# Management of rotable aircraft spares inventory: review of practice and development of new solutions.

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## *Abstract:*

A standard systems development methodology has been applied to depict the supply chain in the aircraft maintenance industry, propose automation applications and seek optimisation problems.

An area of interest that has emerged is that of rotable spares, which presents scope for research.

Questions that arise from examining the rotable inventory management problem include:

(i) how does mainstream inventory practice aid in planning and managing appropriate inventory levels in an environment of changing operating conditions and stochastic demand?

(ii) what special practice is used to calculate demand for inventory and corresponding stock levels for this particular problem?

(iii) How can demand be pooled among multiple locations, aircraft types and airline operators?

The paper will review current practice and propose new inventory management solutions for these issues based on management science techniques. Examples are drawn from on-going action research.

## *Introduction*

A standard information modelling approach (Stevens 1998) has been applied to the aircraft maintenance industry as shown in Figure 1. The '*use-case scenarios'* were developed from an airline (Aer Arann) and a primary maintenance provider (Shannon MRO).

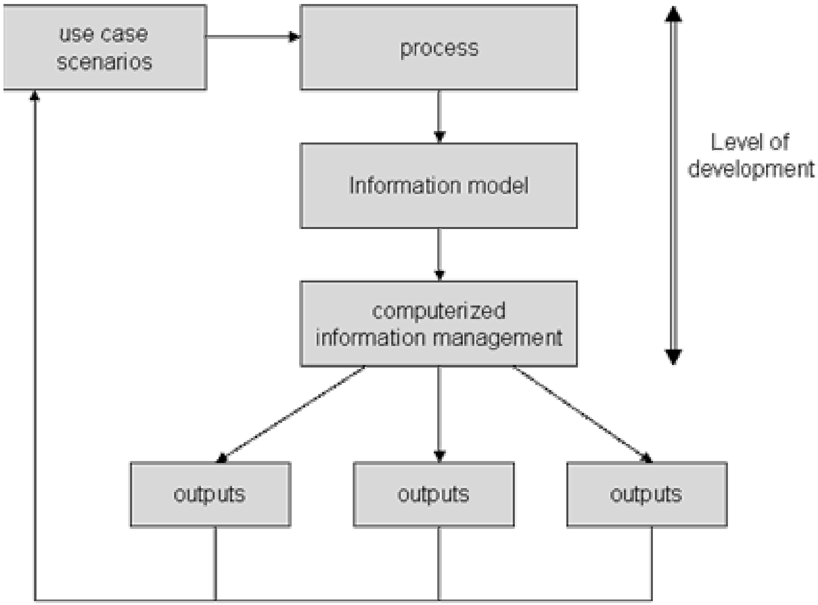

**Figure 1: Derivation of the System**

The *'process level'* of development has been used to define the business process deliverables (e.g., inventory management process for cost and downtime minimisation). This model is referred to in this paper as the *'Aircraft Maintenance Supply Chain Reference (AMSCR) Model'* and is intended to coordinate with other standard models such as the Society of British Aerospace Companies Supply Chain Relationships in Action (SCRIA) model (SBAC 1999) and the Supply Chain Operations Reference (SCOR) model framework (Stephens, 2001).

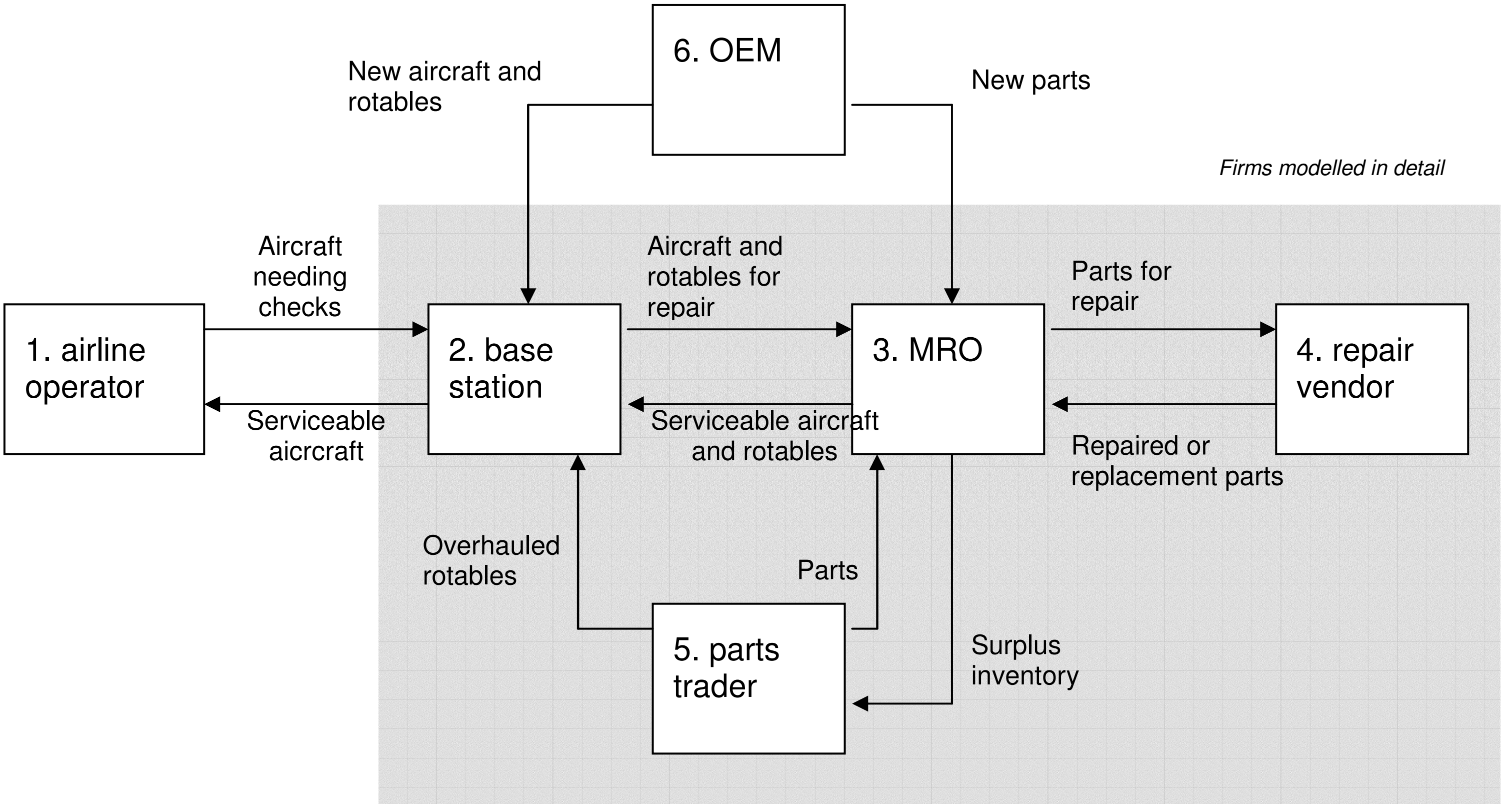

**Figure 2: The Aircraft Maintenance Supply Chain Reference Model – Physical Flows**

The *'information-level'* model is an e-commerce exchange demonstrator. This facilitates the simulation of real business processes in a computer-based system by allowing transactions *between* organisations in the maintenance Repair and Overhaul (MRO) supply chain. The model encompasses the principle of demand-driven management; this requires close integration between providers and consumers of goods and services, and a high level of e-commerce capability (Williams, 2002).

The *'computerised information management level'* embodies agorithms for dynamic inventory control that are embedded in the e-commerce exchange demonstrator; inputs are taken from back-end MRO inventory management ERP systems. The outputs were then validated against the original use-case scenarios to create off-line MRO SCM simulations.

The third level of systems design, the 'computerised information management level' is the focus of this paper; the 'process level' and ‘information level’ are developed further in other work (MacDonnell 2007 forthcoming).

### Computerised Information Management Level: Optimisation for Forecasting Spare Part Inventory

Within the area of rotable material management, the following questions arise:

1. how does mainstream inventory practice aid in planning and managing appropriate inventory levels in an environment of changing operating conditions and stochastic demand?
2. what special practice is used to calculate demand for inventory and corresponding stock levels for this particular problem?
3. how can demand be pooled among multiple locations, aircraft types and airline operators?

**Research question 1**: how does mainstream inventory practice aid in planning and managing appropriate inventory levels in an environment of changing operating conditions and stochastic demand?

A review of a range of popular inventory management techniques for lot sizing shows that no single method works best for aircraft spares since the data is ‘lumpy’ and demand events are quite rare. Consequently, current MRP systems are deficient in their handling of this demand (Friend 2001). Another review of mainstream inventory planning methods applied to spares concludes that production-oriented inventory policies don’t cater for the unpredictability or complex logistics of spares (Fortuin 1999).

Current practice and literature (Airbus 1997, Fortuin 1999) state that demand for spares follows a normal distribution. A detailed analysis of the statistical methods used for predicting failure has been carried out in connection with this work (Cotter 2003). It shows that, with sufficient historical data, substantial benefits can be achieved by deriving distributions from usage history and matching them to a range of common theoretical distributions.

A recent review of British Airways’ spares inventory policy shows room for improvement in forecasting methods, but does not consider the fleet-level solution presented here (Jacskon 2003).

Other work on spares for electrical and electronic equipment in a closed-loop supply chain looks at life cycle management and reverse logistics, although there is a greater focus on end-of-life disposal than rotable management (El Hayek 2005).

**Research question 2**: What special practice is used to calculate demand for inventory and corresponding stock levels for this particular problem?

A calculation for spare parts cover is performed when a fleet is first commissioned (called the Initial Provisioning) and repeated over the lifetime of the fleet as failure rates change (Airbus 1997).

The Airbus Initial Provisioning formula is:

$$E = fh \times n \times N \times \frac{1}{MTBUR \times 365} \times TAT$$

where E = the maximum expected number of concurrent failures of a part, giving the Initial Provisioning quantity for that part

fh = flight hours per year per aircraft

n = number of units per aircraft

N = number of aircraft in operation

MTBUR = Mean Time Between Unscheduled Removals (only removals resulting from the unexpected failure or suspected failure of the unit)

TAT = repair Turn Around Time – time from removal to becoming available as a functioning spare

An example: an airline operates 20 aircraft an average of 12 hours per day. Each aircraft has 4 ignition units (2 per engine), with an MTBUR of 5,000 hours. It takes an average of 30 days to return a removed unit to serviceable stock. The Initial Provisioning quantity for this part is:

$$E = 12 \times 365 \times 2 \times 20 \times \frac{1}{5000 \times 365} \times 30 \approx 3$$

Note the effect of TAT in this formula – doubling the repair time doubles the recommended holding.

Some weaknesses are apparent in this heuristic. (i) The recommended holding grows in proportion to fleet size, so 40 aircraft would need 6 spares. Given the stochastic nature of part failure, this is not borne out by experience, so that doubling the fleet size has a small extra spares requirement. (ii) Failure is based on flight hours – this may not be accurate, but it is the best general approach. For the example above, igniters are sometimes used in an alternating pattern, so each one is used only on alternative flights; they may only be used briefly during takeoff (to minimise the risk of 'flame-out' in cold weather) if at all, and they may only be used for a few minutes regardless of flight length. (iii) the ageing of a fleet is not considered: if the average aircraft utilisation is 12 * 365 = 4,380 hours per year, then the probability of failure should be higher at the start of year 2 than during year 1. Also, following replacement, the probability of failure should be low for some time.

One of the major MRO supply chain partners (FLS Aerospace) expressed concern that excessive inventory existed due to the lack of systemic forecasting. An airline's main inventory investment is in the line items that are maintained and re-used (i.e. non-consumables); these are referred to as *rotable* (as they *rotate* through inventory and are not consumed). Rotable stock needs to be managed differently to consumable material. While there have been some systems developed for this problem, usually looking at the problem of dividing inventory around several airports (Tedone, 1989), specialist solutions are not in widespread use in the industry (Aircraft Technology Engineering and Maintenance, 2001). The standard model followed by ERP inventory systems takes manufacturer's guideline reliability data for each part number and makes a calculation based on several factors. The calculation is performed using proprietary solutions, the example below is from FLS Aerospace and is produced by their Viscalc application, which uses an iterative probability calculation (Kearney, 2003).

Recommended holding for part 763810-1 = f(MTBR,TAT,QPA,FleetUtil,SL) = 8

where:

MTBR =2,314 hours - Mean Time Between Removals Figure

TAT = 30 days - Turn Around Time: time taken to route, maintain and replace item 763810-1 in inventory

QPA = 1 - quantity per aircraft

FleetUtil = 53,229 hours in the past 365 days - total hours flown by the total number of aircraft of the same type (e.g. Boeing 737-800) in a fixed period

SL = 95% target service level: the probability of the part being available)

The calculated number will be a quantity of a given part number: for example, the recommended holding level for a cabin pressure controller (part number 763810-1) is 8, to satisfy 95% of requests for part number 763810-1. Note that no account is taken of the time taken to order a new item as the items are *maintained* as opposed to consumed. This means that ordering costs and economic ordering cost quantities are not needed in this calculation, since they have no bearing on the number of items needed to support operations.

Since the actual time at which a part is needed is stochastic, a probability distribution is used to determine a realistic holding. The Service Level (SL) is the probability of a part being available: a SL of 95% means that there is a 95% probability of the part being available at any time, given the stated utilisation parameters. To guarantee 100% SL would require a full duplication of all items in service, which is excessively costly. In practice, a target SL of 95% is used for essential items (parts without which the aircraft cannot operate, and are referred to as 'no go'). There are lower SLs for 'go if' items (e.g., one radio may be unserviceable if two others are working) and 'go' items (e.g., galley equipment, which the aircraft can operate safely without).

A cumulative Poisson distribution is used to calculate the probability of requests for parts being satisfied: in the above example, the probabilities of 0, 1, 2, 3 ,4, 5, 6, 7 or 8 parts being available exceeds 95% for the given rate of demand.

Using this method, a calculation is made for each line item in turn.

It was proposed that the conventional approach was deficient in its analysis since it considers individual line items (stock keeping units (SKUs) / part numbers) without regard to the other items (Jackson 2003). This highlights two major factors when considering MRO supply chain optimisation:

The relative cost of parts: it is more acceptable to delay the despatch of an aircraft for a US$100,000 dollar part than for a US$100 part. Typically inventory-planning calculations take no account of relative cost and impact on availability. However, it makes sense from an operational perspective to manually manage low stock levels of very expensive items, while providing greater levels of safety stock for less costly items.

The relative failure rates of parts: rather than calculate failure rates at the individual part level, the real business problem is to *maximise the number of requests satisfied for spares*, regardless of the part number. In other words, each time a request is made to stores, there is a required probability of 95% that it be fulfilled. This is quite different to the traditional objective of having a given part available 95% of the times that it is requested.

Thus the objective of the inventory planning function changes as shown in Table I below (where ‘I’ is a part and there are ‘n’ parts).

<table>
<tr><td colspan="2">From: the sum of minima for each item of inventory (current approach)</td></tr>
<tr><td>Total inventory cost = $\sum_{i=1}^{n} min\,(cost_i)$<br>subject to $i$ attaining target SL</td><td>the sum of all items with cost minimised to achieve a target SL</td></tr>
<tr><td colspan="2">To: the minimal sum for all items (new approach)</td></tr>
<tr><td>Total inventory cost = $min \sum_{i=1}^{n} cost_i$<br>subject to $I$ attaining target SL, where I is the set of all $i$ from 1 to n.</td><td>the minimal sum of the cost of all items attaining a fleet-wide service level</td></tr>
</table>

**Table I: objective functions for part-level and fleet-level optimisation**

The new problem statement can be solved as a linear program. The difference between the line-by-line approach and the linear programming solution is shown by the data in Table II using a sample of 5 parts.

Target service level = 90%

*old solution* **LP solution**

| part number | Description | $ | MTBR | calculated service level % for quantity | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 3 | JACKSCREW, FLAP | 2244 | 3589 | 2 | 6 | 17 | 30 | 47 | 63 | 76 | 86 | ***92*** | 96 | 98 | 99 | 99 | 99 | 99 |
| 4 | EXCITER, IGNITION | 1429 | 21864 | 62 | **85** | *95* | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| 5 | PUMP, STANDBY | 1340 | 19486 | **89** | *98* | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| 6 | REGULATOR, HIGH STAGE, | 1507 | 8974 | 57 | 81 | ***93*** | 98 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| 7 | REGULATOR, BLEED AIR, | 3413 | 5602 | 36 | 63 | **82** | *93* | 97 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |

**Table II: recommended holding quantities derived by old and new methods**

Table II shows individual line item calculations with target service level exceeded by the numbers highlighted with a box: for the first part, a SL of 92% is attained with 9 units, exceeding the target SL of 90%. Similarly, values of 3, 2, 3 and 4 are computed for the remaining parts respectively.

The new solution, the linear program, derives a solution to give a service level of 90% for the group of parts, i.e., for all requests for parts, 10% will fail. The LP solution gives lower values for 3 of the 5 parts in the example in table II (values are shown in bold text).

In order to solve the LP, SL calculations as in Table II are performed up to a limiting number of values, which is established by trial and error. Thus in Table II SL is calculated up to a limit of 15 for each line item. Another pre-processing stage is to compute the extended cost for each quantity.

The LP solution is formulated as a binary Integer Program, with a variable representing each cell in Table II above, such that each row can only have one chosen value, as shown in Table III below.

| part number | Description | $ | MTBR | calculated service level % for quantity | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 3 | JACKSCREW, FLAP , | 2244 | 3589 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **1** | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | EXCITER, IGNITION | 1429 | 21864 | 0 | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | PUMP, STANDBY | 1340 | 19486 | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | REGULATOR, HIGH STAGE, | 1507 | 8974 | 0 | 0 | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | REGULATOR, BLEED AIR, | 3413 | 5602 | 0 | 0 | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table III: binary Integer Linear Programming solution for 5-part sample**

The difference in total inventory cost for this sample, *while maintaining the target service level for the fleet*, is shown in table IV below.

| part number | qty by old method | total cost (old method) | qty by LP | total cost (LP) | difference |
|---|---|---|---|---|---|
| 3 | 9 | 20196 | 9 | 20196 | 0 |
| 4 | 3 | 4287 | 2 | 2858 | -1429 |
| 5 | 2 | 2680 | 1 | 1340 | -1340 |
| 6 | 3 | 4521 | 3 | 4521 | 0 |
| 7 | 4 | 13652 | 3 | 10239 | -3413 |
| total | | 45336 | | 39154 | -6182 |
| | | | | | -14% |

The detailed linear programming problem formulation can be stated as follows:

minimise $\sum_{i=1}^{n} cost_i$

subject to

1. global service level ≥ target service level

2. $\sum_{j=1}^{UL} X_{ij} = 1$ each row sums to 1

where i = part number, 1 ≤ j ≤ UL, UL = upper limit quantity, e.g., 15

3. X $\in$ {0,1} X is a binary value

This solution has been tested with a selection of 300 parts from a Maintenance, Repair and Overhaul operator holding customer stock. The actual holding was valued at €10.8M. The LP solution recommended a holding with a value of €6.4M to achieve the same service level (McKeon 2002). There is thought to be some inventory which exceeds the old method recommended levels (over-stocking) so the theoretical improvement is expected to be less than 40% and more in line with the 14% gain shown in the 5-part example above.

Further testing has been carried out: the results, while favourable, have not been published.

**Research question 3**: How can demand be pooled among multiple locations, aircraft types and airline operators?

Regional operators use narrow body Boeing 737 and Airbus A320, while long-haul airlines operate wide body Boeing 747 and Airbus A330 aircraft families. These two aircraft groups are incompatible in terms of crew, airport facilities, spares, maintenance and engineering support, so there is efficiency in concentrating operations on one aircraft type. There is also a trend in airport clustering, e.g., Ryanair traffic to London started with Luton and developed with Stansted. There is an implication for spares: separate logistics networks may emerge for regional and long-haul operators if they use different airports in most destinations. This has the advantage that short-haul airlines have lower costs for handling rotables at lower-cost bases.

With regard to where spare parts should be located, there are two main possibilities: centralise all stock at the main operating base or distribute stock in proportion to some operating criteria (number of landings at an airport, number of inbound flying hours). Factors to be considered include: shipping time and cost around the network, relative costs of bases, additional overheads for multiple bases, distribution of demand, the availability of technical resources to change items at each base (line maintenance).

Airlines are moving to outsourcing: the maintenance provider pools demand for all common fleet in one location or one connected network. The customer pays a premium for outsourcing, but inventory efficiency for large pooled demand should outstrip this, such that it is truly cheaper to outsource. This is unlike manufacturing industry, where outsourcing is used to cater for flexible demand at a higher unit cost: in times of high demand, profit is passed to the contractor. Further, by outsourcing spares provision, the airline can also outsource its technical services function to the maintenance provider, who in turn enjoys economies of scale (source: SR Technics interview).

Once the demand for spares support for all spare parts in a fleet is known, the optimal allocation of inventory around multiple locations can be stated as:

Minimise total cost *or* maximise service level

Subject to:

- global inventory levels calculated for all demand
- demand distribution around the network determined by operating inputs (such as landings at each location)
- order processing and transport time between locations
- transport cost
- holding costs at different locations

It is assumed here that a static inventory level is calculated for all global demand, without taking account of multiple locations, as a first step.

As a further exercise, the problem could also be stated in terms of distributed demand with inventory holding costs and transit times between locations.

## Other industries

Several industries share the characteristics of aircraft spares: rotable, high value, long life span. For example, oil drilling and extraction equipment – a $40 billion market (Datamonitor 2005), power generation (land-based turbines), railway rolling stock, road haulage vehicles, buses, ships, plant hire (e.g., tower cranes) offer potential for investigation in the future. Factors that should be considered include:

- Part value (not as high for buses as for aircraft);
- Repair cost as a proportion of replacement cost (may be a limiting factor for high-wear items such as oil well drill heads);
- Randomness of failure (low for land-based turbines: most maintenance is planned preventative);
- Life cycle of parent equipment (long for ships and trains) – a longer life cycle means better availability of historical data and greater long-term benefit from improved spares planning;
- Geographic distribution of demand and logistics of spare parts provision (remote oil fields have a long lead-time and cost for urgent spares).

## *Conclusions*

The problem of optimal forecasting for the provision of aircraft rotables in a stochastic demand environment is worthy of detailed analysis from both commercial and theoretical perspectives. Current literature and industry practice show that popular inventory management techniques and software products do not address this problem specifically.

The optimisation presented here shows that there is likely substantial benefit in a fleet-wide calculation to advise minimum inventory levels for each stock item, while achieving a desired service level. This solution has been proven in prototype: there is further work to be done in refining and applying the statistical methods used to forecast demand (as an input to the linear programming solution) and further testing of the solution is needed for reliable validation of the results.

There may be further scope for work in analysing the demand profile of a fleet as it ages. Also, it should be possible to predict the probability of failure for individual parts changing over time (failure is more likely approaching the MTBR) so that spares planning could be better managed for further reduction in spares without diminished performance.

There is also scope to apply this theory to similar applications, although it is first necessary to consider the likely benefit to be achieved in other industries.

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