Back to College: Managing spare parts when demand is a mystery

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SERVICE LOGISTICS FORUM

Outline

- *Introduction Service Parts*
- Stocking decisions
- Alternatives - Pooling
- Demand Forecasting
- System versus individual item targets

Rommert Dekker

- Full professor of Quantitative Logistics & Operations Research, Erasmus School of Economics

- Interests
  - reverse logistics and service logistics
  - maintenance optimization
  - transport optimization
  - port and container logistics
  - energy optimization

- Projects: SLF Research, ProSelo, ProSeloNext Revlog and many companies: Fokker Services, Shell, ECT, A16,

View points service logistics

- OEM – designs and makes product / system: provides service and wants to make a profit on it
- User – buys and operates product /system: wants guaranteed operation at lowest costs during lifetime
- (3rd party) Maintenance organization: is responsible for maintenance: needs spare parts to do maintenance on time and operates repair shops.
- Wholesaler: sells as 3rd party parts to users: interested in fast moving parts

Problems OEMs

- Most demanded parts are copied by others (pirates)
- Second hand market also takes interesting demand away, leaving suppliers only with occasional demand.
- At some point parts demand will go down as users discard their systems for better ones: this makes producing parts less attractive
- Supplier may be left with many unsold parts when systems are discarded.

Company – a refinery

Double ABC Analysis spare parts inventory in a refinery

Total inventory value: 25 million USD (1998)

Number of items and % of value

	Value P in USD		
	P<500	500<P<2500	2500 < P
Fast	250 items		
	0.5%		
Normal	400 items		
	0.5 %		
Slow	17.000 items	5000 items	1500 items
	20%	30%	49%

Legend

Fast: in more than 8 out of last 12 months a demand

Normal: in 4 to 8 out of last 12 months a demand

Slow: in less than 4 out of last 12 months a demand

Further split up of the 22.000 slow moving items:

17.000 weres not used in the last 12 months

4.000 were not used in the last 5 years!

Question 1

- Is your SKU list larger or smaller?
- Is there a large group of expensive slow moving parts?
- Do you encounter a lot of obsolescence?

Capital Equipment acquisition

- Is service and maintenance also included?
- Which information is provided / asked?
- Bill-of-Material
- Preventive Maintenance plan (time / runhours)
- Advised spare parts list? Which parts codes used?
- How to include this in an Maintenance / Asset Management Information System? (direct download?)

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Advised parts : To stock or not?

Local stocking:
- reduces lead time, yet
- increases capital costs
- often stocks are not (or never) used: obsolescence

Methods to assist in local stocking

- VED method (Vital, Essential, Desirable)
- EOQ method (economies of scale)
- (S-1,S) method + simplification

Should we stock a part? VED method

VED method (Vital, Essential, Desirable)

- Vital- significant impact on production, service or health / safety
- Essential – important for smooth operations, but some downtime is acceptable
- Desirable – items of less importance,

Issue: although simple and understandable method, it oversimplifies problem and does not take leadtimes nor variability into account

Should we stock a part? EOQ method

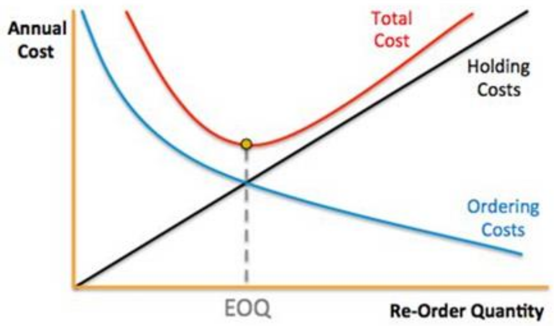
EOQ method - Economic order Quantity

Balances fixed ordering costs with stock holding costs and exploits economies of scale.

Stock if:
Fixed order costs > time to use · stock holding costs

In case of discount:

discount(%) price > time to use · stock holding costs



Should we stock a part? EOQ method

Example fixed order cost

Cost of placing (and delivering) an order S: 50 €
Time between two parts consumption: T: 6 months
Price of item: C 250 €
Stock holding cost rate h: 25% / year

Ordering 2 instead of 1 items:
Stock holding costs: 250 € x 6/12 x 25% = 31.25 €

Savings: one fixed order cost: 50 €

So order 2 instead of one.

EOQ = $\sqrt{2S/hCT}$ = 1.8 parts -> order 2

Should we stock a part? EOQ method

Example discount:

price single item 50 euro,
5% discount if order > 5.
Average time between use: 1 month,
Stock holding cost rate h: 25% / year

Discount obtained per item
$5\% \cdot 50$ € = 2.5 € >?

Extra holding costs compared to ordering 1
2.5 months$\cdot 25\%/12 \cdot 50$ € = 2.6 €

Should we stock a part? (S-1,S) model

Assumes demand is a Poisson process with rate λ, item price C, leadtime L and item fill rate target or stockout penalty *pen* and holding cost rate h.

Simplification: do not stock versus stock 1:
Expected costs stocking 1 part:$C \cdot h$

Expected penalty costs no stocking: $\lambda \cdot L \cdot pen$

Stock item if $\lambda \cdot L \cdot pen \,/\, hC > 1$ or taking logs:

Stock if $\mathbf{\log \lambda + \log L + \log pen - \log hC > 0}$

Works also for deciding where to stock (local or central, in that case L is the supply time)

Stocking Advice table: take sum of indices: if >0 stock else, do not stock

Consumption Rate		CsI
12 or more	per year	5
6 to 11	per year	4
3 to 5	per year	3
1.5 to 3	per year	2
1 per	8-15 months	1
1 per	15-30 months	0
1 per	2.5-5 yrs	-1
1 per	5-10 yrs	-2
1 per	10-20 yrs	-3
less than 1 per	20 yrs	-4

Purchase Cost ($)	PrI
< 250	6
250 - 500	5
500 - 1,000	4
1,000 - 2,000	3
2,000 - 4,000	2
4,000 - 8,000	1
8,000 - 15,000	0
15,000 - 30,000	-1
30,000 - 65,000	-2
65,000 - 125,000	-3
> 125,000	-4

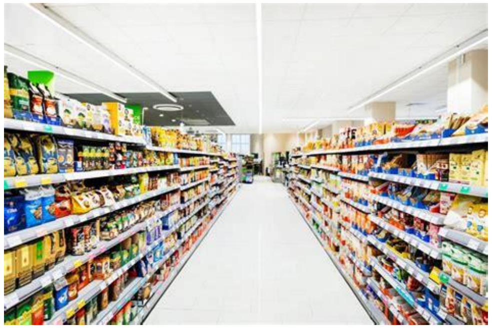
Penalty Cost ($ per day)	PenI
0 – 1,000	-2
1,000 – 7,500	1
7,500 – 30,000	4
30,000 – 60,000	5
> 60,000	6

Lead time			LtI
No lead time			-10
	<=1.5	day	-2
>1.5	<=3	days	-1
>3	<=6	days	0
>6	<=12	days	1
>12	<=21	days	2
>21	<=42	days	3
>1.5	<=3	months	4
>3	<=6	months	5
>6		months	6

Retailer approach to Stocking

- Retail margin is often percentage of costs C. Suppose profit margin is m, demand is D while holding cost rate is h.

  Margin obtained per year mDC
  Holding cost per year hC

  So stock if mDC > hC, or mD > h.
  If m = 10%, D = 2 / year, h = 25%:

  2 x 10% < 25%: so get rid of part

Retailers need demand. Slow moving spare parts are justified by high penalty costs.

Question 2

Methods are useful for determining to stock parts at a location. Interpretation varies.

- Several variants are possible.

- Do you / customers know their penalty costs?
  Should they have an idea about criticality?
  Can they assess need in case of redundancy?

- Science gives a quantification: too complex?

Demand data

- Quite often many parts have no recorded demands.
- A wholesaler approach would discard them
- Yet registering a low demand estimate, would keep them on stock when penalty costs are high

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Parts Pooling / leasing

- Vital parts may have very low demand rates (eg. once in 20 years)
- Example: turbine blades
- Are they unique or not? In latter case: can we pool them with others? Or lease the part?
- Three types of component pools observed: manufacturer (e.g. Fokker Abacus), third party (e.g. Railstock Forum) and user pools.

Which parts to share?

- Consumables – parts with a predictable demand: NO usually cheap.
- Insurance parts – expensive parts with low, unpredictable demand: YES
- Repairables – parts which may be repaired upon failure, usually expensive: YES
- Rotables – parts for which a predictable refurbishment to an as good as new condition is possible, e.g. aircraft engines: YES.

OEM dilemma

- Keeping stocks becomes problematic if parts are out of production, or produced rarely.

  Offering a pool is then beneficial for users, but how to differentiate service to non-participants?

  E.g. stocks are held for a group of companies. Next another company comes in with an urgent demand, what to do?

- Charge higher price?
  Deliver only if enough stock (customer differentiation)?
  Charge entrance fee for entering pool?

How to allocate costs between parties?

- Research by Frank Karsten (TUE)

  A stable cost allocation (= one in which no party is better off by defecting) is obtained if cost are allocated proportional to average usage

- Yet it assumes that the average usage is known, and correctly revealed to all parties.

- Extensions are needed to determine location of stocks and to take care of changing situations (equipment discarded by one company)

Other concepts

- Exchange scheme – an alternative part is supplied when a part is undergoing a repair.
- Pay per use: pool manager provides stocks and user pays a fixed fee per use of system (pay per hour)
- Return schemes – parts can be returned after x years in case of no demand
- Parts supply contracts – users pay for repair and parts supply services with a *guaranteed availability*.

Parts Obsolescence

- Suppliers may stop supplying parts, possibly after a Final Buy -> risk for sustaining system
- Supplier risk analysis and tool developed for Fokker Services. Variable leadtimes may be an indicator for risk as well as long time since last order.
- Idea: place more small orders, keep contact with suppliers.
- Li et al (2017), Hekimoglu et al (2019)

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Stock control

- How to set min-max levels for stocks?
- One needs demand estimates, leadtimes, part prices, importance (criticality) and objectives
- Objectives: availability (fill rates) or total costs
- Objectives can be per part or system

Stock control - demand

- Predictable demand, eg. from preventive maintenance, can be ordered in advance

  No need to stock items for this reason

  Flag these demands: is that done?

- Stocks should be held for unpredictable demand

- Demand needs to be forecasted

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Why Forecasting Spare Parts Demand?

- Observation from practice: large mismatches between stocks and demands:

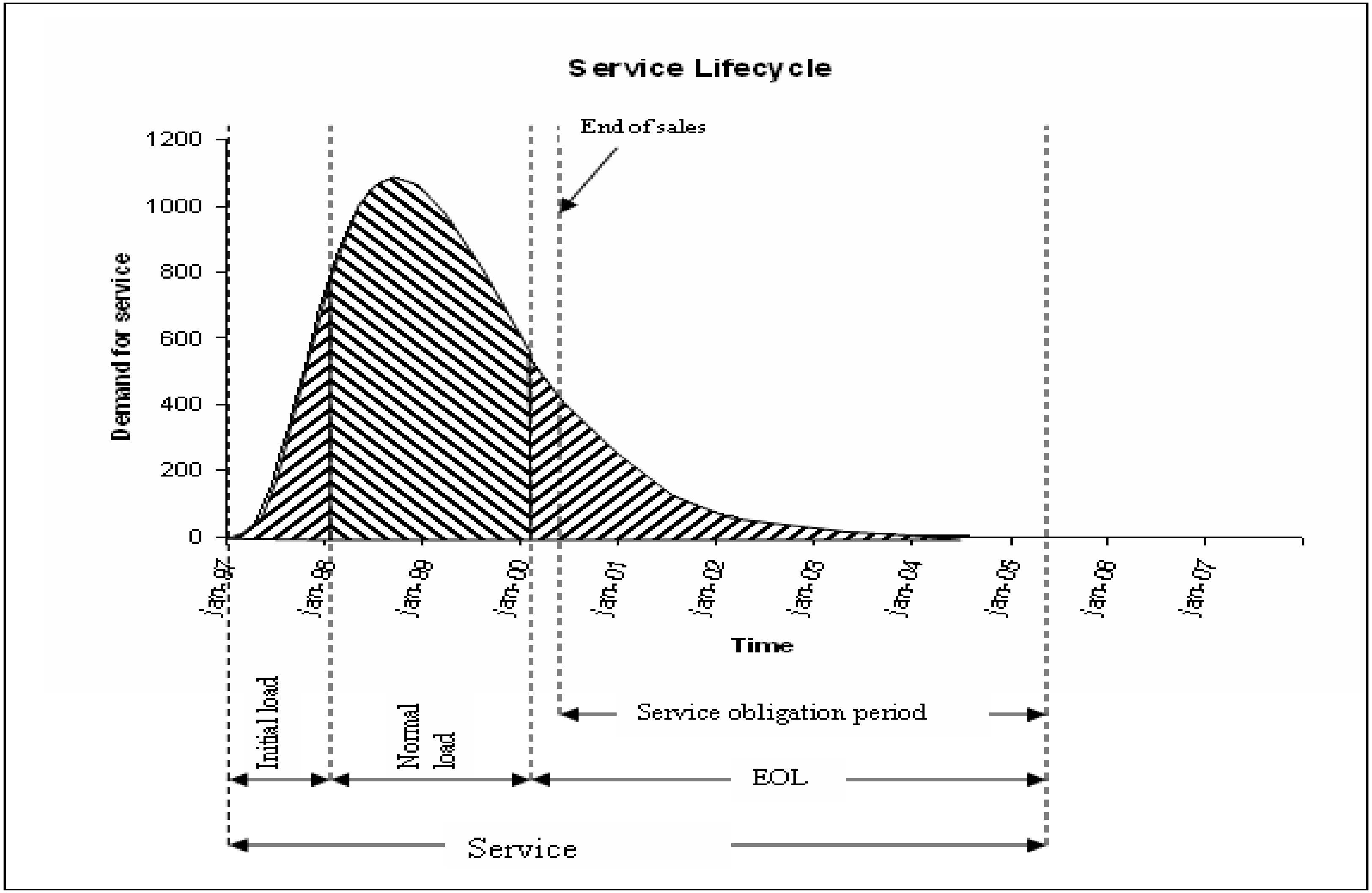
  - large numbers of parts are scrapped because they are no longer needed and

  - many emergency shipments to solve stock outs.

- Initial ordering may yield part stocks for a very long time

- Also Last-Time-Buy at the End-of-Life phase is difficult.

Parts lifecycle



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Spare Parts demand forecasting

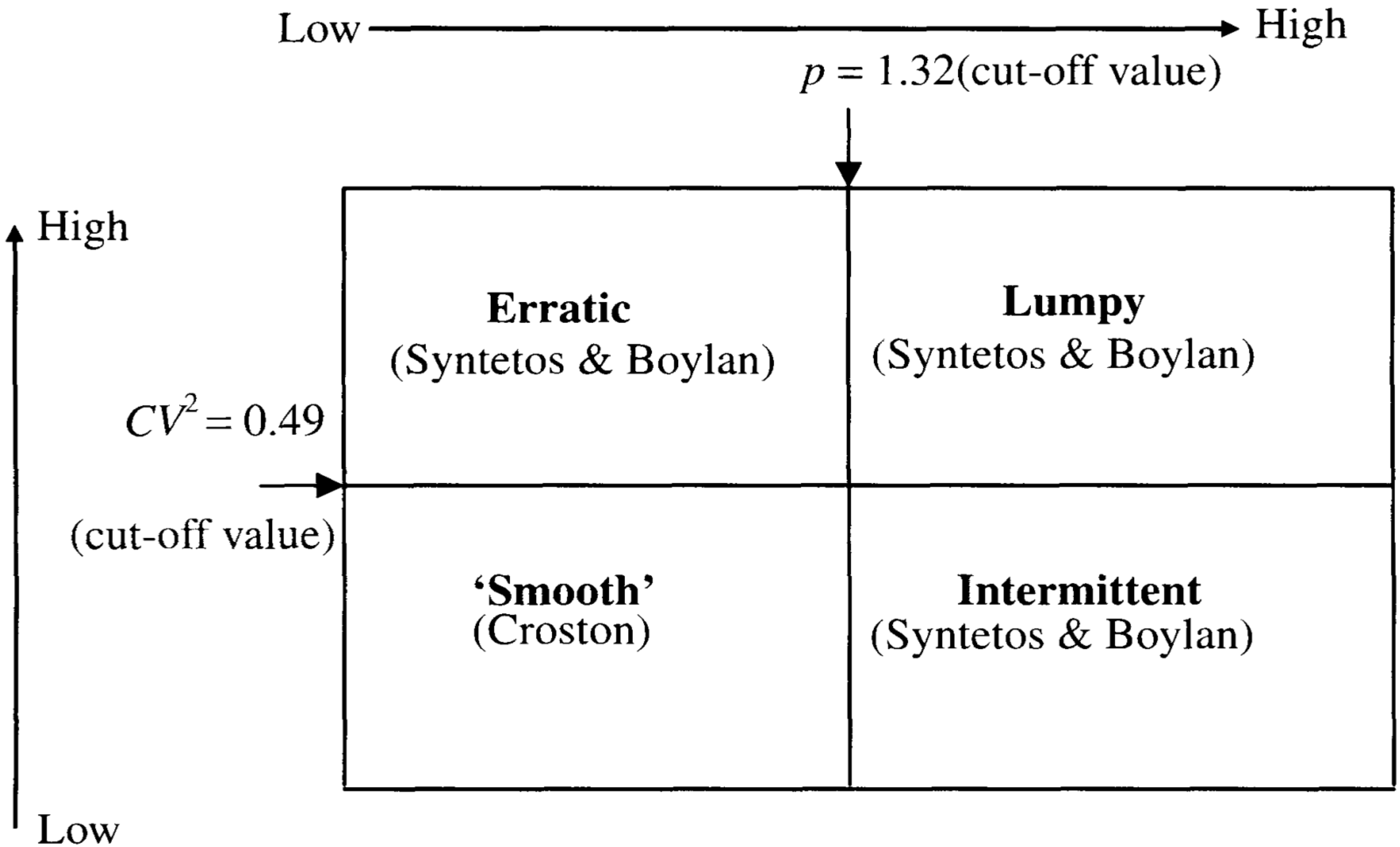
- Well studied problem

- Typical spare parts demand characteristics :
  intermittent – long periods between demands
  lumpy – suddenly high demands

  general types
  erratic – demands change a lot
  smooth – demand changes small
  seasonal / trend

- Many methods proposed. Recently several machine learning methods introduced, but do they work?

Demand classification



CV^2 – coefficient of variation of positive demands

p – interval between positive demands

Example of spare parts demand

Aug-01	Jul-01	Jun-01	May-01	Apr-01	Mar-01	Feb-01	Jan-01	Dec-00	Nov-00
0	**50**	0	0	0	0	0	0	0	0
Oct-00	Sep-00	Aug-00	Jul-00	Jun-00	May-00	Apr-00	Mar-00	Feb-00	Jan-00
0	0	0	0	0	0	0	0	0	0
Dec-99	Nov-99	Oct-99	Sep-99	Aug-99	Jul-99	Jun-99	May-99	Apr-99	Mar-99
0	0	0	0	0	0	0	0	0	0
Feb-99	Jan-99	Dec-98	Nov-98	Oct-98	Sep-98	Aug-98	Jul-98	Jun-98	May-98
0	0	0	0	0	0	0	0	0	0
Apr-98	Mar-98	Feb-98	Jan-98	Dec-97	Nov-97	Oct-97	Sep-97	Aug-97	Jul-97
0	0	0	0	**1**	**1**	0	**5**	0	0
Jun-97	May-97	Apr-97	Mar-97	Feb-97	Jan-97				
0	0	0	0	0	0				

Table 2.2: The demand of item 1

Spare Parts demand forecasting

- Which method do you use?:
- Methods embedded in your ERP (SAP) system
- A specific forecasting system (Slimstock)
- Yet can that package also advice on “best” reorder points and order up to levels (or min / max stock levels). Which methods does it use?

Forecasting models in SAP

Moving average models:

- normal moving average model (G)
- weighted moving average model (W)

First order exponential smoothing models:

- constant model (D)constant model with adjustment of the smoothing factors (K)
- trend model (T)
- seasonal model (S)
- seasonal trend model (X)

Second order exponential smoothing models:

- second order exponential smoothing (B)
- second order exponential smoothing with adjustment of smoothing factors (O)

Other models:

- Seasonal weighting model (R)
- Automatic model selection (J)
- No forecasting model out of the SAP-system, but an external forecasting model (N)
- No forecasting model at all (0)

Research: compare forecasting methods

- Several methods considered
  SES, Croston, SBA, TSB, (Statistical)
  Willemain (empirical)
  Machine learning (MLP, LightGBM)
  Composite method (combines several methods)

- Generate data with a typical demand pattern
  Assess best method for each pattern
  Use this in the ensemble method and test on real data sets

- Compare various demand distributions (gamma, normal, negative binomial)

Single Exponential smoothing (SES)

- Basic equation $$F_t = \alpha D_t + (1-\alpha) F_{t-1}$$

  where D_t is actual demand and F_t the forecast and α is the smoothing parameter

Croston's method for intermittent demand

- Estimate size of demands Z_j using ES:

  $Z_j = (1-\alpha)\, Z_{j-1} + \alpha\, Y_j^*$

- and time between demands P_j

  $P_j = (1- \alpha)\, P_{j-1} + \alpha\, Q_j^*$

- Croston assumes geometric distr. time between demands, an normally distributed demand size and independence between the two.

- Demand estimate for period j+h: Z_j/P_j independent of h.

Syntetos-Boylan (SBA)

- Croston’s method is biased $E(Z_j/P_j) \neq EZ_j \,/\, EP_j$
- Propose a correction to make it approximately unbiased SBA (2005, 2006). Teunter and Saani also publish an improvement (2009) to take care of obsolescence
- Advantages: easy to apply, better forecast than ES
- Shortcomings of these approaches:

  - provide only mean demand, still need distributions
  - reactive approach

Non-parametric approaches

- Willemain et al. (2004) –

  applies bootstrapping (sample from observed demands)

  uses a Markov chain for time between demands (do we switch from demand to non-demand (D>N) or to we have demand after demand (D>D), etc).

  and jittering (pertubes demand sizes) to obtain a leadtime demand distribution

- Patented and claimed to perform quite well.

Data sets

- Four generated data sets of 5 years of demand for lumpy, intermittent, erratic and smooth demand

- Four industrial data sets
  - British airforce (BRAF)
  - Manufacturing company (MAN)
  - Auto producing company (AUTO)
  - Refinery (OIL)

- All monthly demand data of some 5 years

- Data split in training set (70%) and test set (30%), however, sometimes no demand in test set.

Results

- Objective: forecasting (focuses on mean demand) or stock control (focuses on tail)

- Forecasting: MeanSquaredError, Mean Absolute Scaled Error (MASE), RootMeanSquared Scaled Error

- Stock control: trade-off inventory vs (total) fill rate

- Methods: SES, Croston, SBA, TSB, Neural Network, Light GBM, Willemain
  Composite: selects best one based on training data

- Check with industrial / simulated data sets

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Forecast performance

Dataset	Measure	Method								
		Croston	SES	SBA	TSB	Willemain	MLP	LightGBM	Comp. (Avg)	Comp. (Total)
MAN	MSE	12940.104	13327.738	**12921.667**	13293.605	13111.759	13259.361	13901.474	13354.976	12979.859
[I(0.4), L(0.6)]	MASE	2.499	2.335	2.439	**2.321**	2.594	2.997	3.063	2.399	2.498
	RMSSE	5.329	**5.215**	5.304	5.223	5.304	5.451	5.848	5.267	5.337
BRAF	MSE	**199.69**	201.19	199.807	200.945	199.775	202.684	207.561	200.31	**199.69**
[I(0.6), L(0.4)]	MASE	2.08	1.996	2.001	**1.956**	2.344	2.355	2.354	2.045	2.08
	RMSSE	3.3	**3.283**	3.289	3.287	3.365	3.372	3.413	3.3	3.3
AUTO	MSE	86.344	84.445	83.089	90.061	84.182	**80.635**	115.453	83.601	83.23
[S(0.5), I(0.27),	MASE	0.788	0.78	**0.777**	0.792	0.899	0.794	0.94	0.852	0.849
E(0.16), L(0.07)]	RMSSE	1.721	1.71	1.71	1.728	1.863	**1.703**	2.07	1.803	1.8
OIL	MSE	138.605	**129.91**	138.321	130.639	132.939	152.998	160.407	138.773	138.605
[I(0.9), L(0.1)]	MASE	1.998	1.667	1.849	**1.649**	2.319	2.054	2.089	1.707	1.998
	RMSSE	1.666	**1.562**	1.635	1.566	1.726	1.671	1.702	1.595	1.666

Results rounded to three decimals. The best scores is highlighted for each dataset and measure.

Table 7: The forecasting accuracy of all methods on each dataset.

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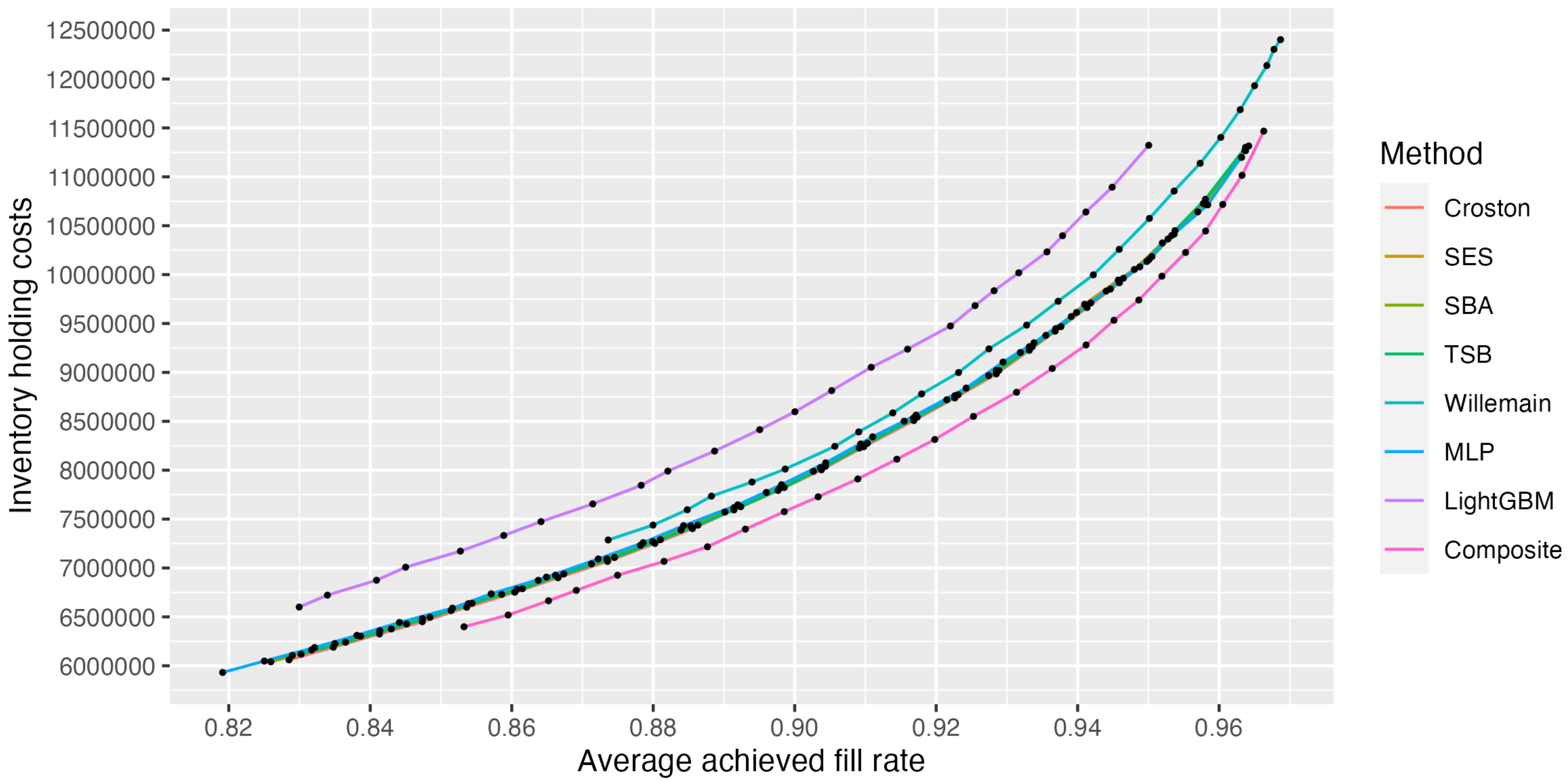
Best Method per data set

Dataset	Forecasting accuracy measures			Inventory performance measures			
				TFR-AFR trade-off		AFR-Holding costs trade-off	
	MSE	MASE	RMSSE	Average AFR	Total AFR	Average AFR	Total AFR
SIM1	W	SBA	SBA	W, LGBM	W, LGBM	MLP	MLP
SIM2	MLP	TSB	SES	Crost, SES, SBA, TSB, W, MLP, LGBM	SES, TSB, W	Crost, SBA	Crost
SIM3	SBA	SBA	SBA	W	W	W	W
SIM4	MLP	TSB	SES	Crost, SES, SBA, TSB, W, MLP, LGBM	SES, SBA, TSB, W, MLP, LGBM	SES, TSB	Crost
MAN	MLP	TSB	SES	W	MLP, LGBM	W	MLP
BRAF	Crost	TSB	SES	SES, TSB, W	Crost/Com, SES, SBA, TSB, W, LGBM	W	Crost/Com, SBA
AUTO	MLP	SBA	MLP	W	W, Com	Com	Crost, SBA, Com
OIL	SES	TSB	SES	SES, SBA, TSB, W, Com	Crost/Com, SES, SBA, TSB, W, LGBM	Com	Crost/Com, SBA

Crost stands for Croston, W stands for Willemain, LGBM stands for LightGBM, and Com stands for Composite method.
Crost/Com indicates the case where the Composite method reduces to the Croston method.

Table 9: Best methods for each dataset based on the selected performance measure.

Inventory – fill rate trade-off curves



Tradeoff curves for the inventory control measures on the AUTO dataset

Conclusions Forecasting

- Best method depends on purpose and classification
- Gamma distribution works best to determine reorder points
- Composite method works well, not always best
- Shortage of data is important problem: longer data ranges are needed, but not available
- Maintenance based planning and Installed Base planning are alternatives
-

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Installed base - IB

- The collection of all products / systems a company (OEM) has produced or sold
- Further subdivision – customers with which OEM has contract
- Indicator for spare parts demand

Installed Base forecasting

- If a plane undergoes a C-check and in C-checks you always replace component 3622Y1, you can do a prediction of demands from the planning of C checks.

- Approach: remove demands from C – checks from data (in case registered). Estimate unplanned demand rates using a Poisson process.

- In forecast combine both.

- Issue: much PM consists of checking status of elements and replacement in case of a bad condition. Hence demand is stochastic.

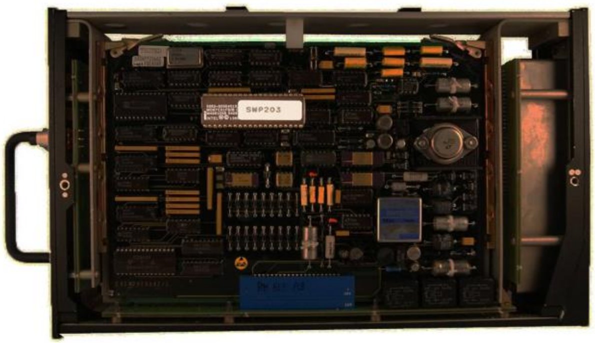
Maintenance based planning

- In case there is statistical info on parts need for repairs. Spare parts demand can be derived from the planning of repairs (in case leadtime is short).

Data analysis on completed repairs of components of a given type:

P/N	Usage prob.	Quantity
MA9541	31.30%	1 (31.30%)
40-882-208	17.39%	1 (15.65%), 2 (1.74%)
...		
40-693-518	4.35%	2 (4.35 %)
...		
KIP1012	0.87%	1(0.87%)
KIP1060	0.87%	1(0.87%)
...		

Excerpt of statistical BOM for component type P0KK-1010-021 (based on 115 repairs).



IB and repairs- evaluation

- Nr. of repair requests R_t known ahead in time. Given $R_t = r$, number of parts needed is binomially distributed with parameter pr,

  compare with SES and a Poisson distribution using empirical data of Fokker Services repair shop

cost	With maintenance plan	Poisson	% cost Red.
Total cost	558147.6	625431.2	10.80%
Ordering cost	427300	354080	-20.70%
Inventory holding cost	70537.6	82496.2	14.50%
Penalty cost	115120	237700	51.60%
Salvage value	54810	48845	-12.20%

you foresee large demands, hence less stock-outs and reduce stocks in case of no repairs

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Item versus System Targets

- Typical target setting: achieve 95% fill rate over all spare parts.
- How to translate this to individual items?
- Easiest way: give each part the same fill rate target
- Yet parts differ in costs, leadtime and demand
- Optimal way: non linear programming problem.

Practical solution

- Define classes and set targets per class
- Classes based on demand, price, (leadtime)
- How to set targets: often manual, yet this can be optimized. This can reduce inventory value with several % (research for Gordian by Saveli (2023)

Example

P > 1000€	Target Stock Availabilty	Target Stock Availabilty	Target Stock Availabilty
100 € < P < 1000 €	Target Stock Availabilty	Target Stock Availabilty	Target Stock Availabilty
P < 100 €	Target Stock Availabilty	Target Stock Availabilty	Target Stock Availabilty
Price P Demand D	D > 12 per year	3 /year < D < 12 per year	D < 3 per year

Conclusions

- There are quite some inefficiencies in parts inventories
- Most problems start at the purchase, as then parts are bought and contracts are arranged.
- It seems that new contract forms are attractive, however, introduction depends on power positions in supply chains.
- Data and tools are needed to make good assessments!

Statements

- OEMs should offer more parts pools or parts supply contracts to reduce costs for users and to maintain a long-term relation ship.

- This relationship may also lead to selling upgrades packages.

- Users: do not buy parts, but the right to get delivered on time.
  Acknowledge that this costs money.

  Certainly avoid unique systems with unique parts, because pooling these is not attractive for OEMs.

(S-1,S) model

Demand: Poisson process with rate λ

Replenishments – after fixed leadtime L

Cost structure – holding inventory costs money per item per time unit

Inventory position = stock on hand + outstanding orders – backlog

Control policy: Base stock Policy:
maintain inventory position S
Make a replenishment order upon each demand

(S-1,S) model

Analysis: $IL(t+L) = IP(t) - D(t,t+L) = S - D_L$

Where IL = inventory level = stock on hand – backlog

D(t,t+L) – demand during time t,t+L
is Poisson distributed with parameter λL,
hence

$$P(D_L = k) = \frac{(\lambda L)^k}{k!} e^{-\lambda t}, k = 0,1,2,...$$

And average stock $E(IL) = S - E\min(D_L, S) \approx S - \lambda L$

Fill rate $= P(D_L < S) = \sum_{k=0}^{S-1} \frac{(\lambda L)^k}{k!} e^{-\lambda L}$

(S-1,S) model - example

Consider a spare part with
Average demand λ = 3 x year
Costs c = 1000 euro
Leadtime L = 3 month
Holding cost rate h = 20% / year

What should the best basestock S be?

Can only be answered if we have target or cost for lack of service.

E.g. 90% of all requests have to be met from stock on hand (filll rate target)
Or if we pay a cost c_d per time unit not having the part when needed

(S-1,S) model - example

Consider costs if S = 1:

what is the probability of having 0 demands in three months: $P(D_L = 0)$?

L = 3 months = 0.25 year & λ = 3 / year

Hence D_L Poisson distributed with parameter λL = 0.75 and $P(D_L=0) = \exp(-0.75) = 0.47$,

so with probability
$P(D_L > 0) = 1 – P(D_L=0) = 0.53$ we have at least one other demand in the 3 months!

According the fill rate = 47%:if that not enough: increase S.

Observed pools

- ProRail's RailstockForum
  Pool of rail parts kept by RailPro, availability is paid by ProRail

- Fokker's Abacus scheme
  focus on repairables and rotables
  pool + exchange scheme

- AF/KLM component pool for other airlines
  as Fokker's, but limited in set-up.

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Intermezzo: RailPro's issues

- Before split up of NS into NS, ProRail, etc, RailPro was the parts supplier of all maintenance operators for NS.

- RailPro was made independent and bought by VoestAlpine. It made money on selling parts. As a result it did not replenish very slow moving parts.
- A switch failure at Alphen a/d Rijn lasted three months because of lack of replacement switch.
- ProRail decided to pay RailPro for having certain stocks: RailstockForum

Which type of pool is best - user?

- Users do not trust each other in the exceptional case parts are needed.
- How to avoid over usage and to allocate costs?
- Users may have different systems, allowing only few parts to be pooled. Hence much overhead for a partial solution.
- What to do if some users abandon systems?
- In case of large industrial complexes where some factories are sold to 3rd parties it is interesting to try out a pool concept.

Which type of pool is best – 3rd party / OEM?

- A third party may provide guarantees in case of part shortage – yet faces high financial costs for setting up a pool and in case companies withdraw.

- The OEM has most experience with parts, has the right identification, knows and wants to learn failure rate and has most opportunity to supply part.

- Yet the OEM often wants to supply new systems rather than providing parts!

- Combination with repairable pool is successful!