Modelling and Analysis of Service Parts Logistics Systems

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Abstract

Many organisations purchase equipment that is subject to unpredictable failures to carry out their services. When these breakdowns occur, maintenance technicians restore the equipment in a timely fashion either through repair or the installation of spare parts. Extensive research has been conducted on optimisation of the stock levels on spare parts, as well on the technician coverage assignment. However, in most of the cases the solutions are developed separately. In this research, the behaviour of the *service parts logistics system* (SPLS) is approximated with a modified M/G/1 HOL queuing model. Then, the costs structure of the SPLS is defined and approximated with a mathematical model that captures the interdependence of the inventory policy and the technician assignment. A heuristic "Assign Locations" is implemented based on the modified M/G/1 HOL queuing, the costs model and a genetic algorithm to search for the near-minimum cost technician assignment given a fixed technician's vehicle inventory policy.

Keywords: Service parts logistics, optimisation, genetic algorithms, *M/G/*1 queuing model, and technician assignment.

1 Introduction

Many organisations purchase equipment that is subject to unpredictable failures to carry out their services. Therefore, the suppliers that sell these complex systems require not only to supply the product, but they must

also ensure that the systems remain constantly functional, which is known as after sales service.

After sales service includes several activities; however, considering that organisations depend on the effective operation of critical equipment subject to unpredictable breakdowns, service parts logistics becomes a critical function in after sales service. When these breakdowns occur, maintenance technicians; either employed or contracted, restore the equipment in a timely fashion either through repair or the installation of spare parts. The collection of the technicians, the stocking network, their vehicles (and their contents), the customers, and their equipment is referred to as a *service parts logistics system* (SPLS).

Service parts logistics systems can be divided into two categories depending on the technicians' contractual agreement: (1) in-house – the technicians are employed by the same organisation that owns the equipment; (2) outsourced – the technicians are contracted by the owner of the equipment. This research is motivated by some of the issues faced by a major retailer that operates in-house SPLS. For such retailer, time response to equipment malfunctions is not contractual. Instead, the time response requirements are based on criticality levels as established by management.

In the SPLS under consideration, a technician is assigned to provide equipment service to a group of customers dispersed throughout a geographic region. He obtains replenishment parts from depots located throughout his assigned region; however given the time response requirements, he carries some inventory of spare parts in his vehicle. When an equipment failure occurs at a customer location, the technician is contacted. Since these failures occur randomly and different failures have different criticality levels, the technician may not always be able to meet the time response requirements. In such cases, the technician is empowered to contact a "backup" local contractor to attend the call.

The objective in SPLS is to minimize the total SPLS costs while meeting the time response requirements. Clearly there are many decisions to be taken in SPLS in order to minimize the total costs, however the most significant ones are: 1) the inventory policies to manage the spare parts, 2) the technician coverage assignment, and 3) the technician operating policy.

2 Literature Review

Extensive research has been conducted on optimisation of the stock levels on spare parts, as well on the technician coverage assignment (network design). However, in most of the cases the solutions are developed in is the network design hierarchical order; that is considering a strategic

decision, while the inventory policies are considered a tactical decision. However, the current trend in the SPL industry is to consider the interdependency that exists between the network design and the inventory policies. In those lines, to our knowledge only two models have being developed; Candas (2007) and Jeet (2009) consider the effects of network design on inventory (and vice versa) in an integrated SPLS model, and Tovia (2004) provides an integrated solution to the technician coverage assignment and the inventory policies with time response service constraints by part criticality. The rest of the research in SPLS has being done by analyzing these policies separately.

Numerous studies have been conducted in the area of service parts inventory systems. Sherbrooke (1968) presents one of the first studies of multi-echelon spare parts inventory systems. The METRIC model, which assumes a continuous-review base stock policy at a central warehouse and multiple depots, is used to minimize inventory investment subject to constraints average number of backorders at each depot. Axsäter (1990) presents an inventory system that consists of one warehouse and multiple depots with constant warehouse replenishment lead times under a base stock policy and constant transportation times. Cohen *et al*. (1986) develop a multi-echelon inventory model with probabilistic time-response constraints. The model finds the optimal stocking policy for each depot using a single-part, single-period, stochastic optimisation model subject to a time response constraints. Cohen *et al* have extended and applied the work on SPLS to several successful applications within the automotive industry (2000) and electronics industry (1990). Hopp *et al*. (1999) present a two-echelon spare parts inventory optimisation model that minimizes total inventory investment subject to a maximum allowable total delay per facility. Graves (1985) presents a model of a multi-echelon spare parts inventory system where the response time to a failure consists of the convolution of the transit time to deliver the failed part, the waiting time for repair at the warehouse, the repair time at the warehouse, and the transit time to return the repaired part from the warehouse back to the depot. Svoronos and Zipkin (1991) consider a multi-echelon inventory system utilizing a base stock inventory policy and probabilistic transit time. They also consider the replenishment lead time for a location as the convolution of the waiting time, the repair time and the transportation time. Caglar (2001) also presents a multi-echelon spare parts inventory model with time response constraints. He develops a heuristic using Lagrangian relaxation for recommending inventory policies, and bases the time response constraints on an average time response limit for the location. Boyaci and Gallego (2002) present a service-constrained (Q,r) inventory model that minimizes average holding and ordering costs

subject to upper bounds on the average and standard deviation of the waiting time of demands that are actually backordered.

Considerable literature exists on problems where machine breakdowns are serviced by repair technicians. Kleinrock (1976) presents the *M*/*G*/1 HOL (head-of-the-line) priority queuing system. In this system, customers are grouped by priority, and when a customer arrives, he joins the end of the queue of his priority group. Customers are serviced by priority, and within the same priority group according to the FIFO discipline. Arrivals to the queuing system occur according to independent Poisson process, and the service is provided by one server with service time modelled using a general cumulative distribution function *G*. Berman and Vasudeva (2003) present a model used to evaluate the performance of a repair technician providing service to geographically-dispersed machines.

Integrated models for SPL inventory models and network design with variable fill rate has only being addressed by Candas and Kutaboglu (2009) and Jeet *et al*. (2009). The former model (2007) linearise the non-linear fill rate and minimize the joint costs of transportation and inventory costs while maintaining the guaranteed the time-response. The later model (2009) incorporates lost-sales due to stock-out, and introduces a new variable substitution scheme. As a result they obtain a smaller linearised model, which is solved using a heuristic algorithm that produces a near-optimal solution to the integrated network location and SPL inventory policies.

3 Problem Definition and Modelling

The analysis of the defined in-house regional service parts logistics systems relative to technician assignment, inventory policies and operating policies is quite complex mathematically, and an integrated solution approach to these problems has not been developed. Therefore, the approach taken for this research is to study each problem individually and then integrate the concepts from multiple problems.

In this paper we present the SPLS mathematical model, and a heuristic to obtain a close to optimal solution of the technician assignment given a fixed inventory policy. In further research we will present an integrated solution to the technician assignment and technician vehicle inventory policies.

3.1 SPL Systems Structure
Consider a retailer with a set of *I* stores dispersed throughout some geographic area. Each store *i* has a set of different units of equipment, and each machine consists of a set of components (parts). In total, each store

utilizes a subset of *J* part types. Failures of part type *j* at store *i* are assumed to occur according to a Poisson process having rate λ_{ij}. Failed parts are self-announcing and each one has a different part criticality (p_j) based on the severity of machine malfunction resulting from the failure of the component, which are classified as follows:

$p_j = 1$ Critical – the failure requires immediate attention

$p_j = 2$ Emergency – the failure requires attention as soon as possible

$p_j = 3$ Medium – the failure requires attention when a technician is idle

$p_j = 4$ Low – the failure needs attention when the technician be at the store

Let $\phi_p = \left\{ j \in \left\{ 1, 2, \ldots J \right\} \middle| p_j = p \right\}$. Failures of criticality *p* at store *i* occur according to a Poisson process having rate λ_{ip} where

$$\lambda_{ip} = \sum_{j \in \phi_p} \lambda_{ij} \tag{3.1}$$

A set of *K* technicians provides equipment maintenance services to the stores, where technician *k* is assigned to cover a regional area $L_k \subseteq \{1, 2, \ldots, I\}$. In this research, a single technician is considered ($K = 1$). Upon a part failure, the technician is contacted. Depending on the criticality of the failure (*p*), the technician has a specified time response window (TRW_p) to travel to the store and repair/replace the failed part. In the event of a late response a corresponding penalty cost d_p is incurred. The technician attends to calls by priority based on criticality (smaller values of *p* have higher priority), and within the same criticality addressed on a FIFO basis. Each day, the technician has a set on duty (κ) and off duty time. The technician does not preempt a service in any event. If the technician cannot attend to a critical ($p = 1$) or emergency ($p = 2$) part failure within the time response window, either because he is off duty or he estimates that he will not be able to attend to the failure in time, a local contractor is dispatched to attend to the failure.

A part failure may require repair or replacement with a spare part. The probability that repair will be sufficient depends on the part type and is denoted by δ_j. In either case, the repair time for a part having criticality *p* is assumed to be normally distributed with mean RT_p and standard deviation SRT_p. Local suppliers have agreed with the retailer to carry and sell spare parts in all the cities where the retail company has a store, therefore, the technician can obtain the required spare parts locally. The time required to travel to the parts supplier is normally distributed with mean *TS* and standard deviation *STS*. However, given the time response constraints the technician carry some spare parts according to a "periodic review, order-up-to-level" (R_j, T_j) inventory policy. The mean travel time from store *i* to store *i'* is represented by $TT_{ii'}$ and the corresponding standard deviation is represented by $STT_{ii'}$.

3.2 *The Technician Assignment Model*

A key issue related to the management of the SPLS is the technician assignment, which needs to consider the time response requirements to part failures. However, the use of the local contractor guarantees that the time response requirements can always be met. Therefore, time response is not enough to evaluate the performance of the SPLS under different technician assignments; therefore, cost is the most appropriate system performance measure. Thus, in this paper we investigate the technician minimum costs assignment to a homogeneous set of stores.

3.2.1 *M/G/1 HOL Queuing Model*

The behaviour of the SPLS is approximated in this research with the *M/G/*1 HOL queuing model. Customers from priority group *p* arrive according to a Poisson process having a rate of λ_p, $p = 1, 2, \ldots, P$. Each customer from priority group *p* has an independent service time distribution having mean $E(S_p)$. The overall arrival rate and average service time across all priority groups are given by

$$\lambda = \sum_{p=1}^{P} \lambda_p$$

and

$$E[S] = \sum_{p=1}^{P} \frac{\lambda_p}{\lambda} E[S_p]$$

respectively.

The server utilisation is denoted by ρ and defined to be the percentage of the time that the server is busy. Let ρ_p represent the percentage of the time that the server is busy with a customer from priority group *p*. Then $\rho_p = \lambda_p E(S_p)$ and

$$\rho = \lambda E(S) = \sum_{p=1}^{P} \rho_p \qquad (3.2)$$

Let T_p and W_p denote respectively the average total time in the system and the average waiting time for a customer with priority *p*. The average total time in the system is given by

$$T_p = E(S_p) + W_p \qquad (3.3)$$

A customer's average waiting time can be decomposed into three parts: the waiting time W_0 due to the fact that the server may be busy upon the arrival of the customer, the average delay due to the number of customers with higher priority that are already in queue upon the arrival of the customer, and the average delay due to the number of customers with higher priority that arrive to the system while the customer waits in the

queue for service. It is important to mention that in this research the server does not preempt a customer's service for a higher-priority arrival.

Consider a new arrival referred to as a "tagged" customer and suppose this customer has priority g. Since ρ_p is the fraction of the time that the server is busy serving a customer with priority p and arrivals follow a Poisson process, ρ_p is the probability that the tagged customer finds a customer from group p in service. According to Kleinrock (1976), the mean residual life of the service time observed by the tagged customer is

$$W_0 = \sum_{p=1}^{P} \frac{\lambda_p E(S_p^2)}{2} \qquad (3.4)$$

All the customers with higher or equal priority ($p = 1, 2, \dots , g$) that are waiting in the queue upon arrival of the tagged customer are served before the tagged customer. Using Little's law, Kleinrock (1976) defines as $\bar{N}_{pg}$ the average number of customers from group p waiting to be served upon arrival of the tagged customer where

$$\bar{N}_{pg} = \lambda_p W_p \qquad (3.5)$$

Likewise, the average number of higher-priority customers that join the queue while the tagged customer is waiting for service is given by

$$\sum_{p=1}^{g-1} \overline{M}_{pg} = \sum_{p=1}^{g-1} \lambda_p W_g \qquad (3.6)$$

Therefore, the long-run average waiting time for a customer in priority group p is given by

$$W_p = W_0 + \sum_{i=1}^{p} E(S_i)\lambda_i W_i + \sum_{i=1}^{p-1} E(S_i)\lambda_i W_p$$

Kleinrock (1976) presents the solution for this set of equations as

$$W_p = \frac{W_0}{(1-\sigma_p)(1-\sigma_{p-1})} \qquad (3.7)$$

where

$$\sigma_p = \sum_{i=1}^{p} \rho_i \qquad (3.8)$$

3.2.2 *Approximation of the RSPLS using the M/G/1 HOL Queuing Model*
The initial SPLS model consists of one technician serving a set of I store locations. Recall failures of part type j at store i occur according to a Poisson process having rate λ_{ij}. Upon part failure, the store personnel contact the technician who provides service according to the criticality of the failed part. The service times are independent and consist of the sum

of the technician's travel time from his current site to the site where the part failed, the maintenance time for the failed part, and travel time to the local depot if the technician is out of stock of a required spare part.

The behaviour of the SPLS is approximated in this research with the *M*/*G*/1 HOL queuing model. However, in order to apply this queuing model to the SPLS, it is necessary to incorporate into the model the technician off duty periods and the participation of the local contractor. The technician off duty periods could be modelled as an *M*/*G*/1 queuing model with priority services and vacations, but this approach would complicate the mathematical model even more. A simpler approach is to assign a fifth and higher priority ($p = 0$) to the "arrival" of the off duty period. Note that this "customer" has deterministic arrival and service times.

From the service discipline point of view, the concern is not with which part failed, but to which criticality group it belongs. The failure rate among all stores could be aggregated by part criticality *p* using equation (3.1). However, the technician does not serve failures from criticality groups $p = 1$ or $p = 2$ during the off duty period. Therefore, equation (3.1) needs to be adjusted to include only the failures that the technician serves.

First, let ρ_0 denote the proportion of time that the technician is in the off duty period and note that

$$\rho_0 = \frac{\kappa}{24} \tag{3.9}$$

Now, an approximation factor can be applied to adjust the failure rate according to the technician on duty and off duty periods. Let Φ_j be the factor for part type *j* where

$$\Phi_j = \begin{cases} 1 & \forall\, j \in \phi_3 \cup \phi_4 \\ 1 - \rho_0 & \forall\, j \in \phi_1 \cup \phi_2 \end{cases} \tag{3.10}$$

and equation (3.1) can be approximated by

$$\lambda_p = \sum_{i=1}^{I} \sum_{j \in \phi_p} \Phi_j \lambda_{ij} \tag{3.11}$$

By using the non-preemption rule, the technician off duty period does not start until the technician finishes with any failure being served at the beginning of the off duty period.

The purpose of applying the *M*/*G*/1 HOL queuing model is to approximate technician utilisation and average response time by criticality group. Technician utilisation is approximated using equation (3.2) with the effective failure rate λ_p given in equation (3.11).

The average waiting time and the average service time comprise the expected response time. The average waiting time in the generic

*M/G/*1 HOL queuing model is defined with the equations (3.4), (3.7) and (3.8). However, these equations do not consider the arrival of the technician's off duty period. Recall that the arrival of the off duty period only affects to the waiting time of criticality groups with $p = 3$ and $p = 4$ since the local contractor attends critical and emergency failures while the technician is in the off duty period. Therefore, equation (3.4) can be modified to include this waiting time, which is approximated by

$$W_0 = \begin{cases} \sum_{p=1}^{P} \dfrac{\lambda_p E(S_p^2)}{2}, & p = 1, 2 \\[2em] \left(\dfrac{\lambda_0 \kappa^2}{2}\right) + \sum_{p=1}^{P} \dfrac{\lambda_p E(S_p^2)}{2}, & p = 3, 4 \end{cases} \tag{3.12}$$

where λ_0 is the arrival rate of the technician off duty period. Note that $\lambda_0 = 1/24$ per hour. Now consider service time. Consider the situation where a technician is idle at store i when a failure occurs at store i'. The elapsed time between the service request from store i' and the completion of the service is the sum of the travel time from store i to store i', the maintenance time for the failed part, and the travel time to re-supply the spare parts inventory (if necessary).

The average travel time from store i to store i' is $TT_{ii'}$. However, the location of the technician and the location of the next store to be served are random variables. Suppose that when a failure occurs the technician is located at store i. Then, the average travel time from store i to the failure location can be approximated by

$$E(TD_i) = \sum_{i'=1}^{I} \frac{\Lambda_{i'}}{\lambda} TT_{ii'} \tag{3.13}$$

where $\Lambda_{i'}$ is the overall effective failure rate at store i' and approximated by

$$\Lambda_{i'} = \sum_{j=1}^{J} \lambda_{i'j} * \Phi_j \tag{3.14}$$

and λ is the overall effective failure rate and approximated by

$$\lambda = \sum_{i=1}^{I} \sum_{j=1}^{J} \lambda_{ij} * \Phi_j \tag{3.15}$$

Thus, the overall average travel time is approximated by

$$E(TD) = \sum_{i=1}^{I} E(TD_i) * \left(\frac{\Lambda_i}{\lambda}\right) \tag{3.16}$$

The last portion of the average service time accounts for the average time that the technician spends travelling to the local depot when a stockout occurs. Suppose part j failed and requires replacement. Recall that in the SPLS the inventory policy used is the periodic-review, order-

up-to-level policy (R_j, T_j). Every day at the beginning of the on duty period, the technician checks the stock level for every part whose periodic review cycle has expired and travels to the local depot if it is necessary to restore the inventory levels. Let Θ_j be the event that a stockout occurs, thus the probability that a stockout occurs can be approximated by

$$\Pr(\Theta_j) = \left(1 - \sum_{r=0}^{R_j} \frac{\theta_j^r e^{-\theta_j}}{r!}\right) \tag{3.17}$$

where θ_j is the average demand for part j during the periodic review cycle and approximated by

$$\theta_j = 24\Omega_j * T_j * (1 - \delta_j) \tag{3.18}$$

Note that Ω_j denotes the total failure rate for part j across all the stores and is approximated by

$$\Omega_j = \sum_{i=1}^{I} \lambda_{ij} \Phi_j \tag{3.19}$$

Since the SPLS has time response window requirements by criticality group, the average service time is calculated by criticality group. Let O_p be the event that a stockout occurs for a part of criticality group p. Then, the probability of a stockout can be approximated by

$$\Pr(O_p) = \sum_{j \in \phi_p} \left(\Pr(\Theta_j) * \frac{\Omega_j}{\sum_{j \in \phi_p} \Omega_j}\right) \tag{3.20}$$

To calculate the probability of stockout, the technician's carry on inventory policies must be defined. Recall that in this phase of the research the inventory policies are assumed to be predetermined, in which the order up-to-level is assumed to be $R_j = 1$ for all part types and the periodic review cycles are assumed to be

$$T_j = \left\lfloor \frac{24}{\Omega_j} \right\rfloor$$

Finally, the average service time is approximated by

$$E(S_p) = E(TD) + E(RT_p) + E(TS) * \Pr(O_p) \tag{3.21}$$

4 A Mathematical Model for Evaluating Technician Assignment

The objective of this phase of the research is to determine the optimal assignment of stores to the technician such that SPLS costs are minimized

over a planning horizon τ. The decision variables are binary variables that represent if a store is covered by the technician:

$$X_i = \begin{cases} 1 & \text{if the technician is assigned to cover store } i \\ 0 & \text{if technician is not assigned to cover store } i \end{cases}$$

$i = 1, 2, \ldots, I$. Furthermore, let A denote the set of stores assigned to the technician.

The modified $M/G/1$ HOL model presented in Section 3.2.2 evaluates the performance of the SPLS considering that all the stores in the region are assigned to the technician. Therefore, failures of parts at unassigned stores should not be considered. In order to include the decision variables in the modified $M/G/1$ HOL model, let λ_{ij}^x represent the effective failure rate at store i for part type j, and note that λ_{ij}^x is given by

$$\lambda_{ij}^x = \lambda_{ij} X_i \qquad (3.22)$$

Then, the modified M/G/1 HOL queuing model presented in Section 3.2.2 is adjusted by replacing λ_{ij} with λ_{ij}^x.

4.1 *SPLS Cost Model*

The costs associated with operating the SPLS can be subdivided into four categories: penalty costs, holding costs, technician costs and sub-utilisation costs.

Penalty Costs

The penalty costs include the costs incurred for not meeting the time response windows (delay costs) and the costs associated with employing an outside contractor to service failed parts (contractor costs). In reality, delay costs are calculated based on the actual time response to each failure; unfortunately, the modified $M/G/1$ HOL queuing model does not permit this calculation. Let Δ_p denote the average time delay for criticality group p, which is approximated by

$$\Delta_p = \max\{T_p - TRW_p, 0\} \qquad (4.1)$$

Recall that the penalty cost is only applied to late response for critical ($p = 1$) and emergency ($p = 2$) failures that occur during the technician's on duty period. Therefore, the total delay costs over the planning horizon (τ) are approximated by

$$TDC(\tau) = \sum_{p=1}^{2} d_p \Delta_p \lambda_p \tau \qquad (4.2)$$

The contractor costs are the costs incurred for calling the local contractor to attend critical or emergency failures either because the technician is busy or off duty. The contractor is called when a critical or

emergency failure occurs and the technician is off duty or he is busy and a failure with the same or higher priority is already waiting for service.

Recall that ρ_0 represents the probability that the technician is in the off duty period. Therefore, the number of times that the contractor attends a failure of criticality $p = 1,2$ during the off duty period is approximated by

$$\rho_0 \sum_{i=1}^{I} \sum_{j \in \phi_p} \lambda_{ij}^x \tau$$

When a critical failure occurs during the technician's on duty period, the contractor is called if another critical failure is already in the technician's queue. Since N_{11} should be a very small number ($<<1$), it is used to approximate the probability of this event. Thus, the average number of failures with criticality $p = 1$ attended by the contractor is approximated by

$$E(NCC_1) = \tau \left(\sum_{i=1}^{I} \sum_{j \in \phi_1} \lambda_{ij}^x \right) \left[\rho_0 + \left(\sum_{p=1}^{P} \rho_p \right) N_{11} \right] \qquad (4.3)$$

For criticality group $p = 2$, the contractor is called if a failure with $p =1$ or 2 is already waiting for service, or if a failure with p = 1 occurs while the emergency failure is still in queue. Therefore, the average number of failures of criticality p that the contractor attends is approximated by

$$E(NCC_2) = \tau \left(\sum_{i=1}^{I} \sum_{j \in \phi_2} \lambda_{ij}^x \right) \left[\rho_0 + \left(\sum_{p=1}^{P} \rho_p \right) \left(N_{12} + N_{22} + M_{12} \right) \right] \quad (4.4)$$

Then, the total contractor costs over τ are approximated by

$$TCC(\tau) = \gamma \sum_{p=1}^{P} E(NCC_p) E(S_P) \qquad (4.5)$$

Note that the average service time used in equation (4.5) is the same as that used for the technician.

Holding Costs
The holding costs capture the cost of carrying spare parts inventory in the technician's vehicle. The holding rate (h_j) and the acquisition costs (a_j) for part j are known, and the holding costs are calculated based on the average inventory level of spare parts in the technician's vehicle. The average inventory level for the periodic review, order up-to-level inventory policy is defined by Hadley and Whitin (1963) and approximated for the SPLS by

$$\bar{I}_j = R_j - E[TS](1 - \delta_j)(\Omega_j) - \frac{\theta_j}{2} \qquad (4.6)$$

The total holding costs over the planning horizon are approximated by

$$THC(\tau) = \sum_{j=1}^{J} \left(\bar{I}_j * h_j * a_j \right) \qquad (4.7)$$

Technician Costs

The technician costs consist of two components, an annual cost (φ) and a variable cost per mile (υ). The technician's variable costs per mile can be subdivided into two categories based on the reason for travelling: operating cost and ordering cost.

Operating costs are calculated based on the average number of times that the technician travels from each location to attend a failure. However, the failures attended by the contractor need to be excluded. Then, the total operating costs over τ can be approximated by

$$TOC(\tau) = \upsilon E(SP)E(TD)\left[\tau\sum_{i=1}^{I}\Lambda_i - \left(\sum_{p=1}^{2} E[NCC_p]\right)\right] \qquad (4.8)$$

Note that the transportation variable cost is multiplied by the average technician travel speed ($E(SP)$) since the variable transportation cost is expressed in dollars per mile.

The ordering cost is calculated based on the average number of times that the technician travels to the local depot to replenish the stock of pare parts. The average number of trips to the local depot to replenish the stock of part type j is approximated by

$$E(NS_j) = \begin{cases} \dfrac{\tau}{T_j * 24} & \text{if } R_j > 0 \\[2ex] \tau(1-\delta_j)\Omega_j & \text{if } R_j = 0 \end{cases} \qquad (4.9)$$

Note that equation (4.9) includes the number of trips due to stockouts, since the replenishment cycle starts any time the technician replenishes the stock level. Therefore, the ordering cost over is approximated by

$$TSC(\tau) = \upsilon E(SP)E(TS)\sum_{j=1}^{J} E(NS_j) \qquad (4.10)$$

Finally, the total transportation costs over τ are approximated by
$$TTC(\tau) = TOC(\tau) + TSC(\tau) + \varphi\tau \qquad (4.11)$$

Sub-Utilisation Costs

To this point, the objective function of the optimisation problem would be to minimize the total penalty, holding and transportation costs. However, if only these costs are considered, the model would tend to assign the minimum number of stores possible because these costs all decrease as the number of stores assigned decreases. Besides, the stores that are not covered by the technician need to be covered by someone else with the subsequent cost. Therefore, a lost opportunity cost associated with not fully utilising the technician is included.

In order to calculate this sub-utilisation cost, maximum technician workload must be defined. The maximum technician workload is defined

as the maximum workload that the technician can handle without exceeding the time response requirements for any criticality group. This workload can de found by solving the following sub-problem:

$$\text{Max} \qquad \sum_{p=1}^{P} \lambda_p^{\max} * E(S_p) \qquad\qquad (4.12)$$

s.t.

$$\lambda_p^{\max} = \sum_{i=1}^{I} \sum_{j \in \phi_p} \lambda_{ij}^{x} \Phi_j \qquad\qquad (4.12a)$$

$$T_p \leq TRW_p, p = 1, \ 2, \ \dots, P \qquad\qquad (4.12b)$$

$$X_i \text{ binary}, i = 1, \ 2, \dots, I \qquad\qquad (4.13c)$$

Once the maximum workload is obtained the sub-utilisation cost can be calculated. First, the overall rate of failures of criticality p not assigned to the technician is approximated by

$$E(SU_p) = \max(\lambda_p^{\max} - \lambda_{p,} 0) \qquad\qquad (4.14)$$

Then, the total sub-utilisation cost over τ can be approximated by

$$TUC(\tau) = \tau u \sum_{p=1}^{P} E(SU_p) * \left(E(S_p) - E(TS_p) * \Pr\left(O_p\right) \right) \qquad (4.15)$$

Note that the time required to deal with stockouts is not penalized for sub-utilisation.

Technician Assignment Mathematical Model

Now that the cost structure and the operation of the SPLS have been modelled, the mathematical model can be formulated as a minimisation problem where the objective function is to minimise the total SPLS costs and the decision variables as binary variables that corresponds to the technician assignment.

$$\text{Minimise } THC(\tau) + TTC(\tau) + TCC(\tau) + TDC(\tau) + TUC(\tau) \qquad (4.16)$$

s.t. $\qquad T_p \leq TRW_p, \ p = 1, \ 2, \ \dots, P \qquad\qquad (4.16a)$

$$\sum_{i=1}^{P} \rho_i \geq \rho_{\min} \qquad\qquad (4.16b)$$

$$X_i \text{ binary}, i = 1, \ 2, \ \dots, I$$

Note that two set of functional constraints have been added to the model. The first equation (4.16a) ensures that the time response limits are met on average. The second equation (4.16b) ensures that the technician achieves some minimum utilisation.

5. An Heuristic Solution Approach for the Technician Assignment

The mathematical models used for evaluating technician assignment result in a nonlinear, integer optimisation problem. Therefore, the objective here is to develop an easily implementable heuristic that obtains a near-optimal solution to the assignment of the stores covered by the technician. This objective is met with the Assign Locations heuristic, which consists of:

1. Minimum Stores Heuristic: Find the minimum number of stores (I_{min}) assigned to the technician that satisfies equation (4.16b).
2. Maximum Stores Heuristic: Find the maximum number of stores (I_{max}) that a technician can cover that satisfies equation (4.16a).
3. Coverage Assignment Heuristic: For each feasible number of stores, find a technician assignment that provides a near-minimum cost. Choose the solution that has the minimum cost across all feasible number of stores. Two approaches are used to obtain the technician coverage assignment: (1) total enumeration, and (2) probabilistic search-based heuristic.

The heuristics are implemented in a VBA macro within a Microsoft Excel ® worksheet.

Minimum Stores Heuristic

The main task accomplished with this heuristic is the calculation of the minimum number of stores that satisfies the minimum technician utilisation constraint.

Step 1: Calculate the technician's utilisation at each store (ρ_i) assuming that $A = \{1, 2, \ldots, I\}$

Step 2: Sort stores in descending order according to ρ_i. Let $\rho_{[i]}$ denote the technician's utilisation at the store in position i after sorting.

Step 3: Return I_{min} as the smallest integer value such that

$$\sum_{i=1}^{I_{min}} \rho_{[i]} \geq \rho_{min}$$

Maximum Stores Heuristic

The main task accomplished with this heuristic is determination of the number of stores that the technician can cover while meeting (on average) the time response window limit for all the criticality groups.

Step 1: Set $A = \{1, 2, \ldots, I\}$ and $I_{max} = I$.

Step 2: Calculate ρ_i, $\forall\ i \in A$, and T_p, $\forall\ p \in \{1, 2, 3, 4\}$.

Step 3: If $T_p \leq TRW_p$, $\forall\ p \in \{1, 2, 3, 4\}$, then go to step 5.

Step 4: Remove the store with the smallest value of ρ_i from A. Set $I_{max} = I_{max} - 1$ and go to step 2.

Step 5: Return the value of I_{max}.

Technician Coverage Assignment: Total Enumeration

Total enumeration is recommended when the number of locations within a region allows obtaining the optimal technician assignment by evaluating the performance of all possible technician assignments with the modified $M/G/1$ and cost models. The total number of possible solutions is given by

$$NP = \sum_{i=I_{\min}}^{I_{\max}} \binom{I}{i}$$

and the total number of solution per I_{use} level is given by $NP_i = \binom{I}{i}$

Step 1: Set $TC^*(\tau) = \infty$.

Step 2: Set $I_{\text{use}} = I_{\min}$ and obtain the NP_i assignments by total enumeration.

Step 3: For each of the NP_i assignments compute $TC(\tau)$. If this value of $TC(\tau) < TC^*(\tau)$ then update $TC^*(\tau)$ and set $X_i^* = X_{NP_i}$, $i = 1, 2, \ldots, I$.

Step 4: If $I_{\text{use}} = I_{\max}$, go to step 6.

Step 5: Set $I_{\text{use}} = I_{\text{use}} + 1$, go to step 2.

Step 6: Return X_i^*, $i = 1, 2, \ldots, I$, and $TC^*(\tau)$.

Technician Coverage Assignment: Probabilistic Search-Based Heuristic

The objective of this research is to produce an easily implementable solution to the technician's assignment and inventory policy in the SPLS for any type of industry. Therefore, for those industries that have a large number of locations obtaining the optimal technician assignment by total enumeration would require an unacceptable computational time.

This heuristic searches for the set of the stores assigned to the technician that generates the minimum SPLS costs. The heuristic randomly generates the set of stores assigned using a genetic algorithm.

Probabilistic search-based algorithms (PSA) are heuristics often used to find near-optimal solutions to combinatorial optimisation problems. The search-based heuristic applied to the SPLS views each store assignment (X_i) as an individual or a chromosome and the set of store assignments as a population member (solution). Each population member is characterized by its fitness, which in this case is the total SPLS cost over the planning horizon. The heuristic works iteratively, and each iteration is called a generation. At each iteration, the heuristic creates a new population from the strongest populations using a probabilistic, genetic-like operator that uses concepts similar to crossover and mutation. Note that the initial population consists of a set of assignments such that I_{use} stores are assigned. Each solution in this initial set is selected by randomly choosing the I_{use} assigned stores.

At each iteration, the heuristic sorts the population members in ascending order based on the total SPLS costs and keep the population

member that generates the minimum total SPLS costs. This solution is the initial member of the next population. For the rest of the next population, each member is generated by randomly interchanging (in the initial solution) uncovered stores with covered stores while maintaining I_{use} stores assigned. (Figure1). This process is repeated until a specified number of iterations or computational time limit is reached.
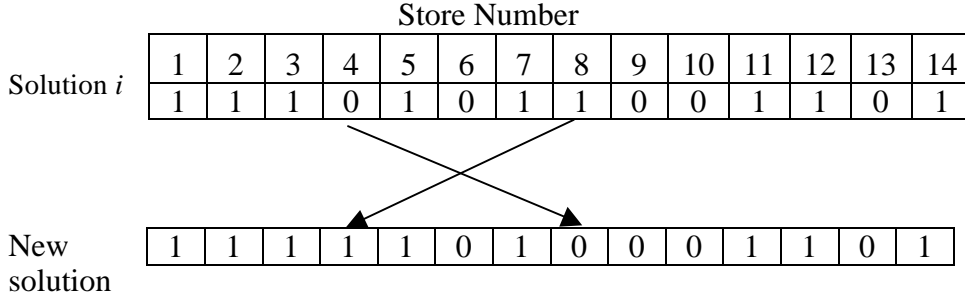
Store Number

Figure.1. Random Interchange of Assigned Stores

Step 1: Set $I_{use} = I_{min}$.
Step 2: Set $X_i^* = 0$, $i = 1, 2, \ldots , I$, $TI = 0$ and $TC^*(\tau) = \infty$.
Step 3: Randomly create an initial population of *NP* assignments such that I_{use} stores are assigned.
    While $TI < NI$
      For each assignment compute $TC(\tau)$. Identify the assignment having the smallest $TC(\tau)$. If this value of $TC(\tau) < TC^*(\tau)$ then update X_i^* , $i = 1, 2, \ldots , I$ and $TC^*(\tau)$ and set $TI = 0$. Else, $TI = TI + 1$.
      Using the elitism strategy (Jong 1975), maintain the assignment with the smallest $TC^*(\tau)$.
      For the rest of the population, perform mutations according to Figure 1 to generate a set of store assignments such that I_{use} stores are assigned.
    Endwhile
Step 4: If $I_{use} = I_{max}$, go to step 6.
Step 5: Set $I_{use} = I_{use} + 1$, go to step 2.
Step 6: Return X_i^* , $i = 1, 2, \ldots , I$, and $TC^*(\tau)$.

6. An Example System

To facilitate the discussion of the set of mathematical models for the SPLS, an example system is presented in this section. The example consists of one district (region) of a retailer that includes fourteen ($I = 14$) stores. Although hypothetical, the system is based primarily on data provided by the industrial partner. Each store utilizes four types of equipment that are needed to operate continuously: freezers, air conditioners, refrigerators and heaters. Each type of equipment is subject

to four types of part failure with one type in each criticality group ($J = 16$ total part types). The time response windows (in hours) by criticality group are $TRW_1 = 4$, $TRW_2 = 4$, $TRW_3 = 24$ and $TRW_4 = 48$, and the corresponding penalty costs due to late response are $d_1 = \$500$ per hour, $d_2 = \$100$ per hour, and $d_3 = d_4 = 0$. Additional part information such as unit volume (v_j), weight (w_j), probability that repair is sufficient (δ_j), and unit acquisition cost (a_j) is presented in Table 1. Note that holding costs are calculated based on an annual holding cost rate of $h_j = 25\%$, $j = 1, 2, \ldots$, J. The fixed transportation, variable transportation, sub-utilisation and contractor cost parameters respectively are: $\varphi = \$55,286$ per year, $\upsilon = \$0.179$ per mile, $u = \$55$ per hour, and $\gamma = \$50$ per hour. The planning horizon is one year or $\tau = 8760$ hours.

The travel time from any store to the spare parts supplier is normally distributed with a mean of $TS = 30$ minutes and a standard deviation of $STS = 3$ minutes. The travel times were assumed normally distributed. The mean of travel times between stores ($TT_{ii'}$) were calculated using the real distance between the stores located in the region under analysis, and assuming that the technician travels at an average speed $E(SP) = 55$ miles/hour. Note that in all cases the standard deviation of travel time ($STT_{ii'}$) is assumed 10% of the mean.

Table 1. Relevant Part Information

Part j	v_j (ft^3/unit)	w_j (lb/unit)	δ_j	a_j
1	4.40	76.47	0.40	100.00
2	4.35	95.19	0.40	50.00
3	5.81	64.90	0.50	25.00
4	1.47	96.91	0.55	10.00
5	5.38	61.42	0.41	110.00
6	2.80	34.46	0.41	60.00
7	4.63	70.96	0.51	35.00
8	3.35	48.63	0.56	20.00
9	1.99	52.08	0.42	90.00
10	2.18	58.34	0.42	40.00
11	2.92	91.66	0.52	15.00
12	1.03	69.70	0.57	5.00
13	1.89	98.66	0.43	105.00
14	4.15	71.34	0.43	55.00
15	2.73	68.13	0.53	30.00
16	0.16	112.96	0.58	15.00

The means and the corresponding standard deviations (RT_p, SRT_p) of the time (in hours) required to provide maintenance (assumed to be

normally distributed) by criticality group are as follows: {(2.15, 0.25), (1.75, 0.20), (1.00, 0.15), (0.75, 0.15)} for p = 1, 2, 3, 4 respectively.

The length of the technician off duty period is κ = 13 hours, so ρ_o = 0.5417 and Φ_p = 1 for p= 3, 4 and Φ_p = 0.4583 for p = 3, 4 . By applying this factor to the weekly failure rates provided by our industry partner and using equation 3.11, approximate hourly effective failure rates by part type are obtained. Then, adding them by criticality group leads to the hourly effective failure rates by part criticality λ_p (Table 2).

The modified $M/G/$1 HOL model can be used to calculate the average servicer time but to calculate the average response time the average waiting time is required. However, the second moment of the service time is required. The second moment is estimated with a discrete-event simulation model (Tovia 2004) that is presented in Section 6. Then, the average waiting time W_p is calculated using equations (3.7), (3.8) and (3.12), and the average response time T_p is calculated with equation (3.3). The results for the defined example are summarized in Table 2.

Table 2. Average Waiting Time and Response Time (Hours) by Criticality

Criticality Group p	$\Pr(O_p)$	ρ_p	σ_p	$\tilde{E}(S_p^2)$	W_p	$E(S_p)$	T_p
1	0.361	0.0202	0.0202	12.491	0.368	3.60	3.97
2	0.361	0.0383	0.0585	9.912	0.391	3.20	3.59
3	3.882	0.1100	0.1685	5.942	4.969	2.46	7.43
4	3.882	0.1109	0.2794	4.875	6.581	2.20	8.78

Finally, the technician optimal assignment is obtained using the SPLS Cost Model and the Heuristics presented in Sections 5 and 6 respectively. Application of the Minimum Stores Heuristic assuming that ρ_{min} = 65 yields to I_{min} = 8. Application of the Maximum Stores Heuristic indicates that when I_{max} = 14, $T_p \leq TRW_p$, p = 1, 2, 3, 4. Therefore, I_{max} = 14.

The optimal technician assignment was obtained with the total enumeration approach and the probabilistic search-based heuristic. Both methods yield exactly the same results, which indicates that the probabilistic based-search heuristic provides high-quality results and for the defined example the technician assignment found is optimal. The results are presented in Table 3, and the respective SPLS costs in Table 4.

Table 3. Technician Coverage Assignment

I_{use}	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
8	0	1	1	1	1	1	1	0	1	1	0	0	0	0
9	0	1	1	1	1	1	1	1	1	1	0	0	0	0
10	0	1	1	1	1	1	1	1	1	1	1	0	0	0
11	0	1	1	1	1	1	1	1	1	1	1	0	1	0
12	1	1	1	1	1	1	1	1	1	1	1	0	1	0
13	1	1	1	1	1	1	1	1	1	1	1	0	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1

6.1 *Model Validation*

In order to validate the results obtained with the Assign Locations heuristic, a discrete-event simulation model of the SPLS was constructed (Tovia *et al.* 2004) using the Arena® simulation language.

The simulation model was run for 21 replications, with each replication simulating one year ($\tau = 1$) with a warm-up period of 3250 hours. Table 5 presents a comparison of the results obtained with the Assign Locations heuristic and the simulation model for the near-minimum cost technician assignment ($I_{use} = 14$). The absolute difference in the total RSPLS costs obtained with the heuristic and the simulation model is less than 8% and the difference in the average time response for critical and emergency failures less than 2%. Note that the only cost category that has a major difference is the delay costs. This difference is due to the fact that penalties for delay in the analytical model are applied to average service times, whereas in the simulation model, penalties are applied to individual service times.

Table 4. Coverage Assignment Heuristic Results

	RSPLS Costs						
I_{use}	$TC(\tau)$	$THC(\tau)$	$TOC(\tau)$	$TTC(\tau)$	$TCC(\tau)$	$TDC(\tau)$	$TUC(\tau)$
8	$125,346	$139	$3,285	$59,968	$13,976	$0	$45,721
9	$123,154	$139	$3,650	$61,096	$15,800	$0	$38,070
10	$116,459	$139	$4,123	$62,631	$18,752	$0	$30,815
11	$114,118	$139	$4,605	$63,419	$20,394	$0	$25,561
12	$112,008	$139	$4,880	$65,135	$23,915	$0	$17,940
13	$108,463	$140	$5,554	$66,739	$27,316	$0	$8,715
14	$104,783	$139	$5,632	$68,276	$30,736	$0	$0

Thus, the modified *M*/*G*/1 HOL model and its application with the

Assign Locations heuristic appear to provide a reasonable approximation of SPLS performance.

Table 5. Assign Heuristics Validation Results

Concept	Heuristc	Simulation	Absolute Difference	Percent Absolute Difference
Total RSPLS Costs	$104,908	$113,466	$8,558	7.54%
Contractor Costs	$30,764	$31,188	$424	1.36%
Penalty Delay Costs	$0	$8,066	$8,066	100%
Transportation Costs	$68,276	$68,649	$373	0.54%
Ordering Costs	$5,632	$5,323	$309	5.80%
Holding Costs	$236	$240	$4	1.67%
Sub-Utilization Costs	$0	$0	$0	0.00%
T_1 (hours)	4	3.98	0.02	0.50%
T_2 (hours)	3.62	3.69	0.07	1.90%
ρ	84.73%	81.47%	0.03	4.00%

6. Conclusion

This research is conducted with the objective of providing an integrated solution to three major problems faced in SPLS: (1) the assignment of the locations to the technician, (2) the technician's inventory policies, and (3) the technician's operating policies.

In the first phase of this research, the behaviour of the SPLS is approximated with a modified $M/G/1$ HOL queuing model. Then, the costs structure of the SPLS is defined and approximated with a mathematical model such that the performance of the SPLS is evaluated based on the total SPLS costs.

Once the baseline models are developed, the first area of interest is addressed in this paper: find the optimal technician assignment given fixed inventory policies for the technician's vehicle. A heuristic-based optimization approach is implemented in this phase, which consists of the modified M/G/1 queuing model, the costs model and a genetic algorithm.

The technician's vehicle inventory policies are addressed in the second phase of this research, and will be presented in a subsequent paper. The mathematical model developed in the phase one is modified by making the inventory policies parameters also decision variables. Then, a three-stage iterative heuristic is implemented to search for the near-optimal simultaneously technician assignment and inventory policies inventory policy.

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