A systemic approach for spare parts management in a Performance Based Contract: a case study in the aviation domain

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Abstract. The supply of spare parts has a crucial role in maintenance activities, especially in industries with strict availability requirements. In the context of spare parts management, several strategies consist of taking advantage of cooperative or commercial agreements, moving from stand-alone scenarios to inventory pooling. The Performance Based Contracts (PBCs) represent valuable management strategies, based on the risk-pooling concept. This paper proposes an innovative analytic approach based on METRIC (Multi-Echelon Technique for Recoverable Item Control) to model a specific PBC. The paper explores the contracts according to the Supplier’s perspective in order to understand and quantify the effects of PBC on traditional inventory management. The model aims at defining technical contractual details that maximize the profit for the Supplier, respecting availability constraint and budget constraint of the Customers. A case study in the aviation domain, solved by a genetic algorithm, shows the outcomes of the model in a multi-echelon, multi-item, single-indenture system.

Keywords: spare parts; inventory; METRIC; multi-echelon; risk pooling.

Notations

A_j^*	fleet availability at the j - th site
A_j^t	fleet target availability at the j - th site
B_j	Customer’s Budget constraint
C_{ij}^{ahc}	ad hoc agreement unit repairing cost of item i for the j - th site
C_i^{obs}	unit obsolescence cost of item i
C_i^{rep}	unit repairing cost of item i at CD
C_{ij}^{tr}	unit transport cost of item i for the i - th site
FH_j	fleet flight hour at the j - th site
i	item index, i = 1, …, I
j	site index, j = 0, 1, …, J. j=0 represents CD
M_j	minimum number of required aircraft at the j - th site
m_{ij}	yearly demand mean value of item i at the j - th site
N_j	number of aircraft at the j - th site
O_i	mean time of order and ship of item i from CD to j - th LW
P_i	market value of item i
r_{ij}	repairing rate of item i at the j - th site
s_{ij}	stock level of item i at the j - th site
T_{ij}	mean time of repairing of item i at the j - th site
x_{fee}	access flight hour fee to access the contract
x_{rent}	percentage rent tax for a spare part at LW

1. Introduction

Spare parts management acquires a crucial role in industry, as a key element to guarantee reliable and stable performance. Aviation is one of the industries where high-availability requirements and high-costs of spare parts push the airlines to manage accurately their inventory, focusing on strategies able to minimize inventory costs and not compromising the fleet availability. On this path, several contractual strategies have been adopted, based on different contractual integration levels and number of participants, as conceptually shown in Figure 1. In the last decades, moving from traditional stand-alone management strategies, several contractual agreements based on cooperative strategies (ad hoc cooperation, cooperative and commercial pooling) gained an increasing research and industrial interest (Kilpi et al., 2009). The tendency to outsource the ownership of spare parts motivated an increasing attention on commercial pooling, which involves two or more companies and represents the tightest management strategy in this context. In a commercial pooling, the maintenance supplier is commonly another airline that benefits of risk compensation, considering the high unlikelihood of simultaneous breakdowns of high-availability parts. Since multiple fleets share the same spare parts, total stocks in the system are lower if compared to a situation where each airline manages its own stock. This paper aims at structuring a specific commercial pooling contract: the Performance Based Contract (PBC).

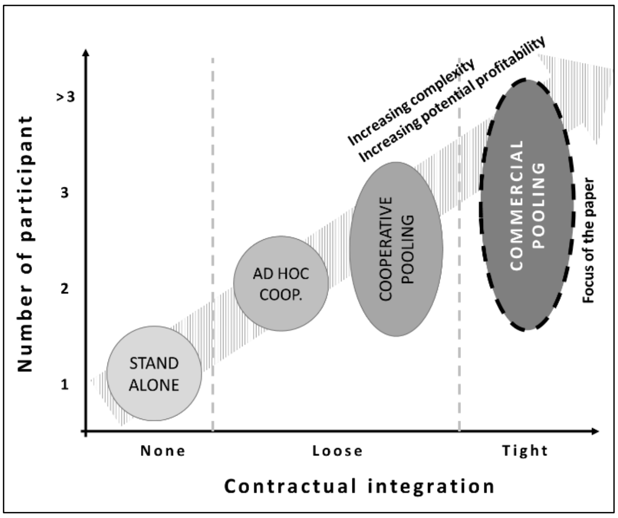

Figure 1: Framework of cooperative strategies for spare parts management.

Adopting a systemic perspective in line with METRIC (Multi-Echelon Technique for Recoverable Item Control) (Sherbrooke, 1968) this paper develops an innovative analytical formulation to model the contract and optimize the stock level, following the Supplier’s perspective. The remainder of the paper is organized as follows. Section 2 describes research and industrial interest in METRIC. Furthermore, it presents some examples of contractual agreements in nowadays airline industry. Section 3 describes the features of the PBC discussed in the study. Section 4 presents a METRIC-like formulation to model analytically the PBC, validated by a case study presented in Section 5. The Conclusions summarize the outcomes of the study, the limitations of the approach and the potential for further research.

2. Literature Review

Starting from 1970s, the METRIC acquired promptly a relevant attention in the field of spare parts management (Sherbrooke, 1968). The target of METRIC consists of distributing spare parts in a multi-echelon system with respect to availability and budget requirements. From its original formulation, METRIC has been widely adopted and customized to specific problems: (e.g.) multi-item networks (Muckstadt, 1973), multi-indenture items (Sherbrooke, 1986), different demand models (Lee and Moinzadeh, 1987), systems with variable TAT (Turn Around Time) (Alfredsson and Verrijdt, 1999), multi-transportation modes (Patriarca et al., 2016b), lateral transhipment among sites of the same echelon (Patriarca et al., 2016a). Other approaches consisted of integrating the level of repair analysis (Driessen et al., 2014), the capacity constraints of the maintenance centres (Selçuk, 2013; Sleptchenko et al., 2002), and the certification skills (Costantino et al., 2013). Several applications prove the relevance of METRIC in different high-availability industries: defence sector (Van Der Heijden et al., 2013), naval fleet (Rustenburg et al., 2000), weapon industry (Sun et al., 2009), military aviation (Costantino et al., 2010) and civil aviation (Sun and Zuo, 2010).

The reasons for the wide range of successful applications of METRIC rely on its conceptually simple and customizable structure. Furthermore, it gains attention in industry since its systemic perspective generates results in line with common managerial variables. More in detail, inputs and outputs of METRIC comply with information traditionally managed by decision-makers, i.e. availability and cost requirements for the whole site - or even system - rather than on data specific of a single item. METRIC is also able to determine the budget needed to increase system’s availability, or assess the effects of variations of system’s parameters. Therefore, METRIC can be used to model a commercial contract and compare it with a different strategy. In terms of spare parts management, originally, there was no evidence of formal contracts in real scenarios, but just courtesy behaviours among airlines selling or borrowing spare parts to face emergencies (Kilpi et al., 2009). Formal contracts have been developed following the birth of the International Airlines Technical Pool association (IATP), for collaborative purposes among KLM, Sabena and Swissair. Currently, several contracts involve producers (including Airbus, Boeing, Rolls Royce) and airlines of different size (Fritzsche, 2012).

The approach discussed in this paper considers and models the Supplier’s decision-making process, considering the effects of the contract on both the Supplier’s and the Customer’s inventory. This paper aims at developing a methodology to assist the decision-maker of the Supplier company to set the PBC and defining the most advantageous contractual specifications that allow respecting the Customers’ needs and maximising the Supplier’s profits.

3. Description of the analysed contract

The PBC discussed in this paper considers two different actors: the Supplier company (only one) and the Customer companies (one, or more than one). The PBC aims at reducing ownership costs of spare parts for the Customers, and finding a solution to generate profits for the Supplier, because of risk compensation due to sharing spares parts with multiple fleets.

In the standalone scenario, the Customer owns all required spare parts to guarantee fleet’s service level and manage its maintenance activities. These latter depend on different certification levels, specific for each item. In case the Customer cannot perform the maintenance activities, it has to require an ad hoc intervention to a third-part Maintenance Company, based on ad-hoc cooperation, rather than on a long-term cooperation. In this case, transportation and obsolescence costs are still managed by the Customer company.

In the PBC scenario, the Supplier has a dominant role in the two-echelon supply chain. It requires paying a yearly access fee to each Customer in order to have the chance of signing the contract. This access fee is proportional to the flight hours of the Customer's fleet. The contract implies the Supplier owning at the Central Depot (CD) all spare parts necessary to comply with the requirements of each Customer. In addition, the PBC allows the Customer to have a limited stock in its Local Warehouse (LW), in order to permit a prompt response to failures. In case the Customer can perform repairing activities, maintenance is entrusted to it, avoiding a turn around to CD.

The Customer does not pay ownership costs for spare parts. However, it pays the Supplier a monthly rent fee for each item stocked in the LW. This rent fee is considerably lower than the ownership cost of spare parts. When a failure occurs in the LW, the Customer can substitute the inefficient item with an efficient one, in case it has a spare part stocked and actually available. In this case, the Customer will have the responsibility to repair the item and replenish its local stock autonomously. If the Customer does not have the required certification to accomplish the repairing activities (depending on r_{ij}), the item is sent to the CD. After O_{ij}, order and ship time, an efficient item is sent back to the Customer to replenish its local inventory in its LW. On the contrary, in case the Customer has decided not to stock the required item in the LW, but it can repair the inefficient item, it will restore the inefficient aircraft after its repairing time T_{ij}. In case $(1 - r_{ij})$ it has not the proper certification, it will send the item to the CD and wait O_{ij} before obtaining an efficient item back. For each item, an (S-1, S) replenishment policy enables the shipment or repairing of a substitute efficient item anytime there is a failure, relying on a continuous stock review system where an order is issued anytime the inventory lowers by 1 item.

4. The analytical model

The model developed in this paper relies on METRIC, adapting its formulation to describe the features of the commercial contract (Sherbrooke, 1968). Based on the traditional assumption of m_{ij} following a Poisson distribution and according to Palm's theorem, the expected value of the pipeline of i – th item for the Supplier at CD (j=0) is a Poisson distribution with expected value $E[\upmu_{i0}]$.

$$E[\upmu_{i0}] = Var[\upmu_{i0}] = m_{i0}T_{i0} \tag{1}$$

where m_{i0} represents the demand at CD, which is the sum of the demands of items not repairable at the sites (2):

$$m_{i0} = \sum_{j=1}^{J} m_{ij}(1 - r_{ij}) \tag{2}$$

The Expected Back Order (EBO) describes the probability that the demand generates a back order for the assigned stock. A back order represents a case when the assigned stock level s is not enough to manage a request m (probability that $m > s$), which remains unsatisfied. Under the assumption of unlimited repair capabilities, EBO at CD can be expressed as follows (3), where $Pr\{\upmu_{i0}\}$, according to METRIC's traditional formulation represents a Poisson distribution with parameters equal to the pipeline $E[\upmu_{i0}]$:

$$EBO(s_{i0}) = \sum_{\upmu_{i0}=s_{i0}+1}^{\infty} (\upmu_{i0} - s_{i0})\, Pr\{\upmu_{i0}\} \tag{3}$$

Similarly, considering the finite repair capabilities of the local warehouses, it is possible to obtain the expected value of the pipeline $E[\upmu_{ij}]$ (4) and the respective $EBO(s_{ij})$, for each j – th Customer, at the j – th LW (5):

$$E[\upmu_{ij}] = m_{ij}r_{ij}T_{ij} + m_{ij}(1 - r_{ij})\, O_{ij} + f_{ij}(EBO(s_{i0})) \tag{4}$$

where $f_{ij} = \frac{m_{ij}(1-r_{ij})}{m_{i0}}$ verifies $\sum_{j=1}^{J} f_{ij} = 1$.

$$EBO(s_{ij}) = \sum_{\upmu_{ij}=s_{ij}+1}^{\infty} (\upmu_{ij} - s_{ij})\, Pr\{\upmu_{ij}\} \tag{5}$$

The availability of an aircraft at a LW can be expressed as the series system of the availability of the considered items (6):

$$A_j = \prod_{i=1}^{I} \left(1 - \frac{EBO_{ij}}{N_j}\right) \tag{6}$$

Considering the potential redundancy of aircraft at the sites, a failure on an aircraft reduces the site availability only if the number of available aircrafts is lower than the minimum required. This situation can be modelled as an active redundancy: for each j – th LW, a redundant system in which M_j of N_j must be operating (7):

$$A_j^* = \sum_{n_j=M_j}^{N_j} \left(\binom{N_j}{n_j} (A_j)^{n_j} (1 - A_j)^{N_j - n_j} \right) \tag{7}$$

Following the Supplier's perspective, it is possible to define a target function, which expresses the Supplier's profits as the difference between the income deriving from the rent of spare parts at each LW and the access fee paid by the customers, minus the purchase cost of spare parts, the repairing cost and the obsolescence costs.

The optimization process, which consists of maximizing (8), is subjected to an availability constraint for each LW (9), and a cost constraint (10). Two additional constraints have be to satisfied as well, i.e. $x_{rent} > 0$, $x_{fee} > 0$.

The cost constraint (10) expresses the need for the Supplier to find a stock allocation that is economically advantageous for the Customer. More in detail, the cost for spare parts management of stock assigned to Customer by the PBC optimization process shall be minor than the costs related to Customer's stock, if not joining the contract s'_{ij}. If not joining the PBC, the Customer would pay another company the repairing costs for ad hoc interventions of item that cannot be repaired at the site. Nevertheless, if the Customer would join the PBC, the Supplier will pay obsolescence and repairing costs, as detailed in (10). Since the PBC does not imply any change in current repairing certification levels (and related maintenance activities) for the Customer, the repairing cost of items repairable at the LW are not included in this constraint.

$$\begin{aligned} s_{ij}, x_{rent}, x_{fee} : MAX \Bigg(& \sum_{j=1}^{J} \sum_{i=1}^{I} s_{ij}\, P_i\, x_{rent} \\ & + \sum_{j=1}^{J} FH_j\, x_{fee} \\ & - \sum_{j=0}^{J} \sum_{i=1}^{I} s_{ij} P_i \\ & - \sum_{j=1}^{J} \sum_{i=1}^{I} m_{ij} (1 - r_{ij}) C_i^{rep} \\ & - \sum_{j=0}^{J} \sum_{i=1}^{I} s_{ij} C_i^{obs} \Bigg) \end{aligned} \tag{8}$$

$$A_j^* > A_j^t \tag{9}$$

$$\begin{aligned} \sum_{i=1}^{I} \left(s_{ij}\, P_i\, x_{rent} + 2m_i\, (1 - r_i)\, C_{ij}^{tr} \right) + FH_j\, x_{fee} \\ < \sum_{i=1}^{I} \big(s'_{ij}\, P_i \\ + m_{ij}\, (1 - r_{ij})\, C_{ij}^{ahc} \\ + s'_{ij} C_{obs_i} \big) \quad \forall\, j = 1, \ldots J \end{aligned} \tag{10}$$

Note that s'_{ij} is the outcome of a minimization process (11) of the spare parts management costs paid by the Customer, subjected to an availability constraint (9):

$$\begin{aligned} s'_{ij} : min \Bigg(\sum_{i=1}^{I} s_{ij}\, P_i + m_{ij}\, (1 - r_{ij})\, C_{ij}^{ahc} + s_{ij} C_{ij}^{obs} \\ + 2m_{ij}\, (1 - r_{ij}) C_{ij}^{tr} \Bigg) \end{aligned} \tag{11}$$

Note that the comparison with the Customer's optimum stock level (10) may be replaced by a budget constraint B_j specified by the Customer itself, based on its current stock allocation and thus potentially different from the optimum obtained by the application of METRIC. In this case the constraint in (10) is expressed by (12):

$$\begin{aligned} \sum_{i=1}^{I} \left(s_{ij}\, P_i\, x_{rent} + 2m_i\, (1 - r_i)\, C_i^{tr} \right) + FH_j\, x_{fee} \\ < B_j \end{aligned} \tag{12}$$

5. Case study

The case study presented in this paper focuses on a PBC among a Supplier and 5 Customers, in a two-echelon system. Therefore:

- J= 5, j = 0 CD, j = 1,…, 5 LW (six sites)
- I=10 (10 items)

The aim of the model consists of determining the stock allocation for each site and determine the access fee x_{fee} and rent tax fee x_{rent}, starting from the input data included in Appendix A. The optimization process relies on a genetic algorithm, based on MI-LXPM. This latter adopts the self-adaptive Laplace Crossover operator (LX) and the tuneable Power Mutation operator (PM) to increase randomness and consequently the possibility of achieving a global optimum. This algorithm is particularly relevant in case of integer variables (stock allocation), but it can be adopted for non-integer ones (access fee and rent tax) using a different scaling parameter (Deep and Thakur, 2007). The algorithm adopts binary tournament selection operator as reproduction operator to increase randomness of generations. For this case study it has been fixed a tolerance in terms of function's evaluation, i.e. 1e-10 (two points are equal if the difference in terms of function value is lower than the tolerance) and a tolerance in terms of constraints' evaluation, i.e. 1e-7 (constraints are respected if the difference between the desired values is lower than the tolerance).

The algorithm defines the access fee ($x_{fee} = 1{,}010$€/FH) and unit rent fee ($x_{rent} = 1{,}0423$€/month) and the optimum stock level for each item at each site (see Appendix B), which maximizes the Supplier's profit and decrease Customers' costs with respect to their original situation, as detailed in Figure 2.

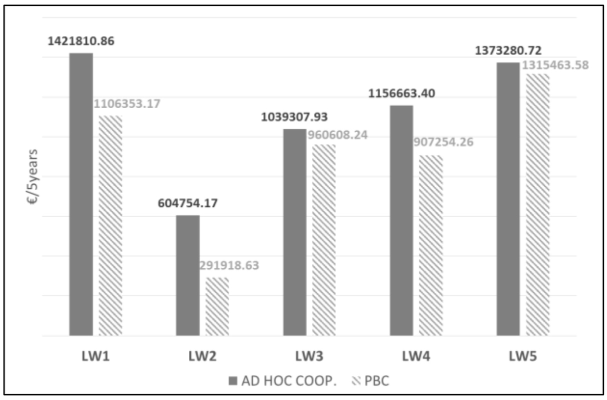

Figure 2: Cost comparison of two scenarios: ad hoc cooperation vs PBC.

Even if applied to a subset of spare parts, these preliminary results prove the relevance of this research. The results confirm the theoretical benefits of risk pooling by a significant cost reduction for each Customers, and the chance for a reasonable profit for the Supplier. The results are positive for each Customer, showing a percentage cost decrement ranging from 5% to 51%. The Supplier, over a time interval of 5 years, will have a net profit of € 478'500. These results reflect the benefits of a pooling strategy with respect to those items with a low demand (and generally respective high costs) which mostly benefit of a pooling strategy.

6. Discussion and conclusions

This paper describes a model to support decision-makers for defining an alternative spare parts management strategy (based on a PBC). This paper aims to advance current research stream focused on inventory management, considering current and upcoming industrial challenges. The methodology draws a path for procurement and logistic managers to explore a different spare parts management strategy, in order to minimize costs and increase availability. Following the Supplier's perspective, this model identifies the most advantageous contractual specifications and stock allocation, which ensure a cost reduction for Customers. The proposed model analyses a reduced set of inventory items confirming the benefits of the approach. These preliminary results motivate other studies to explore the same model in different scenarios.

Firstly, a larger set of items has to be considered to validate these results in a more general scenario. Furthermore, future studies should understand the effects of fleet size (mainly in terms of FH) to the overall costs and the optimum value of access and rent fee, potentially leading to the definition of variable fees. A future research path should focus on determining the variable threshold, even expanding the sensitivity analysis for acknowledging the effects of additional Customers joining (or exiting) the contract after initial contractual definition. Even the robustness of stock level and profits to changes in demand rate and items' market value would need more detailed analyses. Further research should focus on considering the effects of fleet ageing and obsolescence costs for determining optimum stock value. Other research paths should focus on exploring alternative optimization algorithms, (e.g.) based on pattern search (Costantino et al., 2014) or particle swarm optimization (Kadadevaramath et al., 2012). These analyses would generate sensible advantages for the Supplier decision-maker, supporting business resilience of the company.

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Appendix A. Input data for the case study.

j	N_j	M_j	FH_j	A_j^t
1	41	40	13200	0,95
2	30	29	1000	0,94
3	24	24	8200	0,96
4	30	30	9000	0,95
5	45	45	15000	0,96

i	P_i[€]	C_i^{obs}[€]
1	5000	125
2	32000	800
3	41000	1435
4	22000	770
5	29000	435
6	31000	775
7	26000	910
8	3500	122,5
9	60000	2100
10	4600	161

j=1 (LW1)

i	$m_{ij}[p/y]$	r_{ij}	$T_{ij}[y]$	$O_{ij}[y]$	C_{ij}^{tr}[€]	C_{ij}^{ahc}[€]
1	102,34	0,5	0,0045	0,0250	15,00	500
2	14,61	0,7	0,0048	0,0357	25,00	6720
3	13,58	0,5	0,0034	0,0123	15,00	7380
4	17,38	0,4	0,0048	0,0258	50,00	2640
5	15,12	0,7	0,0042	0,0081	70,00	4350
6	15,74	0,3	0,0034	0,0422	15,00	4650
7	13,53	0,4	0,0036	0,0227	25,00	4940
8	11,37	0,5	0,0040	0,0337	25,00	280
9	108,32	0,6	0,0051	0,0164	15,00	13500
10	101,81	0,5	0,0035	0,0224	50,00	690

j=2 (LW2)

i	$m_{ij}[p/y]$	r_{ij}	$T_{ij}[y]$	$O_{ij}[y]$	C_{ij}^{tr}[€]	C_{ij}^{ahc}[€]
1	86,18	0,5	0,0045	0,0250	20,000	471
2	12,65	0,7	0,0048	0,0257	27,500	6629
3	11,72	0,5	0,0034	0,0223	17,500	7252
4	13,57	0,4	0,0048	0,0258	55,000	2575
5	12,13	0,7	0,0042	0,0241	75,000	4161
6	12,18	0,3	0,0034	0,0222	17,500	4488
7	10,82	0,4	0,0036	0,0227	30,000	4785
8	8,57	0,5	0,004	0,0237	27,500	127
9	83,92	0,6	0,0051	0,0264	20,000	13388
10	79,81	0,5	0,0035	0,0224	55,000	491

j=3 (LW3)

i	$m_{ij}[p/y]$	r_{ij}	$T_{ij}[y]$	$O_{ij}[y]$	C_{ij}^{tr}[€]	C_{ij}^{ahc}[€]
1	70,39	0,5	0,005	0,0255	17,50	481
2	11,91	0,7	0,005	0,0271	30,00	6531
3	10,46	0,5	0,003	0,0231	20,00	7258
4	14,07	0,4	0,005	0,0260	52,50	2625
5	11,91	0,7	0,004	0,0245	72,50	4171
6	11,91	0,3	0,003	0,0229	20,00	4634
7	11,91	0,4	0,004	0,0238	30,00	4840
8	10,46	0,5	0,004	0,0248	27,50	106
9	77,43	0,6	0,005	0,0269	17,50	13458
10	79,87	0,5	0,0035	0,0228	55,00	491

j=4 (LW4)

i	$m_{ij}[p/y]$	r_{ij}	$T_{ij}[y]$	$O_{ij}[y]$	C_{ij}^{tr}[€]	C_{ij}^{ahc}[€]
1	72,61	0,7	0,0045	0,025	15,00	346
2	12,39	0,9	0,0048	0,0257	25,00	6683
3	10,88	0,7	0,0034	0,0223	15,00	7299
4	14,53	0,6	0,0048	0,0258	50,00	2577
5	12,39	0,9	0,0042	0,0241	70,00	4185
6	12,39	0,5	0,0034	0,0222	15,00	4562
7	12,31	0,6	0,0036	0,0227	25,00	4815
8	10,88	0,7	0,0040	0,0237	25,00	222
9	79,96	0,8	0,0051	0,0264	15,00	13378
10	72,61	0,7	0,0035	0,0224	50,00	572

j=5 (LW5)

i	$m_{ij}[p/y]$	r_{ij}	$T_{ij}[y]$	$O_{ij}[y]$	C_{ij}^{tr}[€]	C_{ij}^{ahc}[€]
1	112,63	0,6	0,0045	0,025	€ 20,00	396
2	17,012	0,8	0,0048	0,0257	€ 30,00	6539
3	16,42	0,6	0,0034	0,0223	€ 17,50	7263
4	17,01	0,5	0,0048	0,0258	€ 52,50	2447
5	16,42	0,8	0,0042	0,0241	€ 75,00	4153
6	16,42	0,4	0,0034	0,0222	€ 20,00	4493
7	15,83	0,5	0,0036	0,0227	€ 30,00	4743
8	15,25	0,6	0,0040	0,0237	€ 27,50	106
9	11,73	0,7	0,0051	0,0264	€ 17,50	13379
10	104,41	0,6	0,0035	0,0224	€ 55,00	680

Appendix B. Output data: Stock allocation and availability for each site in the PBC contract.

i	$j = 0$	$j = 1$	$j =$	$j = 3$	$j = 4$	$j = 5$
1	0	2	8	5	5	6
2	1	1	1	2	1	1
3	0	1	1	2	2	1
4	0	0	2	3	1	1
5	0	1	0	2	1	1
6	0	1	0	1	1	2
7	0	1	0	1	1	3
8	2	1	7	2	2	2
9	2	4	3	5	4	4
10	0	2	2	8	8	7
		$j = 1$	$j =$	$j = 3$	$j = 4$	$j = 5$
A_j^*		.961	.952	.961	.960	.962