Volume and Product Flexibility: a Case Study for a Refrigerators Producing Facility

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Abstract

This paper presents a study of flexibility for the punching department in a commercial refrigerators manufacturing system. Three different technology solutions for the punching department are studied under different sets of production requirements: conventional press machines, CNC machines and laser machines solution. Analysis of changing the required production volume, as well as the introduction of new products takes place and thereafter volume and product flexibility provided by the punching department has been studied. The flexibility of the system is investigated with the use of the Penalty of Change (POC) method. The application of the method gives a good picture of the flexibility characteristics for the alternative solutions for the punching department.

1. Introduction

Shorter product lifecycles and increased number of new models and variants have forced companies to improve the flexibility of their production systems, so they can easily adapt to changes. Flexibility is a major competitive advantage in response to continuously changing market environment [1]. Consequently, the quantification of flexibility has been the focus of academic work for a long time but its application in industry is limited.

In this paper, volume as well as product flexibility of a punching department in a manufacturing system has been studied. The following definitions for volume and product flexibility are given in [2]:

- *Volume flexibility* is the ability to operate profitably at different production volumes
- *Product flexibility* is the ability to change over to produce new products very economically and quickly

The company, under study, produces commercial refrigerators. The purpose of this study at the company is to analyze the flexibility of the punching department in order to understand the ability of the system to adapt to increasing demand or introduction of new products.

1.1. Background and literature review

In [1] it is stated that '*flexibility of a manufacturing system is determined by its sensitivity to change*' while in [3] flexibility is defined as the ability of the system to quickly adjust to any change in relevant factors like product, process, loads and machine failure. Flexibility, however, cannot be properly considered in the decision making process if it is not appropriately defined in a quantitative manner [2]. A number of approaches have been proposed in the literature for measuring several types of flexibility, such as machine, process, product, routing, volume, expansion, operation and production. The entropy concept [4] and its revised version [5] from thermodynamics provide similarities to the flexibility measures. Simulation of Petri nets that can provide estimates of the time a system needs to adapt to random disturbances and can be used as flexibility measurements, are described in [6]. Alternatively it is suggested that flexibility can be estimated relatively to a reference task set [7]. Other researchers have employed financial analysis to account for the benefits of flexibility [8]. Principles from mechanical system's dynamics have been used for modeling and assessing manufacturing system's flexibility [9]. While in [10] and [11] they employ fuzzy logic rules that include engineers' and managers' expertise for measuring manufacturing flexibility. The value of flexibility has been also explored in financial terms [12], where they suggest an aggregate metric for flexibility in terms of the expected net present value of all relevant cash flows associated with a system's response to random, unanticipated changes. Volume flexibility of a system is studied in [13], by examining the shape of the cost per piece curve of the system for different production volumes while in [14], an extensive list of drivers and sources regarding volume flexibility is presented. Finally, in [15] is studied the flexibility of two assembly lines, by calculating the

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manufacturing costs for changing a system to produce new products. Thorough reviews on approaches for assessing flexibility can be found in [16], [17], [18] and [19].

1.2. Method overview

In order to assess flexibility characteristics of the manufacturing system under study, the Penalty of Change (POC) concept [20] has been adopted. POC is a generic measure since it can be applied in different flexibility types, combines both technological and economical terms, does not require large and complex amounts of data for calculations, it is easy to apply to realistic manufacturing situations by practitioners and be interpreted by the management.

The POC can be defined as:

$$\mathrm{POC} = \sum_{i=1}^{D} \mathrm{Pn}(X_i)\mathrm{Pr}(X_i) \qquad (1)$$

Where:

D is the number of potential changes

X_i is the i^{th} potential change

$Pn(X_i)$ is the penalty cost of the i^{th} potential change

$Pr(X_i)$ is the probability of the i^{th} potential change to occur

The lower POC is, the higher the flexibility. If the cost of change is low, then POC will be low, indicating high flexibility. If the probability of change is low, then POC will again be low, even if the cost of change is relatively high. This reflects the fact that a system should not be considered inflexible when it has a high penalty for changes that have little probability of occurring. By the same token, a system should not be considered much more flexible than another system when it has a minimal penalty for changes, when those changes have little probability of occurring. The value of POC is based on two inputs: penalty for potential change ($\mathrm{Pn}(X_i)$) and probability of potential change ($\mathrm{Pr}(X_i)$), where change X_i is a transition from one "state" to another. The nature of a state depends on the type of flexibility considered: for product flexibility, a state may be the type of products manufactured by the system; for volume flexibility it may be the demanded production rate. The penalty cost includes relevant costs such as equipment investment cost (machines, tooling etc), labour training, reprogramming, opportunity cost and other.

2. Manufacturing system description

The POC method is applied in a real industrial system that produces commercial refrigerators. An overview of the production process of the system is presented in Figure 1. Raw materials go through cutting, punching and bending departments where the first formation of parts takes place. Then the parts end up in a buffer in order to follow the painting, the assembly of internal and external cabins and the insulation while the parts with surfaces that need printing, go through the printing department. Some parts have to pass through the cooling, the electrical, and the doors/shelves departments. At the end, all the parts pass through the final assembly department where the final product is assembled in one assembly line.

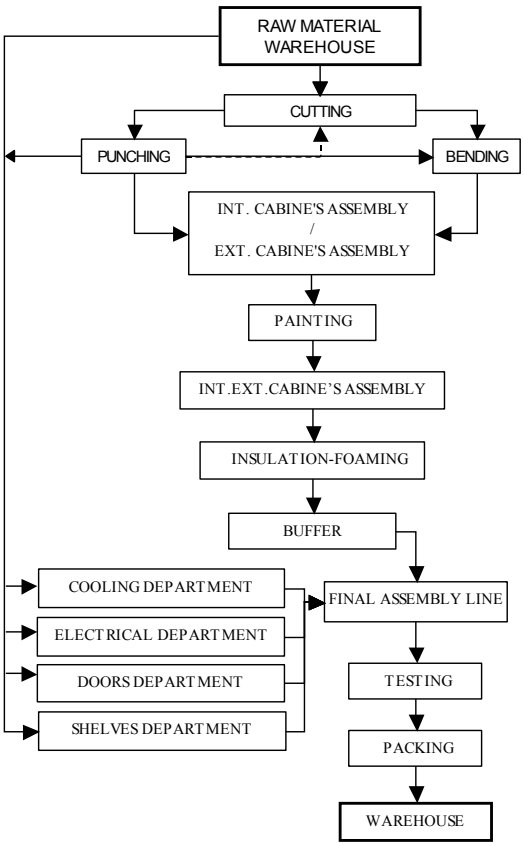


Figure 1: Production process overview

The case study presented in this work focuses on the *punching department*. More specifically three alternatives for the technology that could be adopted by the punching department are analysed using the POC concept. These solutions are:

- *Press machine*: The press machine produces different parts with the use of different tools (mainly dies). Consequently, the penalty costs associated with the press solution are the investment cost for the machine and the costs for the tools. The investment cost per press machine is 70 000 €.
- *CNC punching machine*: The CNC machine produces different parts by loading different programs on the machine. Thus, the penalty costs of the machine associated by the machine are investment, jigs and fixture costs. The investment cost per CNC machine is 120 000 €.
- *Laser machine*: The laser machines can be reprogrammed, thus the only penalty cost is the investment cost, which is 200 000 € per machine.

The system produces four different products. Each product consists of a number of parts that need to be processed by the punching department and each machine spends an amount of time for producing a part. In Tables 1 to 4, the time required by each machine, along with the tool cost associated for producing each part, are presented. Moreover, the punching department operates on a two-shift model (7.5hours/shift). Consequently, the annual machine capacity, if the machine works 220 days/year, is 198 000 min = 60(min)*7.5(hours)* 2(shifts)*220(days) of available processing time. Using this approach, the capacity of the system expressed in products produced per year can be calculated. For example, a press machine can produce 198000/2.23 = 88789 products of model A (if it is assumed that only products of model A are produced).

Table 1: Product A processing times and tool costs

		Press		CNC		Laser
Part	Description	Time(min)	Tool cost	Time(min)	Tool cost	Time(min)
A1	Cabin's base	0.33	20 000 €	0.75	-	1.08
A2	Cabin's bottom	0.30	18 000 €	0.72	-	0.80
A3	Inner liner bottom	0.33	16 000 €	0.67	1 500 €	0.75
A4	Inner liner top	0.33	16 000 €	0.67	-	0.58
A5	Inner liner side	0.67	17 000 €	2.33	-	1.83
A6	Canopy	0.27	9 000 €	0.68	1 000 €	0.43
Total		2.23		5.82		5.48

Table 2: Product B processing times and tool costs

		Press		CNC		Laser
Part	Description	Time(min)	Tool cost	Time(min)	Tool cost	Time(min)
B1	Cabin's base	0.37	27 000 €	0.75	-	1.08
B2	Cabin's bottom	0.37	24 000 €	0.72	-	0.80
B3	Inner liner bottom	0.37	19 000 €	0.67	1 500 €	0.75
B4	Inner liner top	0.37	16 000 €	0.67	-	0.58
B5	Inner liner side	0.67	17 000 €	2.33	-	1.83
Total		2.13		5.13		5.05

Table 3: Product C processing times and tool costs

		Press		CNC		Laser
Part	Description	Time(min)	Tool cost	Time(min)	Tool cost	Time(min)
C1	Cabin's base	0.25	20 000 €	0.75	-	1.08
C2	Cabin's bottom	0.22	18 000 €	0.72	-	0.80
C3	Inner liner bottom	0.25	16 000 €	0.67	1 500 €	0.75
C4	Inner liner top	0.25	16 000 €	0.67	-	0.58
C5	Inner liner side	0.50	17 000 €	2.33	-	1.83
C6	Canopy	0.18	9 000 €	0.68	1 000 €	0.43
Total		1.65		5.82		5.48

Table 4: Product D processing times and tool costs

		Press		CNC		Laser
Part	Description	Time(min)	Tool cost	Time(min)	Tool cost	Time(min)
D1	Cabin's base	0.25	17 000 €	0.67	-	1.08
D2	Cabin's bottom	0.22	15 000 €	0.63	-	0.80
D3	Inner liner bottom	0.25	13 000 €	0.58	1 500 €	0.75
D4	Inner liner top	0.25	13 000 €	0.58	-	0.58
D5	Inner liner side	0.50	13 000 €	1.83	-	1.83
Total		1.47		4.30		5.05

Moreover, the number of machines of each type that should be used for accommodating a required demand can be calculated by equation (2).

$$N_i = \left\lceil \frac{\sum_{p=1}^{P} (Time_{pi} * Demand_p)}{198000} \right\rceil \quad (2)$$

Where:

N_i is the number of machines of type i (i.e. press, CNC or laser)

P is the total number of models that need to be produced in one year

$Time_{pi}$ is the time required by machine i to produce a product of model p

$Demand_p$ is the amount of products of model p that need to be produced in the period of one year

Apart from the investment cost, the tooling cost is also included in the penalty cost (Pn(X_i)) factor of equation (1). The tooling can be shared among the machines of the came type. For example if only models A and B must be produced, and initially there is one press machine (along with both tooling required) that can accommodate the demand, but in the next year another press machine has to be purchased (because demand has increased), then there is no need to purchase the tools again since the tools can be shared among the machines.

The factory in order to facilitate its capacity planning as well as other functions such as balanced production schedule for the final assembly line uses a factoring between the various models produced. Therefore the basic model of the product mix, model A, is considered equal to one Standard Unit (STU) and larger models to higher values and subsequently smaller ones to smaller values. The ratios used mainly depict the required labour time but includes also dimensions like material cost, sales price and profit margin. The STU approach can be used to keep the total production volume constant (in terms of STU) while changing the product mix (as in the case of studying product flexibility). In Table 5 the STU ratio for all models of interest is given:

Table 5: STU equivalence per model

Model	A	B	C	D
STU per model	1	1.7	0.7	0.55

3. Production requirements

The production system is analyzed under the view of two different production requirements. These exemplary requirements were derived from original marketing data that are typical for the sector. The original information was more complex including both volume changes and product mix changes. The data has been filtered in order to accommodate the need to study volume and product flexibility independently.

- *Modifications in volume*: In this set two products (Model A and Model B) are produced throughout the horizon of interest. However, their production volume may change significantly. In the first year, the system produces models A and B in the annual quantities of 60 000 and 25 000 parts respectively. In the second year, there is a possibility of 30% that an increase of 20% in the volume will take place. In the third year, there is the possibility of 60% that an increase of 30% will take place and a possibility 30% that a 40% increase will occur. The possible production volumes for both products are presented in the tree of Figure 2. In Figure 3, the probabilities of each change, that has a corresponding penalty cost, are presented.

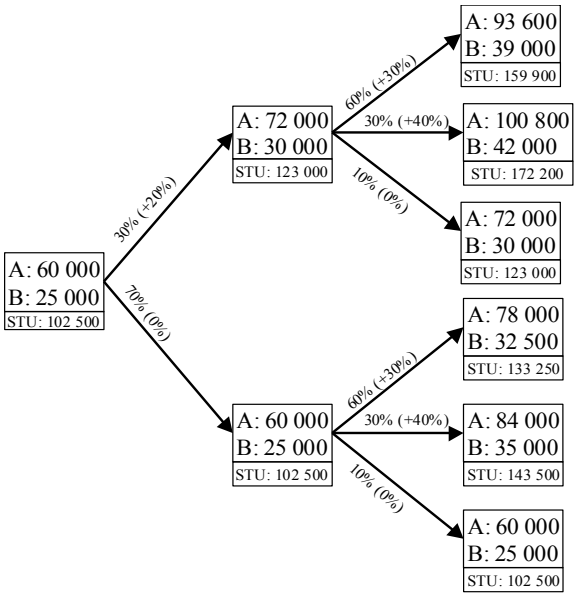


Figure 2: Potential changes in the production volume

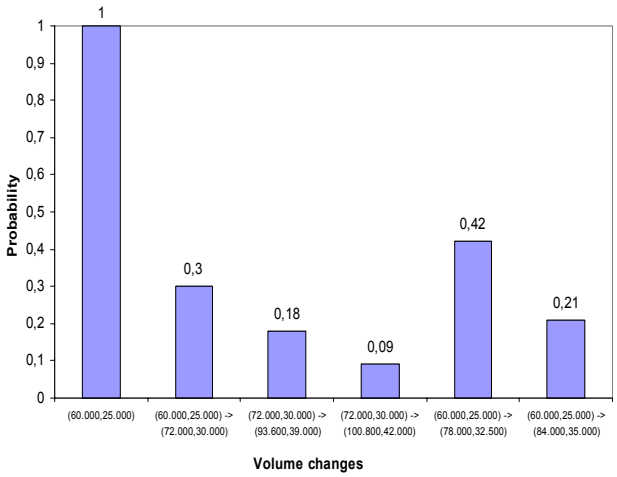


Figure 3: Probability of potential volume changes

- *Modifications of product mix* (by keeping the total factories' capacity constant in STUs): In the first year, only products A and B are produced. Then product C with probability 30% might be produced. In the third year, product D with probability 60% might be produced. The tree in Figure 4 presents all the possible stages in the types of products that might be produced. While in Figure 5 the probabilities of each of the four potential product changes, that have a corresponding penalty cost, are presented. In this case, it should be mentioned that the same total quantity of STUs per year are produced for all possible product mixes. Thus, the required production volume remains constant regardless of the changes in the product types produced.

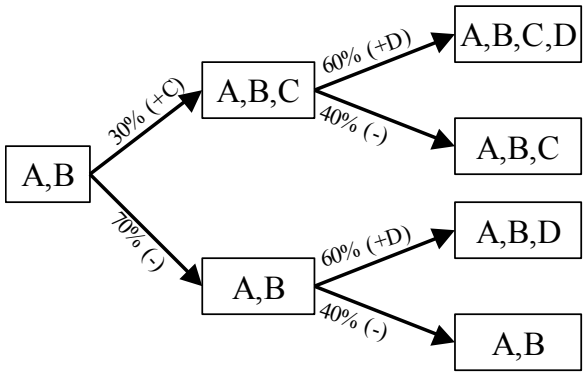


Figure 4: Potential changes in the products

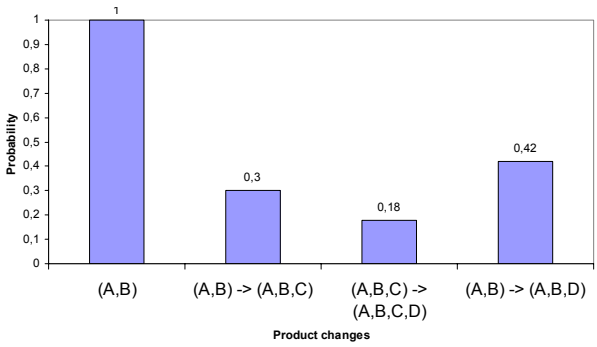


Figure 5: Probability of potential product changes

4. Application and results

The requirements defined in section 3 have been applied in equation (1) for the production system defined in section 2.

4.1. Volume flexibility

Based on the production requirements given in Figure 2 and their probabilities (Figure 3) the POC can be calculated using equation (1) for six changes. In order to calculate the state of the punching system (i.e. the number of machines and tooling used) for each change, equation (2) is used. Then, it is possible to calculate the penalty cost for changing between states. In this case, since only two models are produced throughout the horizon, there is no tooling cost included in the penalty cost, except from the initial state (60 000, 25 000), since tooling reuse is possible. Thus, only machine investment cost is considered in the penalty costs calculations. The penalty for each change is shown in Table 6. Moreover, Table 6 shows the required capacity (in minutes) and number of machines required by each solution

Thus, the volume flexibility of each machine type is given is given by (3), (4), (5)

$$POC_{press} = 1.0*269000+0.3*\ 70000 + 0.18*0 + 0.09*0 + 0.42*70000 + 0.21*70000 = 334100\ € \quad (3)$$

$$POC_{CNC} = 1.0*364000 + 0.3*0 + 0.18*120000 + 0.09*240000 + 0.42*120000 + 0.21*120000 = 482800\ € \quad (4)$$

$$POC_{laser} = 1.0*600000 + 0.3*0 + 0.18*200000 + 0.09*200000 + 0.42*0 + 0.21*200000 = 696000€ \quad (5)$$

The results indicate that the press solution is the best alternative as far as only changes in the production volume are considered since it has the minimum POC value.

4.2. Product flexibility

In the same manner, as in the case of volume flexibility, the product flexibility of the two solutions has been calculated. The changes and their corresponding costs and number of machines required are presented in Table 7. In this case tooling cost is also considered in the calculation of the penalty costs, since new products are introduced during the time horizon.

Thus, the Penalty Of Change of each machine type is given is given by (6), (7), (8)

$$POC_{press} = 269000*1.0 + 96000*0.3 + 141000*0.18 + 71000*0.42 = 353000\ € \quad (6)$$

$$POC_{CNC} = 364000*1.0 + 2500*0.3 + 1500*0.18 + 1500*0.42 = 365650\ € \quad (7)$$

$$POC_{laser} = 600000*1.0 + 0.3*0 + 0.18*0 + 0.42*0 = 600000\ € \quad (8)$$

The results indicate that the press solution is the best alternative as far as only changes in the product models are considered. However, it is obvious that the performance of the press solution has been reduced with regards to the volume flexibility case, while the performance of the CNC machine has been significantly increased.

5. Conclusion

This work investigates volume and product flexibility of the punching department of a production system. The POC approach is used for this purpose. Detailed description of alternative solutions (i.e. conventional press, CNC and laser) is given, as well as description of the requirements imposed by the market. A rather practical approach to define the capacity requirements and the possible states in which the system should operate is given and the penalty costs associated to system changes among states are calculated. The application of the method using real

Table 6: Changes, capacities and penalty costs introduced (volume flexibility case)

Change	Probability	Press			CNC			Laser		
		Capacity (min)	N_{press}	Penalty (€)	Capacity (min)	N_{CNC}	Penalty (€)	Capacity (min)	N_{laser}	Penalty (€)
(60.000, 25.000)	1.0	187 050	1	269 000	477 450	3	364 000	455 050	3	600 000
(60.000,25.000)-> (72.000,30.000)	0.3	224 460	2	70 000	572 940	3	0	546 060	3	0
(72.000,30.000)-> (93.600,39.000)	0.18	291 798	2	0	744 822	4	120 000	709 878	4	200 000
(72.000,30.000)-> (100.800,42.000)	0.09	314 244	2	0	802 116	5	240 000	764 484	4	200 000
(60.000,25.000)-> (78.000,32.500)	0.42	243 165	2	70 000	620 685	4	120 000	591 565	3	0
(60.000,25.000)-> (84.000,35.000)	0.21	261 870	2	70000	668 430	4	120 000	637 070	4	200 000

Table 7: Changes and penalty costs introduced (product flexibility case)

Change	Probability	Press		CNC		Laser	
		N_{press}	Penalty (€)	N_{CNC}	Penalty (€)	N_{laser}	Penalty (€)
(A,B)	1	1	269 000	3	364 000	3	600 000
(A,B) -> (A,B,C)	0.3	1	96 000	3	2 500	3	0
(A,B,C) -> (A,B,C,D)	0.18	2	141 000	3	1 500	3	0
(A,B) -> (A,B,D)	0.42	1	71 000	3	1 500	3	0

data regarding the processing capabilities of the machines and exemplary data for market requirements, indicate that the conventional press solution performs better in most cases and especially when volume flexibility is considered.

However, it is shown that in the case of product flexibility the CNC solution increases its performance considerably and should be further investigated if the number of product models further increases. Laser technology fails to account as a good solution mainly due to its very high initial investment cost. The study shows that in addition to other manufacturing system costs and performance measures, the POC measure provides a quantitative basis for the implementation of critical capital investment decisions in manufacturing technology. Future work will consider studying the impact of setup time introduced for changing production among different models. Moreover, changes regarding both required volume and products will also be studied using the POC concept and the possibility to have hybrid solutions for the punching department (e.g. both press and CNC) will be investigated as well.

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References

[1] G. Chryssolouris, *Manufacturing Systems-Theory and Practice*, (New York: Springer-Verlag), 1992.

[2] G. Chryssolouris and M. Lee, "An Assessment of Flexibility in Manufacturing Systems", *Manufacturing Review*, Vol.5(2), pp. 105-116, 1992.

[3] N. Nagarur, "Some performance measures of flexible manufacturing systems", *International Journal of Production Research,* Vol.30(4), pp. 799-809, 1992.

[4] V. Kumar, "Entropic Measures of Manufacturing Flexibility", *International Journal of Production Research*, Vol.25(7), pp. 957-966, 1987.

[5] A. Y. Chang, D. J. Whitehouse, S. L. Chang and Y. C. Hsieh, "An approach to the measurement of single-machine Flexibility", *International Journal of Production Research*, Vol.39(8), pp. 1589-1601, 2001.

[6] M. Barad and D. Sipper, "Flexibility in Manufacturing Systems: Definitions and Petri Net Modelling", *International Journal of Production Research*, Vol.26(2), pp. 237-248, 1988.

[7] P. H. Brill and M. Mandelbaum, "On Measures of Flexibility in Manufacturing Systems", *International Journal of Production Research*, Vol.27(5), pp. 747-756, 1989.

[8] D. Gupta, "On measurement and valuation of manufacturing flexibility", *International Journal of Production Research*, Vol.31(12), pp. 2947–2958, 1993.

[9] G. Chryssolouris, N. Anifantis and S. Karagiannis, "An approach to the Dynamic Modelling of Manufacturing Systems", *International Journal of Production Research*, Vol.36(2), pp. 475-483, 1998.

[10] N. Tsourveloudis and Y. Phillis, "Fuzzy Assessment of Machine Flexibility", *IEEE Transactions on Engineering Management*, Vol.45(1), 78-87, 1998.

[11] A. Beskese, C. Kahraman and Z. Irani, "Quantification of flexibility in advanced manufacturing systems using fuzzy concept", *International Journal of Production Economics*, Vol.89(1), pp. 45-56, 2004.

[12] R. Ramasesh, S. Kulkarni and M. Jayakumar, "Agility in manufacturing systems: An exploratory modeling framework and simulation", *Integrated Manufacturing Systems*, Vol.12 (7), pp. 534–548, 2001.

[13] M. Khouja, "An aggregate production planning framework for the evaluation of volume flexibility", *Production Planning & Control*, Vol.9(2), pp. 127-137, 1998.

[14] E. P. Jack and A. Raturi, "Sources of volume flexibility and their impact on performance", *Journal of Operations Management*, Vol.20(5), pp. 519–548, 2002.

[15] A. Kurtoglu, "Flexibility analysis of two assembly lines", *Robotics and Computer-Integrated Manufacturing*, Vol.20(3), pp. 247-253, 2004.

[16] A. K. Sethi and P. S. Sethi, "Flexibility in manufacturing: a survey", *The International Journal of Flexible Manufacturing Systems*, Vol.2, pp. 289- 328, 1990.

[17] De Toni and S. Tonchia, "Manufacturing Flexibility: a literature review", *International Journal of Production Research*, Vol.36(6), pp. 1587 – 1617, 1998.

[18] R. Beach, A. P. Muhlemann, D. H. R. Price, A. Paterson and J. A. Sharp, "A review of manufacturing flexibility", *European Journal of Operational Research*, Vol.122(1), pp. 41-57, 2000.

[19] R. Giachetti, L. Martinez, O. Seanz and C. Chen, "Analysis of the structural measures of flexibility and agility using a measurement theoretical framework", *International Journal of Production Economics*, Vol.86, pp.47-62, 2003.

[20] G. Chryssolouris, "Flexibility and its Measurement", *Proceedings of the CIRP Annals*, Vol.45(2), pp. 581-587, 1996.