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**A method for comparing flexibility performance for the lifecycle of manufacturing systems under capacity planning constraints**

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3 **A method for comparing flexibility performance for the lifecycle of**  
4 **manufacturing systems under capacity planning constraints**  
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4 **Abstract.** The objective of this work is to describe a method for comparing the  
5 flexibility performance of manufacturing systems, in an uncertain environment, under  
6 lifecycle considerations and capacity planning constraints. The manufacturing systems  
7 costs are estimated over a time horizon and for a large variety of possible market  
8 scenarios. In order for the lifecycle cost values to be comparable among different  
9 systems, their values are calculated with the use of a special purpose algorithm.  
10 Statistical analysis of the estimated cost values is then employed for assessing the  
11 flexibility of each manufacturing system. The method is applied in an industrial case for  
12 checking, also from a flexibility point of view, the investment on a production system,  
13 using real life industrial data.

14  
15 **Keywords:** Flexibility; Lifecycle; manufacturing systems

## 16 **1 Introduction**

17 Shorter product lifecycles and the increased number of new models and variants have  
18 forced companies to produce products that would meet the demands of a diversified  
19 customer base, in a short development cycle, yielding low cost, high quality and  
20 sufficient quantity. This makes manufacturing flexibility an increasingly important  
21 attribute of modern manufacturing systems (Chryssolouris 2005). However,  
22 flexibility cannot be properly considered in the decision making process, if it is not  
23 defined in quantifiable terms.

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25 Several methods of measuring manufacturing system flexibility have been  
26 proposed. The entropy concept of thermodynamics that provides similarities to  
27 flexibility measures is used by Kumar (1987); the entropy concept has been further  
28 revised by Chang *et. al.* (2001). A number of methods based on the analogy between  
29 a manufacturing and a mechanical system have been proposed (Chryssolouris 1996,  
30 Alexopoulos *et. al.* 2007a, Alexopoulos *et. al.* 2008). Tsourveloudis and Phillis  
31 (1998) have employed fuzzy logic rules that include engineers' and managers'  
32 expertise for measuring machine flexibility. Similarly, Das and Caprihan (2008) use  
33 fuzzy logic to compute an overall manufacturing flexibility index for a company as an  
34 aggregation of individual flexibility factors. Wahab *et. al.* (2008) measure machine  
35 flexibility as a function of the probability of assigning a part to a machine, the

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2 efficiency of the machine and the relative importance of the machining operation on  
3 the part and Hua and He (2009) measure process flexibility under the consideration of  
4 constraints imposed by the products' Bill Of Material. Hua and Benerjee (2000a,  
5 2000b) presented a detailed capacity planning method that considers realistic  
6 constraints such as capacity and budget constraints in order to assist investment  
7 decisions in a multi-product, flexible manufacturing environment. Their work focuses  
8 more on the development of the planning method than on flexibility assessment. A  
9 practical example, from the automotive industry, is presented by Elkins *et. al.* (2004)  
10 that uses the Net Present Value (NPV) for assessing the risk of acquiring  
11 manufacturing systems with a different degree of flexibility. A measure for  
12 evaluating the convertibility of manufacturing systems that considers configuration,  
13 machine and material handling level is proposed by Koren *et. al.* (2003), while  
14 Wiendahl and Heger (2004) propose a method of justifying changeability in  
15 economical terms, using the scenario planning technique. An approach that provides  
16 an integration of different flexibility measures in the form of a "toolbox" is proposed  
17 by Georgoulis *et. al.* (2007). Extensive reviews on the subject of flexibility in  
18 manufacturing systems can be found in De Toni and Tonchia (1998) and Beach *et. al.*  
19 (2000).

20  
21 The work presented in this paper is based on the definition that '*flexibility of a*  
22 *manufacturing system is determined by its sensitivity to change*' (Chryssolouris and  
23 Lee 1992). In Chryssolouris and Lee (1992) flexibility is evaluated by calculating the  
24 expected cost for accommodating possible changes in the operating environment. The  
25 smaller the expected "change cost" is, the less sensitive the system is to changes in its  
26 operating environment and thus, the system is considered as more flexible.  
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Alexopoulos *et. al.* (2005) applied this approach to a real case study of the commercial refrigerators production industry.

The purpose of this paper is to define a measure of flexibility for the lifecycle of a manufacturing system and to describe an algorithm for calculating this measure. The approach in this work is an evolution of the work presented in Alexopoulos *et. al.* (2007b). The reader may refer to that work for detailed description of the approach used for evaluating the flexibility. In the present paper a short description of the method is given for consistency reasons. The current work takes into account additional capacity planning constraints that were not considered in the previous work [and refines the flexibility evaluation formula in order to be applicable for flexibility comparison of systems with different scales of initial investment cost](#). The approach is applied to the selection of a configuration for a real automotive facility.

## 2 A method to assess flexibility for the lifecycle of a manufacturing system

The manufacturing system can be in any configuration  $Conf_m$ ,  $m \in [1, M]$  whereby  $M$  is the number of possible configurations. Changes in the configuration of the system can expand or contract its capacity and this usually has a switching cost. The switching cost addresses several aspects such as purchase of new equipment and opportunity cost that is related to the time required for switching between configurations. The switching cost has normally positive values when expanding capacity and negative when contracting. The switching cost between two configurations  $Conf_k$ ,  $Conf_i$ , is denoted by  $S_{ki}$ , with  $S_{kk} = 0$ . The values of the switching cost could be indicative of the flexibility performance; low switching costs could reflect high flexibility and vice versa. However, flexibility depends not only on the manufacturing system itself, but also on the external demands placed upon it in order to be industrially relevant (Chryssolouris and Lee 1992). The external demand

is described as a set of market scenarios which are usually generated based on forecast data. A market scenario defines the volume of a product that should be produced at each period  $t$  of the lifecycle  $T$ . In the case of  $S$  different market scenarios, an  $[S \times T]$  matrix  $\mathbf{D}$  holds all of the possible volume demands of a product ( $D = \{D_1, D_2, \dots, D_S\}$ ).

$$\mathbf{D} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_S \end{bmatrix}_{S \times T} = \begin{bmatrix} D_1(1) & D_1(2) & \dots & D_1(T) \\ D_2(1) & D_2(2) & \dots & D_2(T) \\ \vdots & \vdots & \ddots & \vdots \\ D_S(1) & D_S(2) & \dots & D_S(T) \end{bmatrix}_{S \times T}$$

Each row vector  $\mathbf{D}_i$  ( $i \in [1 \dots S]$ ) in  $\mathbf{D}$  represents a market scenario.

Due to the uncertainty of external demand and the large number of possible future market scenarios, which represent a sample of the whole range of possible market scenarios, the flexibility of a manufacturing system can be assessed statistically (Alexopoulos et. al 2007b). The Discounted Cash Flow (DCF) of the system is calculated for each market scenario and the spread of the DCF defines the flexibility of the system in the given market environment. The lower the spread of the DCF, the more flexible the system is considered, since it is less sensitive to the changes of the environment as it "stabilizes" better its lifecycle costs. We can calculate the spread of the DCF by the standard deviation of the values. This is measured by  $DEVDCF$  in equation (2). Moreover, if the systems have considerably different initial investment costs the  $DEVDCF$  values are divided to the initial investment cost. In this case the

$NDEVDCF$  measure should be used for comparing the flexibility of systems with different scales of initial investment cost. The  $NDEVDCF$  calculates dimensionless numbers and thus it is more appropriate when comparing production systems evaluated in different monetary units. On the other hand,  $NDEVDCF$  is not valid in the case that the initial investment cost is not a relevant factor (i.e. it is near or equal to zero) such as the case of comparing the flexibility of already installed production

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equipment with no initial investment cost. Moreover, the expected DCF (*EDCF*) is also calculated in (1) in order to be able to have an indication of the trade-off between the flexibility of the system and the expected lifecycle cost.

$$EDCF = \frac{\sum_{i=1}^S DCF_i}{S} \quad (1)$$

$$DEVDCF = \sqrt{\frac{1}{S-1} * \sum_{i=1}^S (DCF_i - EDCF)^2} \quad (2)$$

$$NDEVDCF = \frac{DEVDCF}{Inv} \quad (3)$$

Where:

$DCF_i$  is the Discounted Cash Flow score for scenario  $D_i$ ,  $i \in [1 \dots S]$

$S$  is the total number of scenarios

$Inv$  is the initial investment cost

### 3 Planning in the lifecycle

#### 3.1 Planning problem

In order for the flexibility measure defined in the previous paragraph to be industrially applicable, the DCF estimates for the different manufacturing systems should be comparable. Thus the minimum DCF is calculated for each scenario. In order to calculate the minimum DCF of the system in the lifecycle  $T$ , for a given scenario  $D_i$ , it is necessary to decide on which of the  $M$  possible configurations the system will operate for each period of the lifecycle  $T$ . The costs at each period  $t$  of  $T$  arise from the total cost of the selected configuration in period  $t$  and the switching cost from the configuration selected for period  $t-1$ . The demand in period  $t$  determines the total cost  $O_m(t)$  of each possible configuration  $Conf_m$ ,  $m \in [1 \dots M]$  at period  $t$ . The  $O_m(t)$  value also depends on the 'learning-by-doing' (see equation (5)). The problem of calculating minimum DCF can be formulated as follows:

$$DCF_i = Inv + \text{minimize} \left\{ \sum_{t=1}^T \frac{\{O_m(t) + S_{km}(t)\}}{(1+r)^t} \right\} \quad (4)$$

Subject to

$$C_m \geq D_i(t) \quad \forall t \in [1 \dots T], m \in [1 \dots M] \text{ and } i \in [1 \dots S]$$

Where:

$DCF_i$  is the minimum Discounted Cash Flow score for market scenario  $\mathbf{D}_i$ ,  $i \in [1 \dots S]$

$Inv$  is the investment cost which occurs at period  $t=0$

$O_m(t)$ : is the total cost for period  $t$  if configuration  $Conf_m$  is assigned for period  $t$

$S_{km}(t)$ : is the switching cost for period  $t$  if configuration  $k \in [1 \dots M]$  is assigned for period  $t-1$  and configuration  $m \in [1 \dots M]$  is assigned for period  $t$

$C_m$  is the capacity of the selected configuration ( $m \in [1 \dots M]$ ) for period  $t$

$D_i(t)$  is the demand at period  $t$  according to scenario  $\mathbf{D}_i$ ,  $i \in [1 \dots S]$

$T$ : the total number of periods and

$r$ : is the interest rate which remains constant for whole  $T$

### 3.2 Planning constraints

The above planning problem has to be considered under several constraints in order to be relevant for industrial practice. The constraints that have been considered in this work are given below.

#### 3.2.1 Fulfil demand constraint

This constraint implies that if configuration  $m$  has capacity  $C_m$ , the demand at period  $t$  is  $\mathbf{D}_n(t)$  and  $C_m < \mathbf{D}_n(t)$ , then configuration  $m$  cannot be assigned in period  $t$  because it cannot fulfil the demand.

#### 3.2.2 Predefined configuration for some periods

This constraint enables the engineer to define that one or more configurations among the possible ones, should be chosen in specific periods. This is very useful, when for instance, the configuration of the first period, which is known, has to be defined, or when configurations representing the maintenance state of the system have to be defined as well.

#### 3.2.3 Man-hours limit constraint

In many cases due to legislation or company rules, the amount of time that a worker may work should not exceed a certain limit of successive time periods. For instance, such a constraint may imply that the average working hours per week should not exceed 40 for a period of two months. This limits the alternatives that could be adopted for successive periods.

### 3.2.4 Learning by doing

In industrial practice the production cost function is often “shifted down” as a company accumulates 'experience/learning by doing' (Alvarez and Cerda 2003). This has been incorporated by providing the ability to define a function that modifies the total costs of a configuration, as the configuration remains valid for a number of successive periods. Such a function has the following general form:

$$CP_m(t) = f(t, CP_m(t_0)) \quad (5)$$

Where:

$t$  is the period index and  $t \in (t_0, T]$

$CP_m(t)$  is the cost per piece in  $t$ , for configuration  $m$

$CP_m(t_0)$  is the cost per piece of configuration  $m$  at the first period in which the configuration is applied

$f$  is a user defined function that calculates the production cost for a given period and a given initial cost per part  $CP_m(t_0)$

The application of "learning by doing" restricts the costs of a configuration  $Conf_m$  when it is applied in successive periods.

### 3.3 Solution

The problem can be described as having to find the shortest path in a tree, where a node represents one possible configuration, and a stage represents a period  $t$ . A number of possible nodes (configurations) are available for each stage (period). An edge from node  $Conf_k$  to node  $Conf_l$ , a stage below, shows that the change  $Conf_k$  to node  $Conf_l$  is possible with a switching cost  $S_{kl}$  (see Figure 1). For each stage the algorithm should select the node, which would lead to the minimum lifecycle cost of the system without violating the constraints. In order to address this issue a

customised backward optimization algorithm (Denardo 2003) has been developed.

The steps of the algorithm are given below.

Step 1: Set  $t=T-1$

Step 2: Take the next node  $Conf_k$  in stage  $t$ .

Step 3: Take the next node  $Conf_m$  in stage  $t+1$ .

Step 4: Calculate the  $(t+1)^{th}$  term of equation (4) for  $Conf_m$  considering that  $Conf_k$  is assigned in period  $t$ :  $partialScore_{m,t+1} = \frac{O_m(t+1) + S_{km}}{(1+r)^{t+1}}$ . If  $t=T-1$  Go directly to Step 5 else GoTo Step 4.1

Step 4.1: Set  $partialScore_{m,t+1} = \frac{O_m(t+1) + S_{km}}{(1+r)^{t+1}} + minScore_{m,t+1}$  (see details for calculating  $minScore_{m,t+1}$  in Step 6).

Step 5: If there is another node in  $(t+1)$  GoTo Step 3 else GoTo Step 6

Step 6: For node  $Conf_k$  store plans up to stage T and their partial scores, for each node of stage  $t+1$ . The plans are sorted in descending order. The minimum DCF score for  $Conf_k$  ( $minScore_{k,t}$ ) is the score of the first partial solution score for node  $Conf_k$ .

Step 7: If there is another node in  $t$  GoTo Step 2 else GoTo Step 8.

Step 8: If  $t=0$  then STOP else set  $t=t-1$  and GoTo Step 1.

Although this algorithm is capable of generating the solution with the minimum DCF, it should, however, be ameliorated in order for the constraints to be taken into account, since the generated solution may not satisfy one or more constraints. An approach to implement the constraints is to extend this algorithm to generate  $L$  best solutions instead of one and then apply the complex constraint formulas in each solution until a solution that satisfies all constraints is reached. The extension of the algorithm that has been implemented is capable of generating  $L$  successive solutions. The constraint formulas are applied gradually in parts of the solution and thus they radically reduce the possible solution space. The extension of the algorithm is schematically presented with an example for up to two stages/periods in Figure 2.

As shown in Figure 2 each node has a list of  $k$  possible partial solution paths, ranked in successive order, with the one that has the minimum DCF being first. Then

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2 the solutions move from nodes of the bottom to nodes in higher level to replace  
3 solutions that have either been popped to replace a part of the solution or have been  
4 examined and failed to satisfy one or more constraints. Then the list of  $k$  partial  
5 solutions of the higher-level node is sorted again so as the best partial solution to be  
6 first. The constraint formulas may be applied either at the partial solution path of  
7 each internal node or directly at the final solution. This movement of the partial  
8 solutions from node to node resembles the movement of bubbles within a glass of  
9 sparkle water as one pushes the other to the top.  
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19 [Insert figure 1 about here]

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21 [Insert figure 2 about here]

#### 22 23 24 25 26 **4 Industrial case study**

27 In this section, the proposed method is applied to an investment decision in the  
28 automotive industry. Two different production systems have been proposed for the  
29 production of the body of a car:  
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- 32 • *System A* uses conventional welding equipment and
- 33 • *System B* uses advanced welding equipment.

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35 For both systems, five different configurations are possible, which are  $\mathbf{Conf}_A$   
36 =  $(\mathbf{Conf}_{A1}, \mathbf{Conf}_{A2}, \mathbf{Conf}_{A3}, \mathbf{Conf}_{A4}, \mathbf{Conf}_{A5})$  and  $\mathbf{Conf}_B = (\mathbf{Conf}_{B1}, \mathbf{Conf}_{B2}, \mathbf{Conf}_{B3},$   
37  $\mathbf{Conf}_{B4}, \mathbf{Conf}_{B5})$ . The configurations, within each vector  $\mathbf{Conf}_A$ , and  $\mathbf{Conf}_B$ , differ in  
38 the number of available equipment and working shifts. For each system the  
39 individual cost figures and the capacity for each of the configurations are given in  
40 Table 1, including the fixed cost terms on a yearly basis, such as area cost, energy  
41 cost, labour cost, the variable costs, such as waste cost per piece, additional cost per  
42 piece. Furthermore, the organizational capacity and the capacity of each configuration  
43 are given. The cost figures show that *System B* has higher total costs than *System A*.  
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3 The 'Organizational capacity limit' refers to the capacity of the configuration when the  
4 system operates in its "normal" state, while the 'Capacity' term refers to the maximum  
5 level of products that can be produced, given the technical limitations of the  
6 configuration. The system may have higher production than its 'Organizational  
7 capacity limit' by overtimes and working during weekends. When the production  
8 exceeds the 'Organizational capacity limit' then the 'Additional cost per piece' is  
9 included in the variable cost term. The switching costs for each one of the systems  
10 are given in Table 2 and Table 3.  $Conf_{A0}$  and  $Conf_{B0}$  are configurations that are not  
11 actually applied and are used only for defining the initial switching cost  $S_{0k}$ , from the  
12 initial investment cost. The initial investment cost,  $Inv$ , is 5 500 000€ for *System A*  
13 and 7 500 000€ for *System B*. The learning-by-doing curve is usually calculated  
14 based on statistical data. Since statistical data were lacking, the 'power law' formula  
15 has been used, assuming a 90% learning percent (Zangwill and Kantor 1998):  
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$$28 \quad CP_m(t) = CP_m(t_0) \times t^{\frac{\ln 0,9}{\ln 2}} \quad (6)$$

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31 The scenarios are generated by using uniform and normal probability  
32 distributions as well as forecast data based on realistic information, coming from the  
33 marketing department. This information defines the minimum and maximum demand  
34 in 70 000 and 200 000 parts annually, for a time horizon  $T = 10$  years which is typical  
35 lifetime for the production systems under study. A number of 1000 scenarios are  
36 generated within these limits for different demand boundaries (see first column in  
37 Table 4). The number of 1000 has been selected in order to give statistically relevant  
38 results.  
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48 The results of the experiments are presented in Table 4 and clearly indicate  
49 that *System B* is less sensitive to the diverse market environment than *System A*. In all  
50 cases studied, the *DEVDCF* and *NDEVDCF* value of *System B* are less than that in  
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*System A*. However since the *EDCF* is higher for *System B*, the trade-off between flexibility and its cost becomes more transparent. Additionally, in comparison to the (Alexopoulos et. al. 2007b) results, in which the 'learning-by-doing' constraint was not applicable, it appears that both the *EDCF* and *DEVDCF* values are lower in all scenario profiles. This reduction (approximately 10%) in *DEVDCF* values is due to the reduction of the individual reduction in the *DCF* values due to the application of the 'learning by doing'.

[Insert tables 1-4 about here]

## 5 Conclusions

This paper takes the perspective that the flexibility of a manufacturing system is related to its insensitivity to external changes; the less sensitive a system is the more flexible it should be considered. Taking this perspective and applying it in a lifecycle context, a method of modelling and assessing the flexibility of a manufacturing system is presented. The proposed method can be applied during the initial planning phase for quantifying the tolerance of the manufacturing system during its lifecycle to changes in the market environment, which is a strong flexibility benefit. In order to make the method applicable to the complex industrial reality, a number of capacity constraints, which are relevant in the lifecycle context, have been considered and the method has been extended in order to account for these constraints. The industrial case study indicates that the proposed method can give valuable results when comparing alternative manufacturing system solutions. However, the method does not provide any suggestions for improving the system in terms of flexibility performance. It does not tell the engineers about the flexibility that is actually required in order for a feedback to the design parameters of the manufacturing system to be established; this is subject to future research. Finally, future research will

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[investigate the impact of different learning curves and different demand distribution profiles on the results of the proposed flexibility measure.](#)

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Table 1. Total costs for both systems.

	Config.	Fixed Costs (€)	Variable Cost		Org. Cap. limit (x1000)	Capacity (x1000)
			Waste Cost (€)	Addit. Cost (€)		
Conventional Equipment	Conf <sub>A1</sub>	157 920	0.33 €	1	96.25	110
	Conf <sub>A2</sub>	230 640	0.33 €	1	113.75	130
	Conf <sub>A3</sub>	163 337	0.33 €	1	122.5	140
	Conf <sub>A4</sub>	237 874	0.33 €	1	140	160
	Conf <sub>A5</sub>	252 411	0.33 €	1	175	200
Advanced Equipment	Conf <sub>B1</sub>	167 835	0.33 €	1	96.25	110
	Conf <sub>B2</sub>	248 187	0.33 €	1	113.75	130
	Conf <sub>B3</sub>	173 650	0.33 €	1	122.5	140
	Conf <sub>B4</sub>	256 910	0.33 €	1	140	160
	Conf <sub>B5</sub>	280 169	0.33 €	1	175	200

Table 2. Change cost (in €) matrix for System A.

Config.	Conf <sub>A1</sub>	Conf <sub>A2</sub>	Conf <sub>A3</sub>	Conf <sub>A4</sub>	Conf <sub>A5</sub>
Conf <sub>A0</sub>	0	0	1 434 214	1 434 214	3 430 614
Conf <sub>A1</sub>	0	0	1 434 214	1 434 214	3 430 614
Conf <sub>A2</sub>	0	0	1 434 214	1 434 214	3 430 614
Conf <sub>A3</sub>	-403 333	-403 333	0	0	1 766 400
Conf <sub>A4</sub>	-403 333	-403 333	0	0	1 996 400
Conf <sub>A5</sub>	-761 333	-761 333	-412 000	-412 000	0

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Table 3. Change cost (in €) matrix for System B.

Config	Conf <sub>B1</sub>	Conf <sub>B2</sub>	Conf <sub>B3</sub>	Conf <sub>B4</sub>	Conf <sub>B5</sub>
Conf <sub>B0</sub>	0	0	1 251 514	1 251 514	2 666 314
Conf <sub>B1</sub>	0	0	1 251 514	1 251 514	2 666 314
Conf <sub>B2</sub>	0	0	1 251 514	1 251 514	3 173 914
Conf <sub>B3</sub>	-457 333	-457 333	0	0	1 234 800
Conf <sub>B4</sub>	-457 333	-457 333	0	0	1 003 200
Conf <sub>B5</sub>	-814 667	-881 333	-357 333	-357 333	0

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Table 4: Case study results.

Scenario Profile <sup>a</sup>	System A			System B		
	EDCF	DEVDCF	NDEVDCF	EDCF	DEVDCF	NDEVDCF
U(70 000,200 000)	9 888 399	550 220	10,00%	11 290 760	495 685	6,61%
U(70 000,190 000)	9 660 931	579 951	10,54%	11 092 476	482 558	6,43%
U(80 000,160 000)	8 308 482	277 364	5,04%	10 227 861	269 478	3,59%
U(90 000,150 000)	8 202 413	245 207	4,46%	10 122 060	227 394	3,03%
U(110000,140000)	8 184 877	156 016	2,84%	10 098 834	129 334	1,72%
N(150000,50000)	10 265 421	525 077	9,55%	11 658 148	514 868	6,86%
N(150000,40000)	10 238 873	474 642	8,63%	11 628 984	468 471	6,25%
N(150000,40000)	10 236 499	406 037	7,38%	11 594 422	387 661	5,17%

<sup>a</sup>Note that  $U(i, j)$  is uniform distribution between  $i$  and  $j$ . While  $N(m, d)$  is a normal distribution with  $m$  as mean and  $d$  as deviation

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**List of figures**

Figure 1: Tree representation of the minimum DCF problem instance

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Figure 1: Tree representation of the minimum DCF problem instance

Figure 2: Algorithm extension to generate first  $L$  best solutions

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Figure 2: Algorithm extension to generate first  $L$  best solutions

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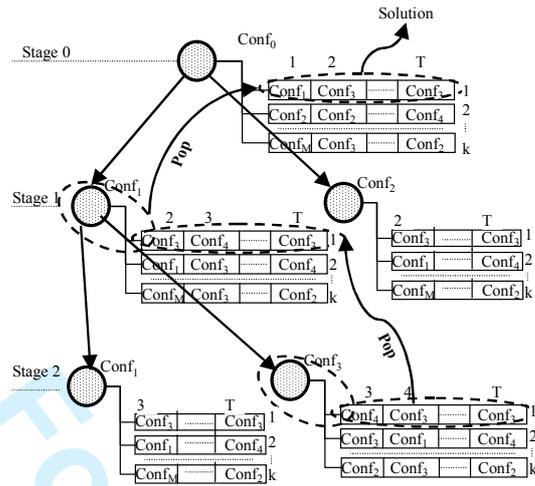


Figure 2: Algorithm extension to generate first  $L$  best solutions

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3 **A method for comparing flexibility performance for the lifecycle of**  
4 **manufacturing systems under capacity planning constraints**  
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**Abstract.** The objective of this work is to describe a method for comparing the flexibility performance of manufacturing systems, in an uncertain environment, under lifecycle considerations and capacity planning constraints. The manufacturing systems costs are estimated over a time horizon and for a large variety of possible market scenarios. In order for the lifecycle cost values to be comparable among different systems, their values are calculated with the use of a special purpose algorithm. Statistical analysis of the estimated cost values is then employed for assessing the flexibility of each manufacturing system. The method is applied in an industrial case for checking, also from a flexibility point of view, the investment on a production system, using real life industrial data.

**Keywords:** Flexibility; Lifecycle; manufacturing systems

## 1 Introduction

Shorter product lifecycles and the increased number of new models and variants have forced companies to produce products that would meet the demands of a diversified customer base, in a short development cycle, yielding low cost, high quality and sufficient quantity. This makes manufacturing flexibility an increasingly important attribute of modern manufacturing systems (Chryssolouris 2005). However, flexibility cannot be properly considered in the decision making process, if it is not defined in quantifiable terms.

Several methods of measuring manufacturing system flexibility have been proposed. The entropy concept of thermodynamics that provides similarities to flexibility measures is used by Kumar (1987); the entropy concept has been further revised by Chang *et. al.* (2001). A number of methods based on the analogy between a manufacturing and a mechanical system have been proposed (Chryssolouris 1996, Alexopoulos *et. al.* 2007a, Alexopoulos *et. al.* 2008). Tsourveloudis and Phillis (1998) have employed fuzzy logic rules that include engineers' and managers' expertise for measuring machine flexibility. Similarly, Das and Caprihan (2008) use fuzzy logic to compute an overall manufacturing flexibility index for a company as an aggregation of individual flexibility factors. Wahab *et. al.* (2008) measure machine flexibility as a function of the probability of assigning a part to a machine, the

1  
2 efficiency of the machine and the relative importance of the machining operation on  
3 the part and Hua and He (2009) measure process flexibility under the consideration of  
4 constraints imposed by the products' Bill Of Material. Hua and Benerjee (2000a,  
5 2000b) presented a detailed capacity planning method that considers realistic  
6 constraints such as capacity and budget constraints in order to assist investment  
7 decisions in a multi-product, flexible manufacturing environment. Their work focuses  
8 more on the development of the planning method than on flexibility assessment. A  
9 practical example, from the automotive industry, is presented by Elkins *et. al.* (2004)  
10 that uses the Net Present Value (NPV) for assessing the risk of acquiring  
11 manufacturing systems with a different degree of flexibility. A measure for  
12 evaluating the convertibility of manufacturing systems that considers configuration,  
13 machine and material handling level is proposed by Koren *et. al.* (2003), while  
14 Wiendahl and Heger (2004) propose a method of justifying changeability in  
15 economical terms, using the scenario planning technique. An approach that provides  
16 an integration of different flexibility measures in the form of a "toolbox" is proposed  
17 by Georgoulis *et. al.* (2007). Extensive reviews on the subject of flexibility in  
18 manufacturing systems can be found in De Toni and Tonchia (1998) and Beach *et. al.*  
19 (2000).

20  
21 The work presented in this paper is based on the definition that '*flexibility of a*  
22 *manufacturing system is determined by its sensitivity to change*' (Chryssolouris and  
23 Lee 1992). In Chryssolouris and Lee (1992) flexibility is evaluated by calculating the  
24 expected cost for accommodating possible changes in the operating environment. The  
25 smaller the expected "change cost" is, the less sensitive the system is to changes in its  
26 operating environment and thus, the system is considered as more flexible.  
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2 Alexopoulos *et. al.* (2005) applied this approach to a real case study of the  
3 commercial refrigerators production industry.  
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6 The purpose of this paper is to define a measure of flexibility for the lifecycle  
7 of a manufacturing system and to describe an algorithm for calculating this measure.  
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9 The approach in this work is an evolution of the work presented in Alexopoulos *et. al.*  
10 (2007b). The reader may refer to that work for detailed description of the approach  
11 used for evaluating the flexibility. In the present paper a short description of the  
12 method is given for consistency reasons. The current work takes into account  
13 additional capacity planning constraints that were not considered in the previous work  
14 and refines the flexibility evaluation formula in order to be applicable for flexibility  
15 comparison of systems with different scales of initial investment cost. The approach  
16 is applied to the selection of a configuration for a real automotive facility.  
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## 27 **2 A method to assess flexibility for the lifecycle of a manufacturing system**

28 The manufacturing system can be in any configuration  $Conf_m$ ,  $m \in [1, M]$  whereby  $M$   
29 is the number of possible configurations. Changes in the configuration of the system  
30 can expand or contract its capacity and this usually has a switching cost. The  
31 switching cost addresses several aspects such as purchase of new equipment and  
32 opportunity cost that is related to the time required for switching between  
33 configurations. The switching cost has normally positive values when expanding  
34 capacity and negative when contracting. The switching cost between two  
35 configurations  $Conf_k$ ,  $Conf_i$ , is denoted by  $S_{ki}$ , with  $S_{kk} = 0$ . The values of the  
36 switching cost could be indicative of the flexibility performance; low switching costs  
37 could reflect high flexibility and vice versa. However, flexibility depends not only on  
38 the manufacturing system itself, but also on the external demands placed upon it in  
39 order to be industrially relevant (Chryssolouris and Lee 1992). The external demand  
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is described as a set of market scenarios which are usually generated based on forecast data. A market scenario defines the volume of a product that should be produced at each period  $t$  of the lifecycle  $T$ . In the case of  $S$  different market scenarios, an  $[S \times T]$  matrix  $\mathbf{D}$  holds all of the possible volume demands of a product ( $\mathbf{D} = \{D_1, D_2, \dots, D_S\}$ ).

$$\mathbf{D} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_S \end{bmatrix}_{S \times T} = \begin{bmatrix} D_1(1) & D_1(2) & \dots & D_1(T) \\ D_2(1) & D_2(2) & \dots & D_2(T) \\ \vdots & \vdots & \ddots & \vdots \\ D_S(1) & D_S(2) & \dots & D_S(T) \end{bmatrix}_{S \times T}$$

Each row vector  $\mathbf{D}_i$  ( $i \in [1 \dots S]$ ) in  $\mathbf{D}$  represents a market scenario.

Due to the uncertainty of external demand and the large number of possible future market scenarios, which represent a sample of the whole range of possible market scenarios, the flexibility of a manufacturing system can be assessed statistically (Alexopoulos et. al 2007b). The Discounted Cash Flow (DCF) of the system is calculated for each market scenario and the spread of the DCF defines the flexibility of the system in the given market environment. The lower the spread of the DCF, the more flexible the system is considered, since it is less sensitive to the changes of the environment as it “stabilizes” better its lifecycle costs. We can calculate the spread of the DCF by the standard deviation of the values. This is measured by  $DEVDCF$  in equation (2). Moreover, if the systems have considerably different initial investment costs the  $DEVDCF$  values are divided to the initial investment cost. In this case the  $NDEVDCF$  measure should be used for comparing the flexibility of systems with different scales of initial investment cost. The  $NDEVDCF$  calculates dimensionless numbers and thus it is more appropriate when comparing production systems evaluated in different monetary units. On the other hand,  $NDEVDCF$  is not valid in the case that the initial investment cost is not a relevant factor (i.e. it is near or equal to zero) such as the case of comparing the flexibility of already installed production

equipment with no initial investment cost. Moreover, the expected DCF (*EDCF*) is also calculated in (1) in order to be able to have an indication of the trade-off between the flexibility of the system and the expected lifecycle cost.

$$EDCF = \frac{\sum_{i=1}^S DCF_i}{S} \quad (1)$$

$$DEVDCF = \sqrt{\frac{1}{S-1} * \sum_{i=1}^S (DCF_i - EDCF)^2} \quad (2)$$

$$NDEVDCF = \frac{DEVDCF}{Inv} \quad (3)$$

Where:

$DCF_i$  is the Discounted Cash Flow score for scenario  $D_i$ ,  $i \in [1...S]$

$S$  is the total number of scenarios

$Inv$  is the initial investment cost

### 3 Planning in the lifecycle

#### 3.1 Planning problem

In order for the flexibility measure defined in the previous paragraph to be industrially applicable, the DCF estimates for the different manufacturing systems should be comparable. Thus the minimum DCF is calculated for each scenario. In order to calculate the minimum DCF of the system in the lifecycle  $T$ , for a given scenario  $D_i$ , it is necessary to decide on which of the  $M$  possible configurations the system will operate for each period of the lifecycle  $T$ . The costs at each period  $t$  of  $T$  arise from the total cost of the selected configuration in period  $t$  and the switching cost from the configuration selected for period  $t-1$ . The demand in period  $t$  determines the total cost  $O_m(t)$  of each possible configuration  $Conf_m$ ,  $m \in [1...M]$  at period  $t$ . The  $O_m(t)$  value also depends on the 'learning-by-doing' (see equation (5)). The problem of calculating minimum DCF can be formulated as follows:

$$DCF_i = Inv + \text{minimize} \left\{ \sum_{t=1}^T \frac{\{O_m(t) + S_{km}(t)\}}{(1+r)^t} \right\} \quad (4)$$

Subject to

$$C_m \geq D_i(t) \quad \forall t \in [1...T], m \in [1...M] \text{ and } i \in [1...S]$$

Where:

$DCF_i$  is the minimum Discounted Cash Flow score for market scenario  $\mathbf{D}_i$ ,  $i \in [1 \dots S]$

$Inv$  is the investment cost which occurs at period  $t=0$

$O_m(t)$ : is the total cost for period  $t$  if configuration  $Conf_m$  is assigned for period  $t$

$S_{km}(t)$ : is the switching cost for period  $t$  if configuration  $k \in [1 \dots M]$  is assigned for period  $t-1$  and configuration  $m \in [1 \dots M]$  is assigned for period  $t$

$C_m$  is the capacity of the selected configuration ( $m \in [1 \dots M]$ ) for period  $t$

$D_i(t)$  is the demand at period  $t$  according to scenario  $\mathbf{D}_i$ ,  $i \in [1 \dots S]$

$T$ : the total number of periods and

$r$ : is the interest rate which remains constant for whole  $T$

### 3.2 Planning constraints

The above planning problem has to be considered under several constraints in order to be relevant for industrial practice. The constraints that have been considered in this work are given below.

#### 3.2.1 Fulfil demand constraint

This constraint implies that if configuration  $m$  has capacity  $C_m$ , the demand at period  $t$  is  $\mathbf{D}_n(t)$  and  $C_m < \mathbf{D}_n(t)$ , then configuration  $m$  cannot be assigned in period  $t$  because it cannot fulfil the demand.

#### 3.2.2 Predefined configuration for some periods

This constraint enables the engineer to define that one or more configurations among the possible ones, should be chosen in specific periods. This is very useful, when for instance, the configuration of the first period, which is known, has to be defined, or when configurations representing the maintenance state of the system have to be defined as well.

#### 3.2.3 Man-hours limit constraint

In many cases due to legislation or company rules, the amount of time that a worker may work should not exceed a certain limit of successive time periods. For instance, such a constraint may imply that the average working hours per week should not exceed 40 for a period of two months. This limits the alternatives that could be adopted for successive periods.

### 3.2.4 Learning by doing

In industrial practice the production cost function is often “shifted down” as a company accumulates 'experience/learning by doing' (Alvarez and Cerda 2003). This has been incorporated by providing the ability to define a function that modifies the total costs of a configuration, as the configuration remains valid for a number of successive periods. Such a function has the following general form:

$$CP_m(t) = f(t, CP_m(t_0)) \quad (5)$$

Where:

$t$  is the period index and  $t \in (t_0, T]$

$CP_m(t)$  is the cost per piece in  $t$ , for configuration  $m$

$CP_m(t_0)$  is the cost per piece of configuration  $m$  at the first period in which the configuration is applied

$f$  is a user defined function that calculates the production cost for a given period and a given initial cost per part  $CP_m(t_0)$

The application of "learning by doing" restricts the costs of a configuration  $Conf_m$  when it is applied in successive periods.

### 3.3 Solution

The problem can be described as having to find the shortest path in a tree, where a node represents one possible configuration, and a stage represents a period  $t$ . A number of possible nodes (configurations) are available for each stage (period). An edge from node  $Conf_k$  to node  $Conf_i$ , a stage below, shows that the change  $Conf_k$  to node  $Conf_i$  is possible with a switching cost  $S_{ki}$  (see Figure 1). For each stage the algorithm should select the node, which would lead to the minimum lifecycle cost of the system without violating the constraints. In order to address this issue a

customised backward optimization algorithm (Denardo 2003) has been developed.

The steps of the algorithm are given below.

Step 1: Set  $t=T-1$

Step 2: Take the next node  $Conf_k$  in stage  $t$ .

Step 3: Take the next node  $Conf_m$  in stage  $t+1$ .

Step 4: Calculate the  $(t+1)^{th}$  term of equation (4) for  $Conf_m$  considering that  $Conf_k$  is assigned in period  $t$ :  $partialScore_{m,t+1} = \frac{O_m(t+1) + S_{km}}{(1+r)^{t+1}}$ . If  $t=T-1$  Go directly to Step 5 else GoTo Step 4.1

Step 4.1: Set  $partialScore_{m,t+1} = \frac{O_m(t+1) + S_{km}}{(1+r)^{t+1}} + minScore_{m,t+1}$  (see details for calculating  $minScore_{m,t+1}$  in Step 6).

Step 5: If there is another node in  $(t+1)$  GoTo Step 3 else GoTo Step 6

Step 6: For node  $Conf_k$  store plans up to stage T and their partial scores, for each node of stage  $t+1$ . The plans are sorted in descending order. The minimum DCF score for  $Conf_k$  ( $minScore_{k,t}$ ) is the score of the first partial solution score for node  $Conf_k$ .

Step 7: If there is another node in  $t$  GoTo Step 2 else GoTo Step 8.

Step 8: If  $t=0$  then STOP else set  $t= t-1$  and GoTo Step 1.

Although this algorithm is capable of generating the solution with the minimum DCF, it should, however, be ameliorated in order for the constraints to be taken into account, since the generated solution may not satisfy one or more constraints. An approach to implement the constraints is to extend this algorithm to generate  $L$  best solutions instead of one and then apply the complex constraint formulas in each solution until a solution that satisfies all constraints is reached. The extension of the algorithm that has been implemented is capable of generating  $L$  successive solutions. The constraint formulas are applied gradually in parts of the solution and thus they radically reduce the possible solution space. The extension of the algorithm is schematically presented with an example for up to two stages/periods in Figure 2.

As shown in Figure 2 each node has a list of  $k$  possible partial solution paths, ranked in successive order, with the one that has the minimum DCF being first. Then

1  
2 the solutions move from nodes of the bottom to nodes in higher level to replace  
3 solutions that have either been popped to replace a part of the solution or have been  
4 examined and failed to satisfy one or more constraints. Then the list of  $k$  partial  
5 solutions of the higher-level node is sorted again so as the best partial solution to be  
6 first. The constraint formulas may be applied either at the partial solution path of  
7 each internal node or directly at the final solution. This movement of the partial  
8 solutions from node to node resembles the movement of bubbles within a glass of  
9 sparkle water as one pushes the other to the top.  
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#### 25 **4 Industrial case study**

26 In this section, the proposed method is applied to an investment decision in the  
27 automotive industry. Two different production systems have been proposed for the  
28 production of the body of a car:  
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- 32 • *System A* uses conventional welding equipment and
- 33 • *System B* uses advanced welding equipment.

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35 For both systems, five different configurations are possible, which are  $\mathbf{Conf}_A$   
36 =  $(\mathbf{Conf}_{A1}, \mathbf{Conf}_{A2}, \mathbf{Conf}_{A3}, \mathbf{Conf}_{A4}, \mathbf{Conf}_{A5})$  and  $\mathbf{Conf}_B = (\mathbf{Conf}_{B1}, \mathbf{Conf}_{B2}, \mathbf{Conf}_{B3},$   
37  $\mathbf{Conf}_{B4}, \mathbf{Conf}_{B5})$ . The configurations, within each vector  $\mathbf{Conf}_A$ , and  $\mathbf{Conf}_B$ , differ in  
38 the number of available equipment and working shifts. For each system the  
39 individual cost figures and the capacity for each of the configurations are given in  
40 Table 1, including the fixed cost terms on a yearly basis, such as area cost, energy  
41 cost, labour cost, the variable costs, such as waste cost per piece, additional cost per  
42 piece. Furthermore, the organizational capacity and the capacity of each configuration  
43 are given. The cost figures show that *System B* has higher total costs than *System A*.  
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The 'Organizational capacity limit' refers to the capacity of the configuration when the system operates in its "normal" state, while the 'Capacity' term refers to the maximum level of products that can be produced, given the technical limitations of the configuration. The system may have higher production than its 'Organizational capacity limit' by overtimes and working during weekends. When the production exceeds the 'Organizational capacity limit' then the 'Additional cost per piece' is included in the variable cost term. The switching costs for each one of the systems are given in Table 2 and Table 3.  $Conf_{A0}$  and  $Conf_{B0}$  are configurations that are not actually applied and are used only for defining the initial switching cost  $S_{0k}$ , from the initial investment cost. The initial investment cost,  $Inv$ , is 5 500 000€ for *System A* and 7 500 000€ for *System B*. The learning-by-doing curve is usually calculated based on statistical data. Since statistical data were lacking, the 'power law' formula has been used, assuming a 90% learning percent (Zangwill and Kantor 1998):

$$CP_m(t) = CP_m(t_0) \times t^{\frac{\ln 0.9}{\ln 2}} \quad (6)$$

The scenarios are generated by using uniform and normal probability distributions as well as forecast data based on realistic information, coming from the marketing department. This information defines the minimum and maximum demand in 70 000 and 200 000 parts annually, for a time horizon  $T = 10$  years which is typical lifetime for the production systems under study. A number of 1000 scenarios are generated within these limits for different demand boundaries (see first column in Table 4). The number of 1000 has been selected in order to give statistically relevant results.

The results of the experiments are presented in Table 4 and clearly indicate that *System B* is less sensitive to the diverse market environment than *System A*. In all cases studied, the *DEVDCF* and *NDEVDCF* value of *System B* are less than that in

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*System A*. However since the *EDCF* is higher for *System B*, the trade-off between flexibility and its cost becomes more transparent. Additionally, in comparison to the (Alexopoulos et. al. 2007b) results, in which the 'learning-by-doing' constraint was not applicable, it appears that both the *EDCF* and *DEVDCF* values are lower in all scenario profiles. This reduction (approximately 10%) in *DEVDCF* values is due to the reduction of the individual reduction in the *DCF* values due to the application of the 'learning by doing'.

[Insert tables 1-4 about here]

## 5 Conclusions

This paper takes the perspective that the flexibility of a manufacturing system is related to its insensitivity to external changes; the less sensitive a system is the more flexible it should be considered. Taking this perspective and applying it in a lifecycle context, a method of modelling and assessing the flexibility of a manufacturing system is presented. The proposed method can be applied during the initial planning phase for quantifying the tolerance of the manufacturing system during its lifecycle to changes in the market environment, which is a strong flexibility benefit. In order to make the method applicable to the complex industrial reality, a number of capacity constraints, which are relevant in the lifecycle context, have been considered and the method has been extended in order to account for these constraints. The industrial case study indicates that the proposed method can give valuable results when comparing alternative manufacturing system solutions. However, the method does not provide any suggestions for improving the system in terms of flexibility performance. It does not tell the engineers about the flexibility that is actually required in order for a feedback to the design parameters of the manufacturing system to be established; this is subject to future research. Finally, future research will

investigate the impact of different learning curves and different demand distribution profiles on the results of the proposed flexibility measure.

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Table 1. Total costs for both systems.

	Config.	Fixed Costs (€)	Variable Cost		Org. Cap. limit (x1000)	Capacity (x1000)
			Waste Cost (€)	Addit. Cost (€)		
Conventional Equipment	Conf <sub>A1</sub>	157 920	0.33 €	1	96.25	110
	Conf <sub>A2</sub>	230 640	0.33 €	1	113.75	130
	Conf <sub>A3</sub>	163 337	0.33 €	1	122.5	140
	Conf <sub>A4</sub>	237 874	0.33 €	1	140	160
	Conf <sub>A5</sub>	252 411	0.33 €	1	175	200
Advanced Equipment	Conf <sub>B1</sub>	167 835	0.33 €	1	96.25	110
	Conf <sub>B2</sub>	248 187	0.33 €	1	113.75	130
	Conf <sub>B3</sub>	173 650	0.33 €	1	122.5	140
	Conf <sub>B4</sub>	256 910	0.33 €	1	140	160
	Conf <sub>B5</sub>	280 169	0.33 €	1	175	200

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Table 2. Change cost (in €) matrix for System A.

Config.	Conf <sub>A1</sub>	Conf <sub>A2</sub>	Conf <sub>A3</sub>	Conf <sub>A4</sub>	Conf <sub>A5</sub>
Conf <sub>A0</sub>	0	0	1 434 214	1 434 214	3 430 614
Conf <sub>A1</sub>	0	0	1 434 214	1 434 214	3 430 614
Conf <sub>A2</sub>	0	0	1 434 214	1 434 214	3 430 614
Conf <sub>A3</sub>	-403 333	-403 333	0	0	1 766 400
Conf <sub>A4</sub>	-403 333	-403 333	0	0	1 996 400
Conf <sub>A5</sub>	-761 333	-761 333	-412 000	-412 000	0

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Table 3. Change cost (in €) matrix for System B.

Config	Conf <sub>B1</sub>	Conf <sub>B2</sub>	Conf <sub>B3</sub>	Conf <sub>B4</sub>	Conf <sub>B5</sub>
Conf <sub>B0</sub>	0	0	1 251 514	1 251 514	2 666 314
Conf <sub>B1</sub>	0	0	1 251 514	1 251 514	2 666 314
Conf <sub>B2</sub>	0	0	1 251 514	1 251 514	3 173 914
Conf <sub>B3</sub>	-457 333	-457 333	0	0	1 234 800
Conf <sub>B4</sub>	-457 333	-457 333	0	0	1 003 200
Conf <sub>B5</sub>	-814 667	-881 333	-357 333	-357 333	0

Table 4: Case study results.

Scenario Profile <sup>a</sup>	System A			System B		
	EDCF	DEVDCF	NDEVDCF	EDCF	DEVDCF	NDEVDCF
U(70 000,200 000)	9 888 399	550 220	10,00%	11 290 760	495 685	6,61%
U(70 000,190 000)	9 660 931	579 951	10,54%	11 092 476	482 558	6,43%
U(80 000,160 000)	8 308 482	277 364	5,04%	10 227 861	269 478	3,59%
U(90 000,150 000)	8 202 413	245 207	4,46%	10 122 060	227 394	3,03%
U(110000,140000)	8 184 877	156 016	2,84%	10 098 834	129 334	1,72%
N(150000,50000)	10 265 421	525 077	9,55%	11 658 148	514 868	6,86%
N(150000,40000)	10 238 873	474 642	8,63%	11 628 984	468 471	6,25%
N(150000,40000)	10 236 499	406 037	7,38%	11 594 422	387 661	5,17%

<sup>a</sup>Note that  $U(i, j)$  is uniform distribution between  $i$  and  $j$ . While  $N(m, d)$  is a normal distribution with  $m$  as mean and  $d$  as deviation

List of figures

Figure 1: Tree representation of the minimum DCF problem instance

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Figure 2: Algorithm extension to generate first  $L$  best solutions

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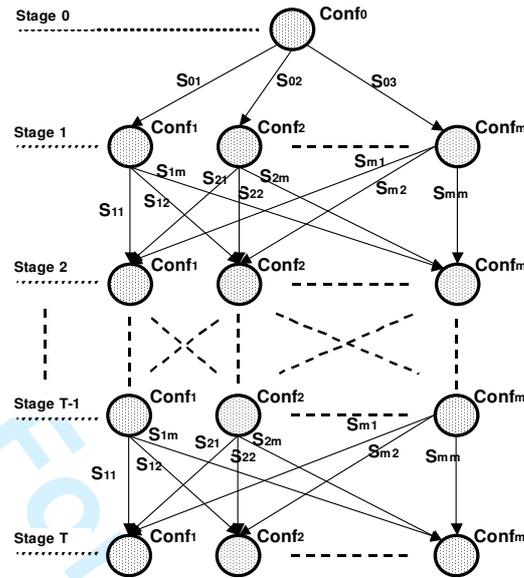


Figure 1: Tree representation of the minimum DCF problem instance

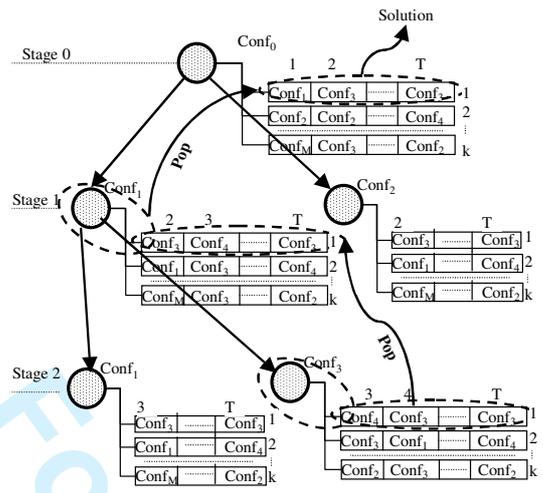


Figure 2: Algorithm extension to generate first  $L$  best solutions