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On Quantifying Manufacturing Flexibility: An Entropy Based Approach

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Abstract— **In this research, an entropy based evaluation is adapted for the quantification of manufacturing flexibility. The aim is to evaluate the manufacturing flexibility in scope of a job shop model and to reach a single numeric value that would represent the overall flexibility level of operations performed in that manufacturing unit. The model proposed is applied to a job shop in which manufacturing is characterized by type of machinery, number and type of operations and routing for each product as well as time spend for operations, machine set up activities and material handling. In the paper, the flexibility level of the job shop is found and the association between the total entropy value and flexibility level is discussed.**

***Index Terms*— Manufacturing flexibility, Entropy, Manufacturing activities, Job shop**

I. INTRODUCTION

THE conversion of raw materials into useful articles by means of physical labor or power-driven machinery simply constitutes manufacturing process [1]. Manufacturing has an on-going, adaptive and complex structure with interrelationships between different components, which are balanced and coordinated into an integrated whole [2]. Industrial firms should have the ability of adapting their own organizational and operational structures according to the change-aimer effects of environment to the utmost.

In addition to the competition and other environmental forces in the market, customers' unique and time-based expectations also require generating some effective organizational adjustments for firms. As a result of this, manufacturing units generally have some serious problems about coping with ever-changing situations.

Flexibility is a strategic imperative that enables firms to cope with uncertainties [3]. It fosters the ability to meet increasing variety of customer expectations with no excessive cost, time or resources. Manufacturing flexibility simply deals with the design and installation of any manufacturing system which is flexible enough to perform a variety of operations in order to produce different variety of components and products [4]. Evaluation of flexibility may help in providing some quantitative results that the manufacturing units require [5].

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II. MANUFACTURING FLEXIBILITY

Manufacturing flexibility involves multiple factors. That's because most of the concepts concerning to flexibility are merely related to particular situations.

In literature, a variety of flexibility types are studied. For instance; adaptation, assembly system, application, dispatch, job, material, state, design, demand and machining system flexibilities are mentioned in [6]. Reference [7] refers to changeover, rerouting and sequence flexibilities. Reference [8] notices operation and expansion flexibilities. Process, program, product and production flexibilities are studied by [9]. Reference [10] distinctly addresses new product, labor and modification flexibilities. When the classification and relevant definitions of flexibility are examined, it can be seen that studies in literature usually consider a limited number of components of overall flexibility of a manufacturing system.

Some authors divide flexibility into its sub-elements. For example, in Zhang's model proposed in [3] the "*Flexible manufacturing competences*" are determined as machine flexibility, labor flexibility, material handling flexibility and routing flexibility. These elements all together result in "*Flexible manufacturing capabilities*" which are volume flexibility and mix flexibility. Fig 1. summarizes how customer satisfaction is provided. In parallel with this definition, [11] claims that focusing on volume and mix flexibility as the main capabilities of flexible manufacturing is not intended to ignore the other components of manufacturing. In order to provide better understanding, the elements of flexibility based on this model are explained below.

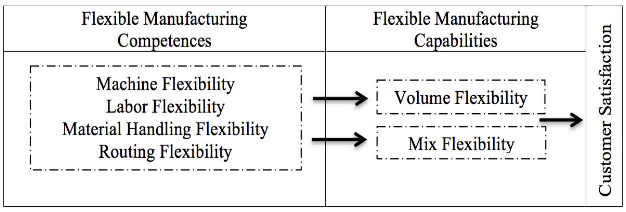

Fig 1. Flexible Manufacturing Competences and Capabilities

A. *Flexible Manufacturing Competences*

Machine Flexibility

Machine flexibility enables the machine process for different operations to keep a low machine idle time [4]. It defines the ability of a machine to be set up quickly and to handle product variety [12]. Among the various types of manufacturing in literature, machine flexibility is regarded

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one of the most important and fundamental one that other types of flexibility generally depend on [13].

Machining time, inefficient idle time, setup time, and repair time determine the general machine status. Among these, the machining activity is the only activity that adds value to the parts produced and other activities are in fact no needed for manufacturing [14].

Labor Flexibility

It shows the ability of a worker to handle various types of jobs and the easy adaptation for the transitions among several tasks. The level of flexibility may be affected by the physical conditions of workers as well as the degree of their capabilities, experiences and personal tendencies.

Material Handling Flexibility

Material handling flexibility is the ability of the material handling system to transport and locate workpieces of different types and sizes. The larger material handling flexibility is, the better the machines can be supplied with workpieces. Thus, flexibility of the machines is not hindered by the limitations of material handling system. Technical design and the layout of transportation paths can influence material handling flexibility [8].

Routing Flexibility

Routing flexibility enhances a system easier scheduling of parts by better balancing the machine loads and allows the system to produce a given set of part types or part families without interruption [15]. It applies when a workpiece with a given process plan can follow different routes through the system. Several identical machines can be alternatively used for performing an operation [8]. The flexibility of system routing reduces the possibility of bringing a production line to a halt when unexpected events occur [15]. A system with alternative production routes can maintain a high production performance when one of the machines is broken down or under maintenance.

In a job shop environment which are characterised by large variety of components and functionally grouped general-purpose machines; the routing flexibility is especially more important. The parts are routed around in small lots to various machines and the products are diverse so as to provide customer satisfaction.

B. Flexible Manufacturing Capabilities

Volume Flexibility

Volume flexibility is defined as the ability of a production system to adjust amount of output for demand fluctuations [12]. It is also described as the ability of the system to work economically at different output levels.

Changing production volume for some products requires to use production equipment for different additional tasks and have the ability to change output rates of machines and work cells [9]. Therefore, volume flexibility can be defined as a property of the system as a whole [8].

Mix Flexibility

The uncertainty as to which products will be accepted by customers creates a need for the mix flexibility. It includes changeover and modification flexibilities together. Changeover flexibility deals with the uncertainty as to the length of product life cycles and modification flexibility is directly about the uncertainty as to which particular attributes customers would desire [7].

III. Entropy as a Measure of Flexibility

Entropy is a thermodynamic property which is a measure of energy that is not available for work in thermodynamic processes. It is defined by the second law of thermodynamics and expresses the disorder, randomness or complexity in the system. The close relationship between uncertainty and flexibility suggests the use of entropy to measure flexibility. Entropy simply measures the degree to which energy is mixed up inside a system that is spread or shared among the components [16].

The static complexity of the manufacturing system may be assessed through the Shannon entropy [17]. Entropy is a logarithmic measure of number of states. The general equation for Shannon entropy is given in (1). Relevant parameters of the equation are as follows.

S: Total entropy value

k_B: Boltzzman's constant

P_i: Relative share of ith outcome in an experiment (Probability of being at ith state)

n: Number of possible outcomes in an experiment (Number of possible states)

$$S = -k_B \sum_{i}^{n} P_i \ln P_i \qquad (1)$$

Through the mathematical inference, S attains the maximum value in the equiprobable case, when $p_i = {}^1\!/_N$ for all i values.

Conversely, S vanishes in the case that some $p_j = 1$ (and thus, $p_j = 0$ if $i \neq j$) [18].

IV. Application

In order to reach a single numeric value to represent the overall flexibility level, the input parameters of this study are selected from manufacturing competences. Because of the fact that the concept 'time' is an an integrating indicator for the characteristically different types of flexibility elements; the attributes corresponding to the machine, labor, material handling and routing are included to the model in a time-based view. Manufacturing flexibility is calculated according to the type and operational sequence of machinery, number and type of operations and routing for each product as well as time spend for operations, machine set up activities and material handling.

The job shop examined has the capability of producing 10 different products via 10 machines located in a certain layout plan.

The machines in the job shop are encoded as T035, T043, F30, F31, F32, M6, PL6, BS2, BA1 and PAH. The types of machines and corresponding codes are listed at Table I according to their functions.

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TABLE I
MACHINES AND CODES [19]

Machine Codes	Machines
TO35	Turning machine
TO43	Turning machine
PL6	Planer
M6	Drilling machine
BA1	Vertical slotting machine
BS2	Broaching machine
F31	Hobbing machine
PAH	Deburring machine
F30	Hobbing machine
F32	Milling machine

The layout in job shop enhances the system for easier scheduling of parts by better balancing the machine loads and allows the system to produce a given set of part types or part families without interruption. Manufacturing flexibility could be addressed at different levels: the individual machine, the local system of machines, a manufacturing section of the factory that makes a particular part or product or the entire factory or company. For the static measurement of manufacturing flexibility, a snapshot should be analyzed to reflect the instant situation in the job shop.

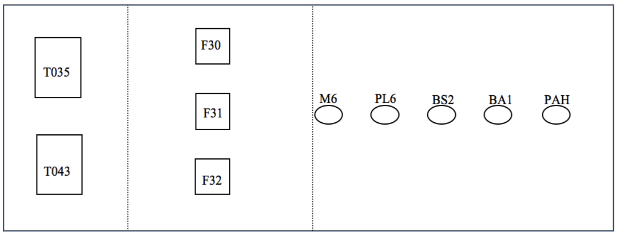

Fig 2. Layout of machines

Fig.2 shows the layout plan of machines. Any product to be processed is transported to the required *first* machine (according to its operational sequence) in 60 seconds. The transportation of products between the machines is performed according to the time table shown in Table II. The values for the transportation time between two machines are given in seconds, which have to be converted into minutes in the calculation phase. Matrix given below is symmetrical across the diagonal.

TABLE II
TRANSPORTATION TIME MATRIX (SEC.)

	T035	T043	PL6	M6	BA1	BS2	PAH	F30	F31	F32
T035										
T043	10									
PL6	60	60								
M6	40	40	20							
BA1	100	100	40	60						
BS2	80	80	20	40	20					
PAH	120	120	60	80	20	20				
F30	20	20	40	20	80	60	100			
F31	20	20	40	20	80	60	100	10		
F32	20	20	40	20	80	60	100	10	10	

In the job shop, some products are produced through several operation steps whereas some are completed in only one operation. The operational data including operational sequences for each product type are given in Table III.

TABLE III
OPERATION AND SETUP TIMES [19]

Product Type	Operational Sequence	Machinery Sequence	Operation Time (in minutes)	Machine Setup Time (in minutes)
P1	1	TO35	180	45
	2	TO43	60	25
	3	PL6	60	5
	4	M6	130	5
	5	BA1	120	25
P2	1	TO43	166	23
	2	TO35	158	43
	3	PL6	60	15
	4	M6	90	3
	5	BA1	64	23
P3	1	BA1	37	37
P4	1	BA1	37	37
P5	1	BA1	26	37
P6	1	BA1	37	37
P7	1	BS2	12	23
	2	F31	40	43
	3	PAH	10	5
	4	F32	32	43
P8	1	F30	20	25
P9	1	F30	32	25
P10	1	F31	100	43
	2	F32	60	43
	3	PL6	64	5

Each worker has different working speed from one another. However, the speed value remains same for each operator. The time losses are determined under another assumption of longer lasting operational activity on its specific machine, necessitates a higher level of qualified worker.

In order to capture the dynamic aspect of machine and routing flexibilities, elements such as the probability of assigning an operation to a machine and the probability of assigning and transferring an operation from one machine to another can be considered [20]. In this study, relative shares are used to determine the contribution of each operation to the total entropy value. With this aim, the operations are considered separately and products are transferred as production planning requires.

To observe the overall operating pattern in sequence for each machine, a sample manufacturing plan is firstly prepared to have a general point of view. In this plan, according to product type (x) and related operational sequence (m), the operation process sequences are named as (xm) – with a two digit indicator. (e.g. The indicator 73 shows the 3rd phase of product 7). It is accepted that, the process goes through continually until the last operation is accomplished and there is no interruption in producing the products requiring multi-processes as long as the machines are available for the next operation. Each machine is used immediately after the last process is finished. The sequence priorities are also considered within the operation phases of a product but there is no priority between producing different products. The uncertainty is about which set of products to be produced or which products to be desired by the customers. Therefore an uncertainty also exists about which products to produce and how much time that it is allocated in total time.

For the analysis, data is grouped in machine based approach at onset. Time values corresponding to process, machine set up time and downtime originated from labor and transportation are separately analysed according to the product type that each machine performs. Table IV shows the product types and relevant machines.

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TABLE IV
MACHINES AND PRODUCT TYPES

Machines	Products
TO35	P1-P2
TO43	P1-P2
PL6	P1-P2-P10
M6	P1-P2
BA1	P1-P2-P3-P4-P5-P6
BS2	P7
PAH	P7
F30	P8-P9
F31	P7-P10
F32	P7-P10

Each product is treated for different period of times in different operational sequences and on different machines in order to gain its last form. The time passed to produce one type of product through different phases on different machines can be seen in Table III. The period of time defined as the manufacturing time of the job shop is the sum of the all periods of time that are allocated for given products.

From the system view, overall flexibility is the sum of the flexibilities of the system's functions [7]. Therefore, the total entropy value can be calculated as the sum of the portions of the entropy belongs to each machine in the system.

The input parameters of the model proposed are as follows:

t_o: Machine operation time
t_s: Machine set up time
t_t: Transportation time between subsequent machines
t_l: Downtime originated from labor
n: Indicator for machine type
m: Indicator for operation sequence in the production steps on machine n
t_{total}: Total time for production of all products in job shop
S: Entropy value
k: Constant for entropy calculation
p: Relative share

$$t_{total} = \sum_{n=1}^{10} \sum_{m=1}^{10} (t_{o_{nm}} + t_{s_{nm}} + t_{t_{nm}} + t_{l_{nm}}) \quad (2)$$

The entropy for a manufacturing unit is calculated by the entropy formula where p is the relative share and the constant k is set to 1 [9].

$$S_i = -k \sum_{i=1}^{m_i} p_{ij} ln\, p_{ij} \quad (3)$$

The relative share p is calculated by a proportion of total time spend for all manufacturing activities on a machine to the total time spend for all machines.

For each machine subject to $n = [1,10]$;

$$p_n = \frac{(to_n + ts_n + tt_n + tl_n)}{T_{total}} \quad (4)$$

Then the entropy value on a specific machine can be calculated by means of Shannon formula as in (5).

$$S_n = -(p_n \ln p_n) \quad (5)$$

The total entropy which is also an indicator for the flexibility degree of the manufacturing unit can be calculated as in (6).

$$S_{total} = -\sum_{n=1}^{10} p_n \ln p_n \quad (6)$$

The relative shares and entropy values of machines are summarized in Table V.

TABLE V
RELATIVE SHARES AND ENTROPY VALUES

Machines	p_n	$-p_n \ln p_n$
(T035)	0,19038	0,31579
(T043)	0,12274	0,25747
(PL6)	0,095742	0,22462
(M6)	0,102492	0,23347
(BA1)	0,234951	0,3403
(BS2)	0,016389	0,06738
(F31)	0,102047	0,2329
(PAH)	0,007783	0,03779
(F32)	0,080607	0,20298
(F30)	0,046867	0,14343
Total Entropy		2,05615

The graphical distribution of relative shares and related entropy values of each machine may be observed in Fig. 3. It can be seen that both parameters show similar characteristics at different numeric value levels. Higher values for each machine represent the entropic variation while lower values indicate relative shares.

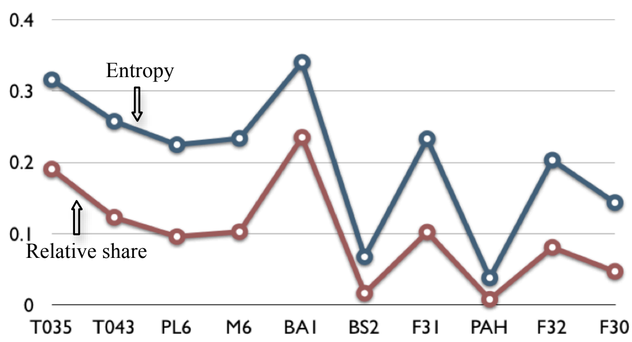

Fig 3. Entropy and relative share variation

The entropy shares calculated through Shannon formula for job shop and the results on processing time, set-up time, transportation time and downtime caused by operators are grouped based on relevant machines and the results are calculated accordingly. The total entropy value of the operations on the manufacturing unit is as in (7).

$$S_{total} = 2.05615 \quad (7)$$

In Fig. 4. it can be seen that the machine based group total entropies are different for each machine. The maximum value belongs to the machine BA1 while the lowest values belong to PAH and BS2. That is directly related to the number of part types that these machines can perform. The machines that are able to process various kinds of parts have

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a higher impact on both entropy value and overall flexibility.

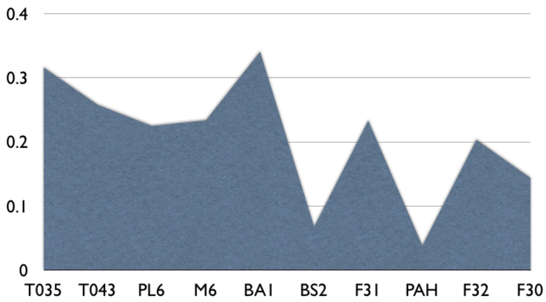

Fig.4. Entropy measurement results of machines

Entropy values are analyzed by means of the time that separately allocated for process, set up, transportation and labor operation for each product type. The relative shares of machines are calculated as follows:

Relative share for each process;

$$p_p = \frac{t_p}{\sum_{i=1}^{10} t_{p_i}} \quad (8)$$

Relative share for each machine set-up;

$$p_s = \frac{t_s}{\sum_{i=1}^{10} t_{s_i}} \quad (9)$$

Relative share for each transportation period;

$$p_t = \frac{t_t}{\sum_{i=1}^{10} t_{t_t}} \quad (10)$$

Relative share for the time lost originated from labor;

$$p_l = \frac{t_l}{\sum_{i=1}^{10} t_{l_i}} \quad (11)$$

In order to analyse the distribution of entropy, relative shares are used. The entropy values of process set up, transportation and the time loss stemmed from operators for each machine are calculated.

It can be observed that the time losses for the work to be performed on specific machine entropies are equal to "0". That means the *p* values (relative share) is equal to "1" since $\ln 1 = 0$.

The basic difference of these "0" entropy value machines from the others are the number of their operation steps. During the manufacturing period, the PAH and BS2 machines have only 1 process step for this production. Therefore we can claim that these machines as inflexible. In other words, if the relevant product is taken out of product mix; the machine would not perform any operation within that manufacturing unit. Analyzing the maximum entropy values of all belong to BA1 machine operation has the maximum operation steps of "6". The operations performed for the production of relevant products on this machine is the most flexible one among various operations grouped.

In Table VI the entropy values for manufacturing activities are given in detail.

TABLE VI
ENTROPY VALUES

Operations	Entropy of The Time Spent	Operations	Entropy of The Time Spent
Process T035	0,6910274	Process BS2	0
Set up T035	0,6928889	Set up BS2	0
Transport T035	0,4011899	Transport BS2	0
Labour T035	0,6931472	Labour BS2	0
Process T043	0,578718	Process F31	0,5982696
Set up T043	0,6922789	Set up F31	0,6931472
Transport T043	0,4011899	Transport F31	0,6931472
Labour T043	0,6931472	Labour F31	0,6931472
Process PL6	1,098,143	Process PAH	0
Set up PL6	0,9502705	Set up PAH	0
Transport PL6	0,9936232	Transport PAH	0
Labour PL6	10,986,123	Labour PAH	0
Process M6	0,676526	Process F32	0,6460905
Set up M6	0,6615632	Set up F32	0,6931472
Transport M6	0,6931472	Transport F32	0,2976804
Labour M6	0,6931472	Labour F32	0,6931472
Process BA1	16,400,083	Process F30	0,6662784
Set up BA1	17,729,916	Set up F30	0,6931472
Transport BA1	17,917,595	Transport F30	0,6931472
Labour BA1	17,917,595	Labour F30	0,6931472

V. CONCLUSION

The external dependencies and corresponding uncertainties in manufacturing environments force manufacturing units to adapt themselves to volatile conditions. Numerous studies in relevant literature advice manufacturers to enhance the adaptability level of their manufacturing units. Despite this interest, it remains poorly understood and has limited reflection on practice.

Manufacturing flexibility is a complex and multidimensional subject. This nature of flexibility encourages researchers to limit their studies with few dimensions. In addition, the studies that focus on the measurement of flexibility are scarce in literature.

This study proposes a model that consider overall operational flexibility for a job shop. In the model proposed, manufacturing characteristics such as type of machinery, number and type of operations and routing for each product as well as time spend for operations, machine set up activities and material handling are considered to calculate flexibility level of manufacturing unit. An application of the model to a job shop is performed to analyze whether or not a time based flexibility measure can adapt to entropy based evaluation method for flexibility including the total time loss in every step of the manufacturing.

The overall entropy is calculated as the sum of the partial entropies of 10 machines in job shop. The machines that perform work on more products have higher relative share and thus, have the higher entropy value. It is accepted in literature that higher entropy value indicates a higher level of manufacturing flexibility.

However the total entropy value (2.0516) can not be evaluated as a standard in a universal scale such as the value read from a thermometer. That makes the result difficult to compare among the various manufacturing units. The measure is a more suitable indicator for comparing the pre or post results of the same manufacturing unit. In this way, minor contributions that would decrease the time loss and their effects on flexibility level may be observed.

Relative share is the hidden indicator of entropic evaluations. Any change in time does not only change the related time variable but also affects the total time value. Therefore, the relative share change does not have a regular or predictable form.

Research into the measurement of flexibility, when viewed at the system level, is likely to continue to appear inconsistent and confusing. For further research, a computer simulation of the job shop can be used to test the measure through a number of different scenarios using a discrete-event stochastic simulator in order to evaluate the performance of the measurement system with various possible values of relevant parameters.

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