Evaluation Of The Routing Flexibility Of Flexible Manufacturing System

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***Abstract*—The current competitive and dynamic economic context, requires to manufacturing companies to be reactive and dynamic. For that, they should get a flexible manufacturing system able to change the production plan easily and economically. A good Flexible Manufacturing System (FMS) must have a transportation system able to support a dynamic scheduling and potential failure of the manufacturing system. In this paper, we present a methodology for the dynamic evaluation of the routing flexibility of a manufacturing system. This methodology is based on the computation of entropy and uses Coloured Petri Net model and simulation. We have two objectives:(1) the development of a simulation model able to forecast the level of flexibility of a FMS before its implementation, (2) the definition of an indicator for measuring flexibility. For illustrating our methodology we take an example of a flexible job shop of four machines and one transport resource.**

I. INTRODUCTION

Flexible Manufacturing Systems (FMSs) consist of *a set of flexible machines (robot, multi-purpose machines or workstations), an automatic transport system and a decision making system (scheduler) to decide at each instant (When) what has to be done (What) and on which machine (Where)* [1]. The concept of flexibility of a manufacturing systems have been addressed by several researchers such as [2], [3], [4], where they define more than ten levels of flexibility in a manufacturing system. Namely, machine flexibility, material handling flexibility, operation flexibility, process flexibility, product flexibility, routing flexibility, volume flexibility, expansion flexibility, program flexibility and market flexibility. it was demonstrated that the cost of FMS is higher than the classical manufacturing system (Dedicated production lines for example) [5], [4]. In order to reduce the cost of this kind manufacturing systems, each flexibility should be evaluated and optimized. Several researchers have proposed methods for the evaluation of the flexibility [6], [7], [8], [9], [10], [11]. The routing flexibility is an important aspect on flexibility and it is closely related the scheduling and the production plan. It's also related to other kind of flexibility such as the machine flexibility and the process flexibility. The evaluation of the routing flexibility represents an interesting research issue[12]. This paper propose a methodology for the dynamic evaluation of the routing flexibility of a FMS. Our methodology is based on definition of dynamic decision matrix, that can be tested on a simulator developed using Hierarchical Coloured Petri Net (HCPN) model. In the section II we detail the concept of routing flexibility, in the section III we present the developed methodology and in the section IV the case study used to implement the developed methodology is presented.

II. THE ROUTING FLEXIBILITY

In literature, there are many definitions of the Routing Flexibility (RF). [2] defines RF as *the ability to handle breakdowns and to continue producing the given set of part types. This ability exists if either a part type can be processed via several routes or, equivalently, if each operation can be performed on more than one machine.* Recently, [13] defines the routing flexibility as *the ability of a manufacturing system to use multiple alternate routes to produce a set of parts.* In [2], [14] the authors take in consideration three aspects of the routing flexibility: the efficiency, the versatility, and the homogeneous distribution of the alternative routes. The efficiency of routing flexibility considers the operating costs and time of the alternative routes for producing parts. The versatility take into consideration the number of routes of parts. The proposal of our work is to evaluate the RF of a FMS. Chang et *al.* [15] proposed a model for the measurement of routing flexibility considering two of its aspect namely: efficiency and versatility. In [16] they define an indicator named routing variety which is an attribute that quantifies differences of the alternative routes available for processing a family parts. To compute the efficiency of routing flexibility [17] used an output Concurrency and Coordination Runtime (CCR) model taking into account manufacturing costs and operating data as input variables and the quantity and the quality of the routes as output. [18] proposed an entropic measure of the versatility of the routing flexibility. In the recent research of [14] the three aspect of flexibility has been developed and more indexes has been developed such as:

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the Alternative Route Efficiency (ARE), Job Routing Average Efficiency (JRAE), Job Routing Range (JRR), Job Routing Versatility (JRV), Global Routing Efficiency (GRE), Global Routing Range(GRR), Global Routing Versatility (GRV) and Global Routing Flexibility (GRF), most of this indicators are correlated and presenting different aspects of the same three basic indicators. In that paper authors defined routing flexibility for each part type and then define a global routing flexibility for the whole manufacturing system. In our work we will measure the routing flexibility of a whole manufacturing systems through the entropy calculation of a decision matrix that we define in the section III. This matrix is computed for each basic element of the path of the product.

In this paper will develop a methodology based on simulation model and coloured Petri Nets for the evaluation of routing flexibility through the three aspect of routing flexibility namely: versatility, efficiency and homogeneous distribution of each elementary path.

III. METHODOLOGY OF ROUTING FLEXIBILITY EVALUATION

This section presents a methodology based on Hierarchical Coloured Petri Nets (HCPN) for the evaluation of the routing flexibility of manufacturing systems. The effect of the other type of flexibility, mainly the flexibility of machine, and the product flexibility, on the routing flexibility is demonstrated through different scenarios implemented in the developed simulator. It's also possible to observe, through the simulation, how the scheduling strategy affects this routing flexibility. This methodology is divided in four steps.

- Development of a simulation model based on HCPN of the manufacturing systems
- Definition of a decision matrix embedded in the simulation model
- Definition of an entropy matrix based on the decision matrix.
- Simulation of model and evaluation of the flexibility of the manufacturing system.

A. Definition of the hierarchical Coloured Petri Nets Models

We use the hierarchical coloured Petri Nets models in our work the following reasons:

- Petri Nets is useful for the modelling and the simulation of discrete event systems.
- Coloured Petri Nets(CPN) improves the description power of simple Petri Nets. CPN allows the easily modelling of discrete event systems. For example the differentiation of product inside a manufacturing systems is more difficult with the using of simple Petri Nets than the use of Coloured Petri Nets.
- Hierarchical Coloured Petri nets model of machine can be re-used for the modelling of other manufacturing system.

The developed HCPN model is shown in the Figure 1

The transitions `M1`, `M2`, `M3`, `M4` represent Machines and transitions `MDT` and `SCT` are used to model the transportation system. The transportation task is divided in two steps: (1) the selection of the product (transition `SCT`) and (2) the movement of a product from a pick-up area towards a drop-off area (the transition `MDT`). Places `IN1, IN2, IN3, IN4` are the drop-off area, and places `OUT1,OUT2,OUT3,OUT4` are the pick-up areas. This model have been detailed in our previous publications ([19]). The Figure 2 shows the first steps of the transportation system.

Places `IN1`, `IN2`, `IN3`, `IN4` and places `OUT1`, `OUT2`, `OUT3`, `OUT4` are respectively the pick-up and drop-off areas as shown on Figure 2. The presence of token in place `Mvt` means that a product and a transporter has been reserved for insuring transport. The place `LTM` contains the list of tools of each machine. The place `Time` represents the clock of the simulation model. The fact that each place is connected to the transition `T1` has one main advantage namely the control of transportation process. Indeed, this configuration allows to collect information concerning stocks and transport resources at each step of the transport process. This information allows the definition of a criteria matrix in order to define a decision making process for the transportation control. In the next section (section III-B) we present the criteria matrix which will be used to define the decision making process.

B. Definition of the decision matrix

A decision matrix is defined in order to solve decision making problem such as scheduling, and transportation through heuristics. The transportation system, in a FMS, consists of materials handling, and the pick-up and drop-off area. A transport activity consist in the movement of a product from one pick-up area towards a drop-off area. The drop-off and pick-up area are most of time respectively the input and output buffer of workstations. The control problem can be divided in two levels: (1) the problem of scheduling of the waiting queues in the drop-off and pick-up areas of machines and (which product will be transported first in the same drop-off queue (2) the management of transport policy (from where the transporter will pick-up the product and where he will drop-off it).

In order to manage the transportation system, we need information about pick-up and drop-off area, material handling and products.

The important information concerning the pick-up area (output buffer) are: the position of this area, its size, the number of product present in the buffer and the next operation of each product present in the buffer. The important information concerning the drop-off area (input buffer) are: its position, its size, the time process of each product and the capability of the workstation related to this area. The important information concerning the material handling are: the number of transporters, their current positions, their velocity and their transport capacity (in our case we assume that there is only one transporter with a capacity of one product).

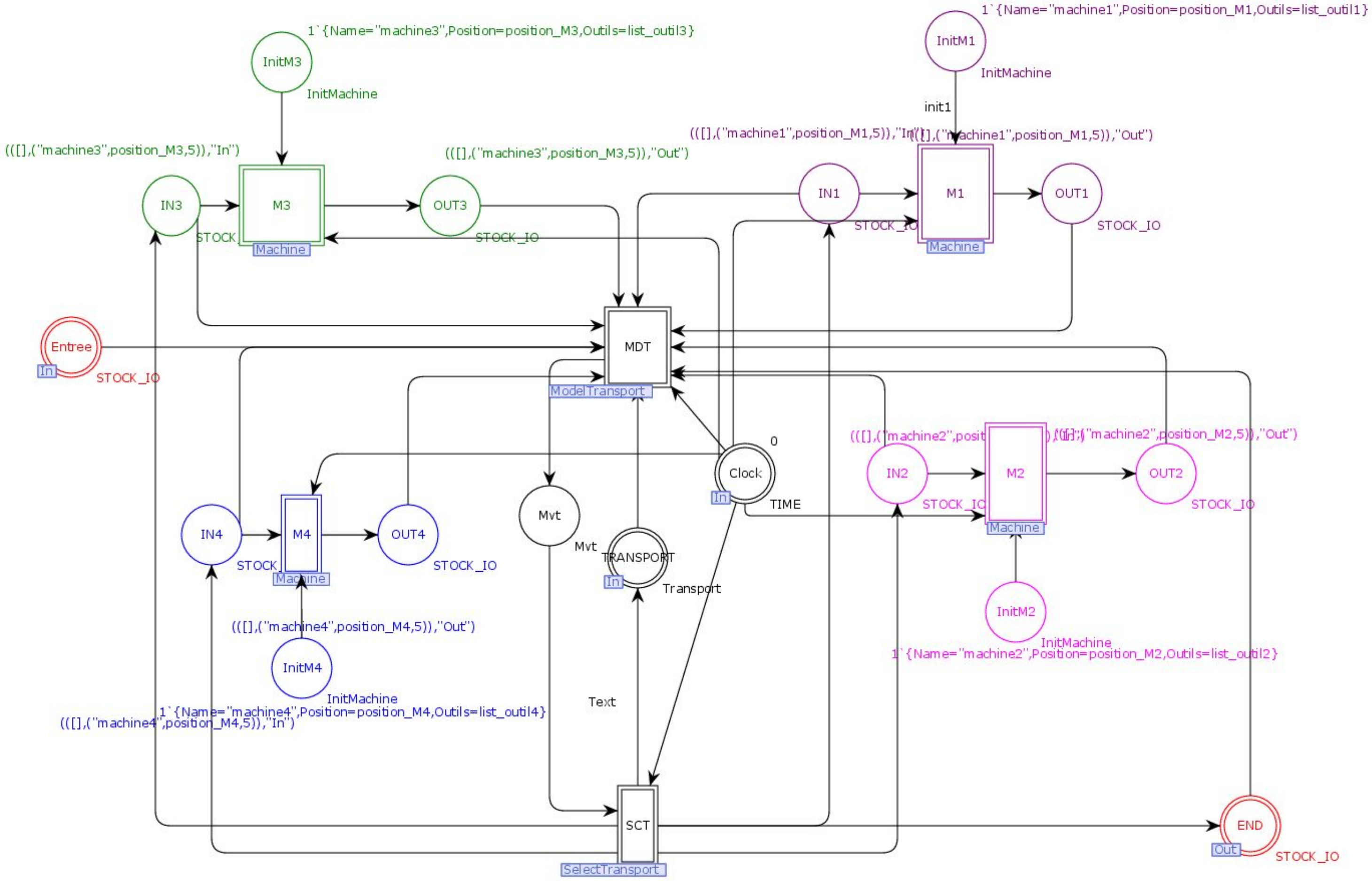

Fig. 1. Hierarchical Petri Nets Models of Job Shop

We have defined some working hypotheses to define the framework of the study: (1) The material handling flexibility is total (each material handling is able to perform all the transport operations); (2) The management rule of stocks is First In First Out (FIFO) for all stocks and buffers of the workshop; (3) A machine and its input and output buffer are supposed to have the same position in the workshop; (4) There is only one transportation resource with a transport capacity of one.

The decision matrix at the instant t for a workshop composed of m workstation and $m+1$ pick-up area and $m+1$ drop-off area and one transporter with consideration of J decision criteria can be defined as shown on the Table I.

Where :

- PuA_k is the Pick-up-Area number k with $0 \leq k \leq m$;
- DoA_l is the Drop-off Area number l with $0 \leq l \leq m$;
- $A_{i,j}$ is the value of the criteria j if the path i is chosen;

This table is generated at each time where the transportation resources have to perform a transport task. This matrix will be used for the decision making algorithm to help transporter to chose the product to transport and its destination. In the simulation model, presented above, the criteria table are automatically generated when the transition `T1` is enabled.

C. Routing flexibility evaluation

The evaluation of the routing flexibility is defined by the entropy of the corresponding decision matrix. In order to evaluate the flexibility regarding several criteria we propose to normalise the criteria values and compute the sum of entropy of each criteria. We follow the following steps for the evaluation of the routing flexibility:

- Computation of the normalized value AN of the decision matrix A where:

$$AN_{ij} = \frac{A_{ij}}{\sum_i^I A_{ij}} \tag{1}$$

- Computation of the entropy for each criteria value :

$$h_{ij} = AN_{ij} \times ln(AN_{ij}) \tag{2}$$

- computation of the entropy of each criteria :

$$H_j = \sum_{i=1}^{I} h_{ij} \tag{3}$$

- The computation of the level of the routing flexibility of the workstation :

$$H = \sum_{j=1}^{J} H_j \tag{4}$$

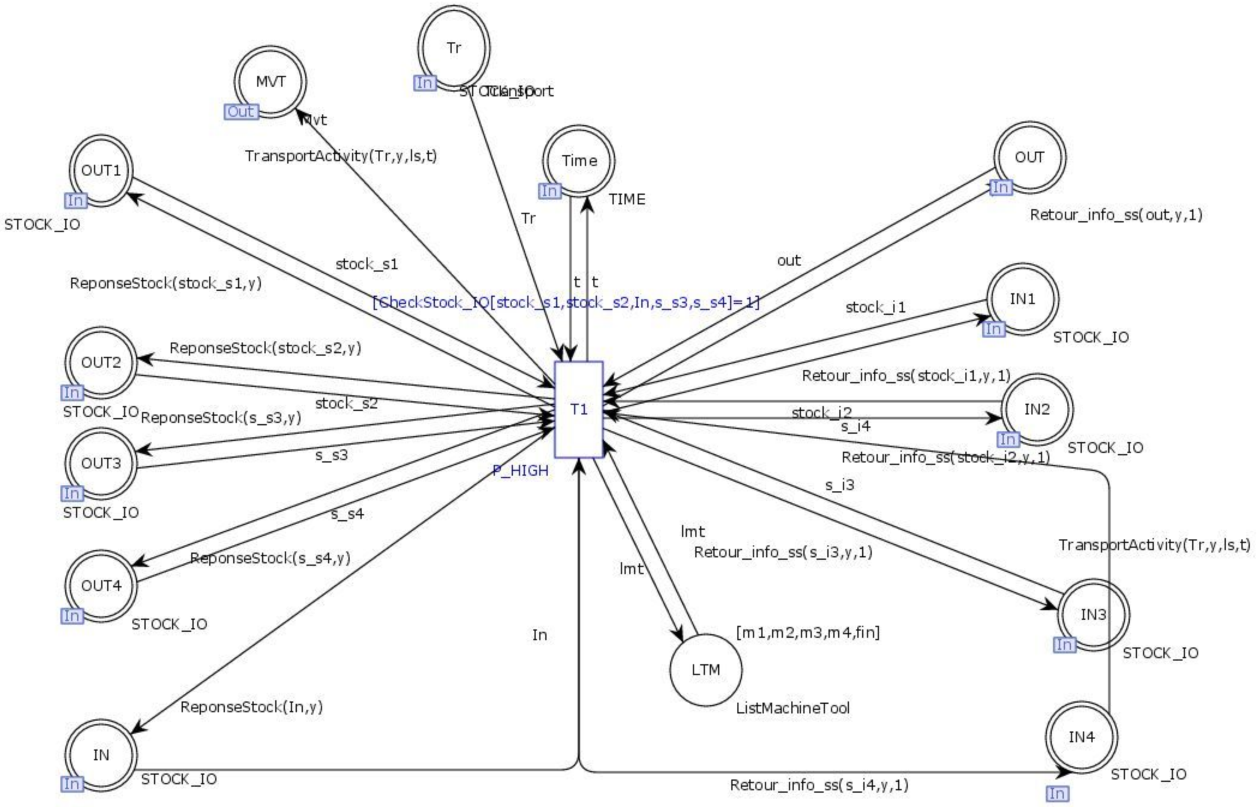

Fig. 2. Petri Nets Module of Selection of product

TABLE I
TABLE OF DECISION

		Data relative to transport activities				
		$criteria_1$	$\ldots$	$criteria_j$	$\ldots$	$criteria_J$
Possible path	$PuA_0 \longrightarrow DoA_1\ (path_1)$	A_{11}	$\ldots$	A_{1j}	$\ldots$	A_{1J}
	$PuA_0 \longrightarrow DoA_3\ (path_2$	A_{21}	$\ldots$	A_{2j}	$\ldots$	A_{2J}
	$PuA_1 \longrightarrow DoA_3\ (path_3)$	A_{31}	$\ldots$	A_{3j}	$\ldots$	A_{3J}
	$\vdots$	$\vdots$	$\ldots$	$\vdots$	$\vdots$	$\vdots$
	$PuA_k \longrightarrow DoA_l\ (path_i)$	A_{i1}	$\ldots$	A_{ij}	$\ldots$	A_{iJ}
	$\vdots$	$\vdots$	$\ldots$	$\vdots$	$\vdots$	$\vdots$
	$PuA_J \longrightarrow DoA_J\ (path_I)$	A_{I1}	$\ldots$	A_{Ij}	$\ldots$	A_{IJ}

IV. EVALUATION OF A JOB SHOP ROUTING FLEXIBILITY

This section presents a case study of a job shop composed of four flexible machines. The goal is to evaluate the routing flexibility during a production cycle. In this section we present first of all the case study of a flexible job shop and then how we measure the flexibility during a production cycle.

A. Operating data

Let a job shop with four flexible machines and one transport resource. A machine is considered as flexible if it can perform more than one operation requiring several tools. The list of tools used by each machine is shown in the Table II.

We have named tools with the letters **A** to **G**. The production range of the job shop is given by the table III

TABLE II
CAPABILITIES OF MACHINES IN TERM OF OPERATIONS

Machines	**Type of tools**	**Position of Machines**
M_1	A,B,E	(1.8;9.5)
M_2	C,D	(9.84;17.42)
M_3	D,C,B	(18.99;9.05)
M_4	E,F	(9.88;1.2)

Each operation is defined by the name of the tool used to perform it. The operation E is performed by the tool E. The operation IN is the entrance of product in the manufacturing system, and the OUT operation is the retirement of the product

TABLE III
OPERATION PERFORMED BY PRODUCTS

products	Tool used
$item_1$	IN → F→E→D→C→OUT
$item_2$	IN → F → B → E → C → D → OUT
$item_3$	IN → B → F → E → C → D → C → OUT

TABLE IV
OPERATION PERFORMED ON PRODUCTS IN CASE 1

products	Machine used
$item_1$	IN → M4→ M1 → M2 → M3 → OUT
$item_2$	IN → M4→ M1 → M4 → M2 → M3 → OUT
$item_3$	IN → M1→ M4 → M1 → M2 → M3 → M2 → OUT

from the manufacturing system.

B. Evaluation of flexible job shop

For the evaluation of the routing flexibility, we have considered an example of a production cycle of 150 products with a mix of three product type (50 products of each type item1, item2 and item3). The constraints of the scheduling are:

- The queuing strategy is FIFO for the pick-up and drop-off areas.
- The order of entering of the product in the Job Shop is *[item3, item2, item1, item3, item2, ..., item3, item2, item1]*
- In the beginning of the production cycle all the 150 products are already present in the global input buffer of the job shop.

For the evaluation of the flexibility, three cases study of flexibility are considered:

- *Case 1:* the problem of the assignment of operations to machines is supposed to be solved. It means that each operation is already assigned to a machine as it's shown in the Table IV
- *Case 2:* the products are not pre-assigned to machines. The production range defined in the Table III is used, where each product can be processed on any machine able to accomplish the needed operation. The capabilities of machines are defined in Table II .
- *Case 3:* each machine can perform any operation. in this case the products follow also the production range defined in the Table III.

As we use a simulation model, it is compulsory to defined control strategy of the simulation model [20]. We have used the matrix composed by the evaluation of the each elementary path regarding several scheduling rules III-B. This matrix will allow a dynamic evaluation of the routing flexibility of the production system.

C. Transport management strategy

The transport management strategy includes dispatching rules for the management of the transportation activity and rules for queueing management such as FIFO, LIFO . . . .

We have defined some dispatching rules in order to help transporter to take decision regarding the product to transport and buffer to deal with. We use the decision matrix defined in the section III-B (c.f. Table I) as input data of the control Algorithm 1. In order to construct the decision matrix, we have choose the following dispatching criteria.

- Size of pick-up area
- Size of the drop-off area where the part is supposed to be dropped.
- Distance travelled by the transportation resource to perform the transport between the pick-up area and the drop-off area.
- Waiting time of the product in the next probable drop-off area
- Processing time of the next operation

For insuring the control of the simulation model, we have developed an algorithm based on the decision matrix of possible paths to select the path that respects the defined rules classification. The objective of this algorithm is the choice of the decision concerning the transportation of one product toward one machine.

The next paragraph explains this algorithm:
Let $P_i = (A_{i1}, A_{i2}, A_{i3}, \ldots, A_{iM})$ a transport operation susceptible to be performed by a transportation resources. A transport operation is defined by the pick up area, the drop off area and the path used by the transporter for the product moving. To simplify we abusively call path the transportation operation of a product from a pick up area toward a drop off area. A_{ij} is the j^{th} criteria which characterizes the path i.
A_{ij} is the element of the decision matrix as defined in the Table I. The algorithm classify criterion according to its importance. The most important criteria is the first criteria of the decision matrix(from the left to the right) and the less important is the last column of the matrix. In this way the criterion of rang j is also the criterion of the j^{th} column of the decision matrix. The objective of the following algorithm is the choice of a best path in order to perform a transport activity. This algorithm is executed every time a decision of transport activity have to be taken.
We have implemented this algorithm in the HCPN simulator presented in Figure 1 in order to schedule the operations of transportation during the simulation. It is executed at each simulation step needing a transport operation. The use of this algorithm requires the classification of the dispatching criteria.

```
$P \leftarrow [P_1, P_2, P_3, \ldots, P_M]$    ▷ List of possible paths
$j \leftarrow 1$
$L \leftarrow min_{C_j}\{P_i\}$  ▷ List of paths with the smallest criteria of type $j$;
while $Length(L) > 1$ and $j \leq J$ do
    $j \leftarrow j + 1$
    $L \leftarrow min_{C_j}\{L\}$
end
$path \leftarrow hd(L)$  ▷ $hd$ is the function which shows the first element of a list $L$
```

Algorithm 1: Algorithm of transport management

Each criterion represents one column of the decision table. The importance of a criterion is defined by its position in the decision table. The criterion in the column 1 is more important that one in the last column.

For the case of study we have adopted the following classification of the dispatching criteria :

- *Criterion 1* :the size of pick-up area
- *Criterion 2* :the size of the drop-off area where the part is supposed to be dropped.
- *Criterion 3* :the distance travelled by the transportation resource to perform the transport between the pick-up area and the drop-off area.
- *Criterion 4* :the waiting time of the product in the next probable drop-off area;
- *Criterion 5* :the processing time of the next operation;

In the next section we present results of simulation for the evaluation of the flexibility.

D. Simulation and results

In this section we present the simulation results of the three cases that we have explained in the section IV-B. We have implemented the algorithm 1 inside the Hierarchical Coloured Petri Net model. The enabling of the transition T1(products wait for transportation) defines in the Figure 2 leads the construction of a decision table and the calculation of its entropy.

For each case we have determined the Makespan of the manufacturing systems process, the distance travelled by the transportation resource, The evolution of the entropy from the beginning at the end of a production cycle and the mean value of this Entropy. The calculation of makespan and the distance travelled by the transporter is the good to show how the flexibility affects the performance of a manufacturing system. The simulation results with the three cases are shown in the Table V. Figure 4 and Figure 3 are the evolution of the entropy and the number of possible paths in case 3. The Figure 3 is the evolution during a production cycle of 150 products and the Figure 4 represents this evolution between 150 and 1000 secondes. Figure 5 and Figure 6 are similar than Figure 4 and Figure 3 but for the case 2. Figure 7 and Figure 8 also present the evolution of the entropy and the number of possible paths in case 1. The Figure 5 is the evolution during a production cycle of 150 products and the Figure 8 represents this evolution between 150 and 1000 secondes.

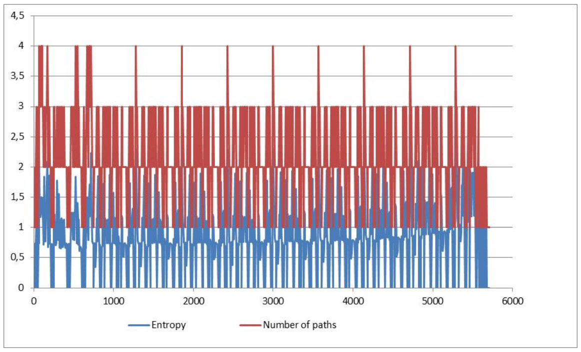

Fig. 3. Entropy of the routing flexibility of a cycle of 150 products

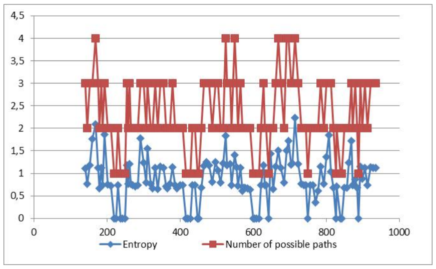

Fig. 4. Entropy of the routing flexibility

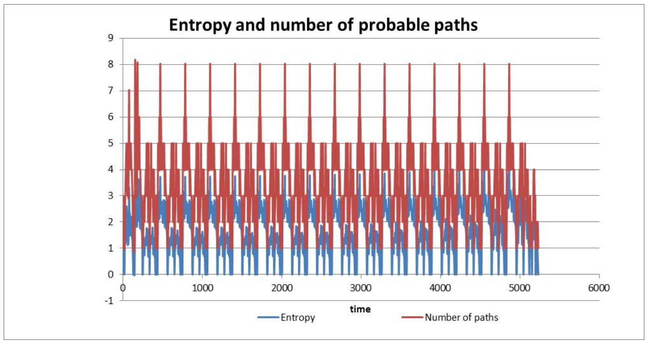

Fig. 5. Entropy and number of possible paths during a production cycle in case 2

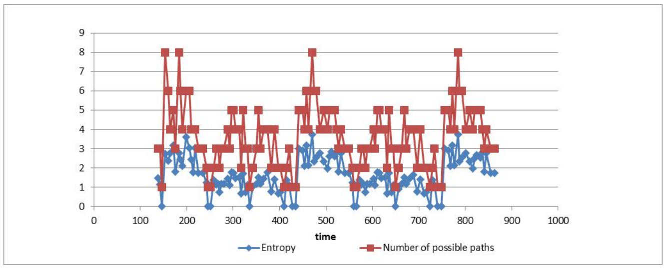

Fig. 6. Entropy and number of possible paths between 100 and 1000 seconds in case 2

The first observation that we can made for all curves is that the number of possible paths as the entropy have an serrated evolution. However the maximum values of this curves are not the same. For the case 1 the maximum number of paths is 4 and the minimum is 1; and the maximal value of entropy is 2 while the minimum value is 0. For the case 2 the maximum value of the number of possible paths is 8 and the minimum value is 1; and the maximal value of the entropy is around 4 and the minimal value is 0. Compared to the case 1 the maximum value of the number of possible paths, and entropy. It is due to the improve of the flexibility of the product. Indeed in case 1 each operation is already assigned to a machine and only one; for this reason the number of possible paths is lower than that one of the case 2. In the case 1 as there are four machines and each operation is assigned to only one machine, the maximum number of probable paths is four. In case 2, with the introduction of the product flexibility there is some

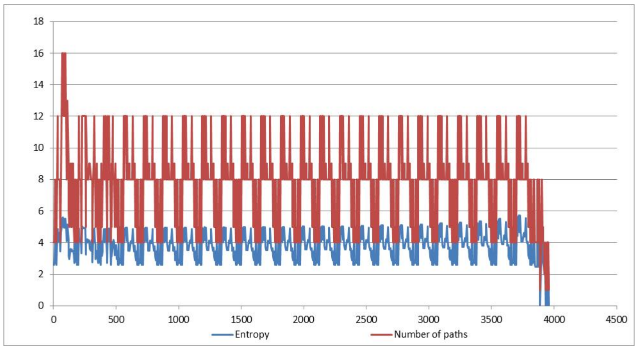

Fig. 7. Entropy and number of possibles paths in case 3

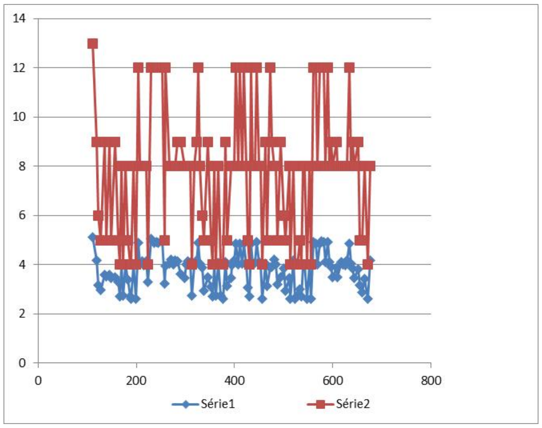

Fig. 8. Entropy and number of paths between 100 and 700 secondes in case 3

operations which can be performed by more than one machine. In this situation, it is normal than the number of probable paths is higher than 4 as in the case 1. In the case 3 the maximal number of possible paths is 16 and the minimum 4. Similarly, the maximal value of entropy is 5.72. This case presents a number of possible paths higher than the cases 1 and 2. The increase of the entropy and the number of possible paths in the case 3 is due to the total machines flexibility and product flexibility where the number of alternative solution is higher. With the introduction of the total flexibility of machines at each decision making instant there are at least four probable paths when there is also one product to move and in the case there one product to each pick up area, the number of probable paths is 16.

We also observe a relation between the augmentation of the flexibility and the entropy of the system. Indeed the introduction of the flexibility of the product (case 2) leads the increase of the entropy. We can conclude that the increase of the flexibility increase the entropy of the decision matrix. Finally we can observe that the improvement of the flexibility of the manufacturing system improves its efficiency. The gain of makespan between the case 2 and case 3 is to more than 30%, and the distance travelled by the transporter is reduced to 40%.

TABLE V
INDICATORS OF THE MANUFACTURING SYSTEM

	case 3	case 2	case 1
Average Entropy	3.83114	1.61	0.85
Distance Travelled	11556	17395	19641
makespan	3958	5238	5714

V. CONCLUSION

The purpose of our paper is the evaluation of the routing flexibility of a flexible manufacturing system. Indeed, we present a methodology of evaluation of the routing flexibility. As presented in the section II there are three main aspects of the routing flexibility: the versatility, the efficiency and the homogeneous distribution of the routes. This study has proposed a tool of computation of the routing flexibility based on all the three routing aspects. For this, we have used HCPN tools to model and simulate a flexible manufacturing system. A matrix containing an evaluation of each elementary path regarding all the considered decision criteria for dispatching is used to compute an indicator able to evaluate the routing flexibility including in the same time the structure of the production system and the strategy used to manage the transportation tasks.

We have illustrated the efficiency of the proposed routing flexibility indicator by testing it on a simple case study composed by one transporter and four machines. We have considered three situations with different levels of routing flexibilities.

Results confirm that the routing flexibility is highly impacted by the product and machine flexibility and the work in process (WIP). The proposed indicator has shown also that the routing flexibility is impacted by the adopted scheduling strategy for transport. Results show also that the routing flexibility is dynamic and variate in the time.

Our next works will focus on the development of a dynamic scheduling algorithm with several objectives. The establishment of such algorithm can help us to define relation between routing flexibility and other performance indicators of a FMS.

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