process in this table to ensure that reasonable break times have been allocated for each on-duty AME.

Table L1 – A Possible STLM Task Allocation Plan at the Case Organisation's Main Base in Response to the Disrupted Flight Schedule on 08 June 2011

Note:
Disrupted maintenance events are shaded in orange and significant rostering conflicts are marked in red bold text.

A/c Registration	Flt Number	STLM Event	Departure or Arrival Time	Number of AMEs Used	Task Start Time	Task Finish Time	Morn AME 1	Morn AME 2	Morn AME 3	Morn AME 4	Aft'n AME 1	Aft'n AME 2	Night AME 1	Night AME 2
ZS-NRH	8751	J41 PF	6:15	1	5:00	5:25	X							
ZS-OEX	8851	J41 PF	6:25	1	5:00	5:25		X						
ZS-NRJ	8823	J41 PF	6:30	1	5:05	5:30			X					
ZS-SJX	8100	ERJ135 PF	6:30	1	5:10	5:30				X				
ZS-SNV	8801	ERJ135 PF	6:35	1	5:30	5:50		X						
ZS-SSJ	8747	RJ85 PF	7:00	1	5:30	6:15	X							
ZS-SNZ	8160	ERJ135 PF	6:35	1	5:35	5:55			X					
ZS-SNX	8050	ERJ135 PF	6:40	1	5:35	5:55				X				
ZS-OTM	8012	ERJ135 PF	6:50	1	5:55	6:15		X						
ZS-NRL	8827	J41 PF	9:00	1	7:35	8:00	X							
ZS-ASW	8154	RJ85 PF	9:45	1	8:00	8:45		X						
ZS-ASX	8730	RJ85 TC	8:05	1	8:05	8:20	X							
ZS-NRE	8843	J41 PF	10:00	1	8:35	9:00	X							
ZS-SSK	8220	RJ85 PF	10:50	1	9:05	9:50		X						
ZS-SNV	8802	ERJ135 TC	9:05	1	9:05	9:20	X							
ZS-NRJ	8823	J41 TC	9:05	1	9:05	9:25			X					
ZS-OTM	8013	ERJ135 TC	9:25	1	9:25	9:40	X							
ZS-OEX	8852	J41 TC	9:40	1	9:40	10:00			X					
ZS-NRI	8052	J41 PF	10:25	1	9:45	10:10	X							
ZS-SSI	8841	RJ85 PF	11:10	1	9:55	10:40		X						
ZS-NRH	8752	J41 TC	10:00	1	10:00	10:20				X				
ZS-SSJ	8732	RJ85 TC	10:00	1	10:05	10:20			X					
ZS-OMZ	8853	J41 PF	11:45	1	10:20	10:45	X							
ZS-SJX	8101	ERJ135 TC	10:35	1	10:35	10:50			X					
ZS-SNZ	8161	ERJ135 TC	11:10	1	11:10	11:25		X						
ZS-NRL	8828	J41 TC	11:20	1	11:20	11:40	X							
ZS-SNX	8051	ERJ135 TC	11:45	1	11:45	12:00		X						
ZS-SNV	8768	ERJ135 TC	12:50	1	12:50	13:05	X							
ZS-NRH	8993	J41 TC	13:30	1	13:30	13:50					X			
ZS-NRI	8053	J41 TC	14:20	1	14:20	14:40						X		
ZS-SSJ	8111	RJ85 TC	14:25	1	14:25	14:40					X			

Table L1 – A Possible STLM Task Allocation Plan at the Case Organisation's Main Base in Response to the Disrupted Flight Schedule on 08 June 2011 (Continued)

Note:
Disrupted maintenance events are shaded in orange and significant rostering conflicts are marked in red bold text.

A/c Registration	Flt Number	STLM Event	Departure or Arrival Time	Number of AMEs Used	Task Start Time	Task Finish Time	Morn AME 1	Morn AME 2	Morn AME 3	Morn AME 4	Aft'n AME 1	Aft'n AME 2	Night AME 1	Night AME 2
ZS-SSI	8842	RJ85 TC	14:25	1	14:25	14:40							X	
ZS-SNX	8995	ERJ135 TC	14:45	1	14:45	15:00					X			
ZS-NRL	8810	J41 TC	14:45	1	14:45	15:05						X		
ZS-OMZ	8854	J41 TC	14:55	1	14:55	15:15							X	
ZS-SNV	8818	ERJ135 TC	15:20	1	15:20	15:35					X			
ZS-ASW	8155	RJ85 TC	15:30	1	15:30	15:45						X		
ZS-ASY	8849	RJ85 PF	17:30	1	15:45	16:30					X			
ZS-SSK	8221	RJ85 TC	16:15	1	16:15	16:30						X		
ZS-OEX	8738	J41 TC	16:25	1	16:25	16:45							X	
ZS-NRJ	8052	J41 AF	10:25	2	16:40	17:25					X	X		
ZS-SNZ	8215	ERJ135 AF	15:40	1	16:50	18:35								X
ZS-OMZ	8854	J41 AF	16:35	2	17:30	18:15					X	X		
ZS-OTM	8015	ERJ135 TC	17:35	1	17:35	17:50							X	
ZS-SJX	8231	ERJ135 AF	16:45	1	17:55	19:40							X	
ZS-NRI	8063	J41 AF	17:20	1	18:40	20:05								X
ZS-ASX	8253	RJ85 AF	18:00	2	18:45	19:40					X	X		
ZS-SSJ	8742	RJ85 AF	18:15	2	19:45	20:40					X	X		
ZS-SNV	8770	ERJ135 AF	19:10	1	20:10	21:55							X	
ZS-NRL	8756	J41 AF	19:10	1	20:35	22:00								X
ZS-SSI	8845	RJ85 AF	19:20	2	20:45	21:40					X	X		
ZS-NRH	8858	J41 AF	19:20	1	22:00	23:25							X	
ZS-OEX	8816	J41 AF	19:35	1	22:05	23:30								X
ZS-NRE	8844	J41 AF	19:35	1	22:10	23:35					X			
ZS-ASY	8848	RJ85 AF	19:40	1	22:10	0:00						X		
ZS-OTM	8009	ERJ135 AF	19:55	1	23:40	**1:25**					X			
ZS-SNX	8165	ERJ135 AF	20:25	1	23:55	**1:40**							X	
ZS-ASW	8103	RJ85 AF	20:35	1	0:00	**1:50**								X

Summary of Rostered Versus Final Working Times by On-Duty AME

Work Group	AMEs per Work Group	Rostered Start Time	Rostered Finish Time	AME 1 Final Task Finish Time	AME 2 Final Task Finish Time	AME 3 Final Task Finish Time	AME 4 Final Task Finish Time
Morning Shift	4	5:00	13:00	13:05	12:00	10:50	10:20
Afternoon Shift	2	13:00	0:30	**1:25**	0:00		
Night Shift	2	14:30	1:00	**1:40**	**1:50**		

Result:
Ignoring the 5 minute shift overrun against AME 1 on the Morning Shift, 145 minutes of overtime are required to implement this AME deployment plan in response to the STLM requirements of the day.

Appendix M: Components of Line Maintenance and Associated Demand Drivers

Subsection 1.2.1.1 of this study includes a basic description of aircraft line maintenance activities. Expanding on this description and including unscheduled aircraft breakdowns or technical faults as a maintenance input, the maintenance components that make up the line maintenance function in the case setting are as follows:

- **Component A:** Performing routine inspection and servicing tasks (i.e. STLM checks) on aircraft deployed to line operations. Demand levels for these checks are closely linked to the prevailing activity levels of the airline flight schedule.

- **Component B:** Investigating aircraft technical anomalies that are reported by flight crew members and, if applicable, rectifying in-service faults or breakdowns on aircraft deployed to line operations.

- **Component C:** Investigating and rectifying aircraft system faults that are identified through the regular system of STLM checks. In addition, implementing repair actions where areas of structural damage are identified during such checks.

- **Component D:** Performing higher level scheduled maintenance tasks that are beyond the scope of daily routine checks, as well as rectifying any system faults or damage areas that are identified as a result of these tasks. This maintenance component covers scheduled tasks up to and including the level of aircraft A-checks.

Note:
Looking at Component D of the line maintenance function, higher level scheduled tasks in the line maintenance environment are driven by interval limits that are defined according to one or more operational measurement parameters. These parameters include ‘aircraft flight hours’, ‘aircraft operating cycles’ and ‘calendar time’ (University of Westminster Transport Studies Group 2008). For clarity, an aircraft operating cycle is generally equivalent to a single flight leg for a given aircraft from the commencement of the take-off roll at the departure airfield to the completion of the landing roll at the destination airfield. As a result, aircraft utilisation rates in terms of the number of flight hours and operating cycles accumulated per day generally play a major role in determining the incidence rates that are experienced for these tasks.

Working from the interview transcripts that are detailed in Table F1 in Appendix F, one can infer how the various line maintenance components in the case setting have been allocated amongst the available work teams under the case organisation’s current line maintenance system. In this regard, the day shift line maintenance work teams have traditionally provided services within the bounds of Components A, B and C in the preceding bullet points. The night shift line maintenance work teams, on the other hand, have traditionally provided comprehensive services across all four of the listed maintenance components, as applicable based on the demands of a given work shift. If the demand drivers of each line maintenance component are scrutinised, the following sources of variability in demand levels can be identified:

- Demand levels for routine checks (i.e. STLM checks) in the case setting are closely related to the aircraft utilisation profiles that are generated by the published flight schedule. It has been observed that planned aircraft arrival and departure profiles at the case organisation's main base can vary significantly from one day to the next and from one hour to the next on a given day. As a result, demand levels for STLM tasks vary significantly depending on the planned flight activity levels of the day and the time of day in question. Demand levels for these tasks can also be varied by late schedule changes that are implemented in response to schedule disruption events such as lengthy aircraft arrival delays.

- Although not a specific focus area of this study, it has been deemed likely that callouts to investigate flight crew technical queries and to respond to aircraft in-service faults or breakdowns will exhibit incident rate profiles similar to those of randomly-occurring events. This assessment has been made because modern airliners are composed of an intricate mix of interrelated and independent systems, each of which has its own unique reliability characteristics and architecture of hardware and software components. This complexity is compounded by variable system working conditions due to geographical, operational and seasonal factors. For example, more regular cycling of anti-icing devices will occur where icing conditions relating to the presence of atmospheric moisture are prevalent. In addition, factors pertaining to the user interfaces of aircraft equipment and associated man-machine errors are likely to be complex in nature and non-uniform in distribution. In support of this assessment, Figure M1 shows a bar graph profile of the occurrences per day of technical callouts across the case organisation's route network that were associated to aircraft delay events over the period 01 January to 30 June 2011. This profile has been compared to an equivalent Poisson distribution as a proxy for a random arrival profile. The figure shows a visibly high level of correlation between the case data profile and the equivalent Poisson profile. With reference to Subsection 2.3.3 of the study, it is noteworthy that the assertions made under this bullet point are supported by the work of Higle and Johnson (2005) which claims that unscheduled maintenance events occur randomly.

- Similarly to technical callouts in support of flight crews, it has been deemed likely that the reporting of system faults and damage areas on line operational aircraft as a result of the inspection or testing requirements of STLM checks will also exhibit random or near-random incidence rates. The reasoning highlighted in the preceding bullet point also applies for this line maintenance component, i.e. that occurrences will tend to occur randomly due to the complex systems composition of modern airliners and the variable loading conditions to which these aircraft are subjected during ongoing line operations.

- Higher level scheduled maintenance tasks that are beyond the scope of routine checks are not a specific focus area of this study. However, these tasks are detailed definitively in the maintenance program for a particular aircraft type and are thus readily predictable from a production planning perspective. As has already been discussed, the tasks that fall within this maintenance component are generally based on interval limits defined in flight hours, operational cycles or calendar time (or a combination thereof). In this regard, interval limits expressed in calendar time will remain fixed in time regardless of aircraft operating profiles. However, tasks whose interval limits are based on aircraft flight hours or cycles of operation will vary in calendar time frequency according to the frequency and duration of flights that are called out in the associated airline flight schedule.

Based on the contents of this appendix, it is expected that demand levels for line maintenance services at an airline will exhibit significant variability by day and time of day. It is therefore logical that labour planning strategies for line maintenance services should allow for appropriate levels of flexibility in the labour supply in order to efficiently meet this variable demand.

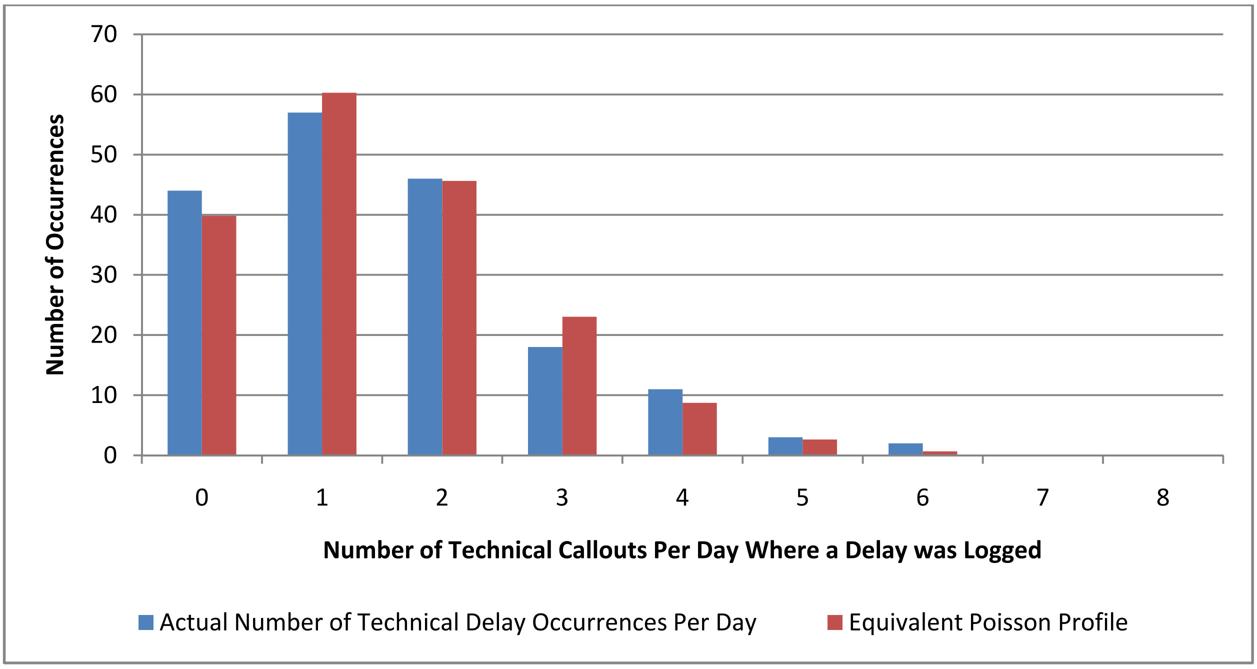

Figure M1 – Incidences per Day of Technical Callouts across the Case Organisation's Route Network that were Associated to Aircraft Delay Events over the Date Range 01 January to 30 June 2011

Appendix N: Specification of the Modular Nature of the Experimental STLM Labour Scheduling Model

With reference to the writings of Ernst *et al.* (2004) that are summarised in Table B1 in Appendix B, a modular structure is evident in the experimental computational model that has been employed in relation to Research Question 1. In this regard, the personnel scheduling process of this model encompasses the following distinct elements or modules:

- **Step 1: Demand Modelling** –
  - The demand for STLM tasks in the case setting is a typical example of a task-based demand scenario.
  - Mathematical programming has been applied to optimise the distribution of STLM tasks that are called out by the daily airline flight schedule.
  - The primary goal of this mathematical programming has been to minimise the maximum number of STLM tasks that are in work concurrently across the course of each weekday that has been modelled.
  - To enable this optimisation, task timing flexibility has been applied within predetermined start time windows for each category of STLM task.
  - Random number generation and global-to-local search techniques have been applied to test a realistic number of solutions from an extremely large set of feasible solutions for each weekday.
  - The best task demand solution that has been achieved for each weekday cannot be confirmed to be the most optimal solution amongst the total set of feasible solutions, so is described as 'near-optimal'.

- **Step 2: Days Off Scheduling** –
  - Optimisation modelling has not been applied in this area as requirements for days off have been taken from the existing shift system in use at the case organisation.
  - Days off requirements have thus been specified as a predefined input to the modelling processes that have been implemented.

- **Step 3: Crew Scheduling** –
  - Similarly to Step 1, use has been made of mathematical programming in this modelling step in order to optimise the arrangement of work shifts (or teams) on each weekday that has been modelled.
  - The goal of this mathematical programming has been to achieve the lowest possible labour costs in meeting prevailing demand levels for STLM tasks within the boundaries of a predefined set of rostering constraints.

- In essence, this component of the personnel scheduling process constitutes the supply modelling component.
- Numbers of feasible solutions in this modelling step have been found to be considerably less than the corresponding numbers from the demand modelling step.
- However, these numbers have still been found to be sufficiently large that the modelling processes in Microsoft Excel become cumbersome.
- In order to reduce the number of feasible solutions that have been considered during this modelling step, manual manipulations have been applied where possible to remove clearly sub-optimal supply solutions in relation to the associated demand levels.
- In addition, global-to-local search techniques have been applied in certain instances to limit the number of feasible solutions that have been considered.
- Given that the modelling processes in this step have not enabled all feasible solutions to be considered for each weekday, the solutions achieved have again been described as ‘near-optimal’.

- **Step 4: Line of Work Construction** –
  - In this component of the labour scheduling process, the optimised shift arrangements for each weekday have been linked into a continuous operational shift system.
  - The line of work construction process has had to achieve this output whilst complying with certain predefined human factor constraints that limit shift start time variations from one day to the next.
  - In this regard, certain adjustments in shift start times from those of the near-optimal solutions for each weekday have had to be applied in order to achieve an output that is compliant with the applicable rostering constraints.
  - The line of work construction process has been implemented manually in the study as the modelling case at hand is relatively simple and has not warranted the development of a dedicated mathematical logic model.

- **Step 5: Task Assignment** –
  - Manual and zero-one linear programming methods have both been applied successfully in this study for the purpose of assigning STLM tasks to the rostered work teams and associated AME slots for each weekday.
  - From a process automation perspective, Microsoft Excel has been used to construct a zero-one linear programming model that employs the built-in Excel Solver feature to produce feasible results in terms of the task assignment process.
  - However, it has been noted in the study that a manual assignment method achieves better results in ensuring that work tasks are evenly shared amongst the rostered work teams and that break (or meal) times are fairly allocated to the affected AME slots.

- A more detailed set of constraints for the linear programming model is needed if human factors such as equitable job queuing and adequate break times are to be considered in the task assignment process.
- The use of a manual task assignment method in this study has also enabled periods of idle time on AME work slots to be readily identified, which can be of significant value in maximising staff occupancy levels if the operational environment supports short-term transfers to other maintenance areas during idle periods on an affected AME slot.

- **Step 6: Staff Assignment** –
  - Under the assumption that all AMEs on the case organisation's FLM Team hold at least limited line release certification on each of the three aircraft types that are maintained in the case setting, the staff assignment problem is effectively of no material consequence in this study.
  - As a result, the study has not considered the staff assignment process in any detail.
  - This process will be of critical importance in an environment where AME certification levels are variable and where inadequate staff assignments against the shift roster may limit the capability of a given work team to certify and release the workloads that have been demanded of it.