USING THE OAG TO BUILD A MODEL DEDICATED TO MODE HANDLING OF FMS

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Abstract: This paper deals with a modeling approach for *mode handling* of Flexible Manufacturing Systems (FMS). We show that using the plant model enables to establish aggregate operations. These are generic entities which depend only on the plant and do not depend on production goals. Aggregate operations are then used to build the model dedicated to mode handling. This study is illustrated through an example of a flexible manufacturing cell.

1 INTRODUCTION

We are interested in problems of monitoring and supervision in a fault tolerant control system dedicated to Flexible Manufacturing Systems (FMS) (Ranky, 1990). According to our approach, the supervision is made up of three functions: *decision*, *piloting,* and *mode handling*. The *monitoring* function (Elkhattabi et al., 1995; Toguyeni et al., 1996) detects and localizes the failures at the plant level. The *decision* function (Berruet et al., 2000) determines the new configuration of the FMS. The functions of *mode handling* and *piloting* (Tawegoum et al., 1994) implement the decisions about the new configuration of the FMS.

In order to achieve the role of *mode handling* within the control system, one should provide models representing the operating modes of the production system and its subsystems. The existing modeling approaches of operating modes of Automated Production Systems (APS) are compared in (Hamani et al., 2006). The advantages of functional modeling approaches are showed. Such approaches are concerned with the services delivered by the FMS rather than production means. Our approach (Hamani et al., 2006) is based on a functional modeling method. This approach is well adapted to FMSs because it is based on the mission concept (a production goal) which represents the flexibility which characterizes the FMS production. The obtained model is generic. For a given FMS, the predefined functional subsystems (called entities) are instantiated to generate the model. An aggregate operation is a generic entity depending only on the plant and not on production goals.

The purpose of this paper is to present a method to calculate aggregate operations from the plant model. The paper is organized as follows. Section 2 reminds the basic concepts of our modeling method and the steps of building the FMS functional model. Section 3 presents a method to determine aggregate operations from the plant model. An example of a flexible manufacturing cell is used to illustrate this study.

2 THE FMS MODEL

2.1 Basic Concepts

An FMS produces simultaneously a set of parts. Usually we desire to change production goals. That is why the mission concept is introduced in (Hamani et al., 2006). A mission ($\mathcal{M}$) is the subset of Logical Operating Sequences (LOS) which are produced simultaneously. A LOS is a set of ordered machining functions performed on some parts. A LOS is noted LOS $f_1 \ldots f_n$ or LOS f_i (i = 1, n).

With each function of a Logical Operating Sequence is associated its possible achievements. They are aggregate operations for which the machining operation is defined. An aggregate operation is a generic entity which depends only on the FMS plant and not on production goals. An aggregate operation corresponding to a machining Major Characteristic Area (MCA) noted $Op_{MCA\_machining}$ is a set of the corresponding elementary machining operations and Access Transfers. MCA concept is defined in (Hamani et al., 2006).

In an FMS, an operation (Op) is defined as a function carried out by a resource (Berruet et al., 2000; Toguyeni et al., 2003). An operation is noted $Op_{Ri,\ fi}$ where f_i is the performed function and R_i the resource which implements it. An elementary operation is an operation carried out only once, continuously, i.e. without the possibility to choose another alternative during the normal execution of the operation.

Access Transfers (TrA) associated with a machining area (or a MCA), noted $TrA_{machining\_MCA}$, correspond to the set of elementary transfer operations that connect this area to the other MCA of the FMS. An elementary transfer (TrE) is performed by one resource between two MCA. An elementary transfer is noted $TrE_{R_i}^{S \to D}$ with S a source CA, D a destination CA, and R_i the transfer resource.

2.2 The Specification Steps

The specification steps (Figure 1) of the FMS functional model are described in the following.

1st Step: Identification of the entities of the model

- list the missions that the FMS should carry out
- list for each mission its corresponding Logical Operation Sequences
- for each Logical Operating Sequence identify the corresponding machining functions

A machining function is implemented by one or several elementary machining operations. Each one is belonging to an aggregate operation.

- identify the aggregate operations of the FMS (see the 2nd step)
- for each aggregate operation, identify the resources which perform it (see the 3rd step)

2nd Step: Determination of aggregate operations (Figure 2). For each machining area of the FMS:

- identify elementary machining operations which are performed in this area
- identify the Access Transfers related to this area
- gather elementary machining operations together with Access Transfers identified previously to obtain aggregate operations

3rd Step: Determination of the resources that perform elementary operations

For each aggregate operation:

- associate with each elementary machining operation the resource or the configuration of the resource (in the case of a polyvalent resource) which performs it
- associate also with each elementary transfer operation the resource (or the resources) which performs it, redundant resources are linked with a logical OR.

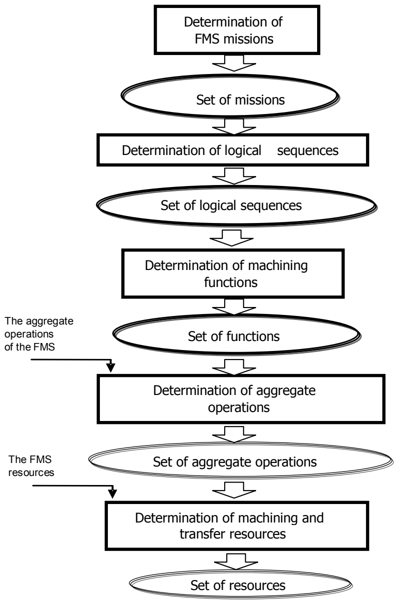

Figure 1: Specification steps of the FMS entities.

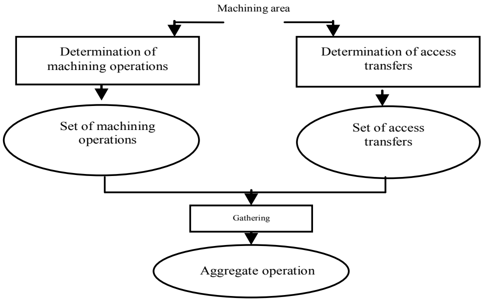

Figure 2: Aggregate operations specification.

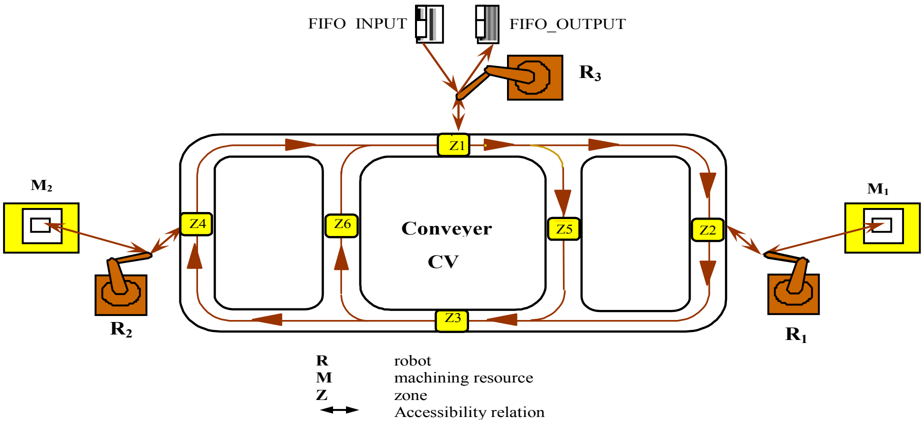

Figure 3: An example of a flexible cell.

The functional model of the machining cell is represented using the following entities:

- The missions
- The Logical Operating Sequences
- The machining functions
- The aggregate operations
  - elementary machining operations
  - Access Transfers (set of transfer operations)
- Transfer resources, machining resources

2.3 Illustration Example

Consider an example of a flexible manufacturing cell (Figure 3) with two machines M_1 and M_2 and INPUT/OUTPUT buffers. The machines are loaded with a transport system using three robots R_1, R_2 and R_3 and a conveyer (CV). Moving directions of CV are $Z_1 \rightarrow (Z_2$ or $Z_5)$, $(Z_2$ or $Z_5) \rightarrow Z_3$, $Z_3 \rightarrow (Z_4$ or $Z_6)$, $(Z_4$ or $Z_6) \rightarrow Z_1$. It is assumed that M_1 is loaded with R_1 and M_2 is loaded with R_2. The parts are loaded on the conveyor using the robot R_3. The machining functions performed by the system are turning (t) and milling (m). Turning is carried out by M_1, milling by M_1 and M_2.

According to the functional requirements of this illustration example, three missions can be required by the operator: $\mathcal{M}_1$, $\mathcal{M}_2$ and $\mathcal{M}_3$. The corresponding Logical Operating Sequences are the following: $\mathcal{M}_1$: LOS_1 and LOS_2, $\mathcal{M}_2$: LOS_1, LOS_2 and LOS_{12} and $\mathcal{M}_3$: LOS_1, LOS_{12} and LOS_{21}

The machining functions which compose each Logical Operating Sequence are the following: LOS_1: turning; LOS_2: milling; LOS_{12}: turning then milling; LOS_{21}: milling then turning.

Turning function is performed by the elementary machining operation $Op_{M1,t}$ belonging to the aggregate operation Op_{M1}. Milling function is performed by the elementary machining operation $Op_{M1,m}$ belonging to the aggregate operation Op_{M1} or by the elementary machining operation $Op_{M2,m}$ belonging to the aggregate operation Op_{M2}.

For the machining area M_1: the elementary machining operations performed by M_1 are $Op_{M1,t}$ and $Op_{M1,m}$. Access Transfers related to M_1 are $TrA_{M_1} = AND\ (\ Tr_{MCA\_source \rightarrow M_1}\ ,\ Tr_{M_1 \rightarrow MCA\_destination}\ )$.

This notation is using the logical AND and OR and also three distinct levels: ‘{’ for the first level, ‘[’ for the second level and ‘(’ for the third level.

Section 3 presents a method to determine TrA using the plant model.

The aggregate operation related to the machining area M_1 is $Op_{M1} = AND\ [OR\ (Op_{M1,t}\ ,\ Op_{M1,m})\ ,\ TrA_{M_1}\ ]$. The aggregate operation related to the machining area M_2 is obtained in the same manner.

Op_{M1} is performed by the following resources: the polyvalent machining resource M_1 performs the elementary operations $Op_{M1,t}$ et $Op_{M1,m}$. For transfer resources: R_1 performs the elementary transfer operations $TrE_{R_1}^{Z_2 \rightarrow M_1}$ and $TrE_{R_1}^{M_1 \rightarrow Z_2}$; R_2 performs the elementary transfer operations $TrE_{R_2}^{M_2 \rightarrow Z_4}$ and $TrE_{R_2}^{Z_4 \rightarrow M_2}$; R_3 performs the elementary transfer operations $TrE_{R_3}^{IN \rightarrow Z_1}$ and $TrE_{R_3}^{Z_1 \rightarrow OUT}$; CV performs the elementary transfer operations $TrE_{CV}^{Z_1 \rightarrow Z_2}$, $TrE_{CV}^{Z_2 \rightarrow Z_3}$, $TrE_{CV}^{Z_1 \rightarrow Z_5}$, $TrE_{CV}^{Z_5 \rightarrow Z_3}$, $TrE_{CV}^{Z_3 \rightarrow Z_4}$ $TrE_{CV}^{Z_4 \rightarrow Z_1}$, $TrE_{CV}^{Z_3 \rightarrow Z_6}$ and $TrE_{CV}^{Z_6 \rightarrow Z_1}$.

The obtained model (AND/OR graph) for the machining cell is represented in Figure 4. The underlined entities are not developed. AND nodes do not have any notation, however OR nodes are denoted using +. These nodes correspond to an inclusive OR or an exclusive OR according to the constraints given in the functional requirements. For example, an exclusive logical OR is necessary for safety reasons, like two machining operations which are performed by the same resource for instance.

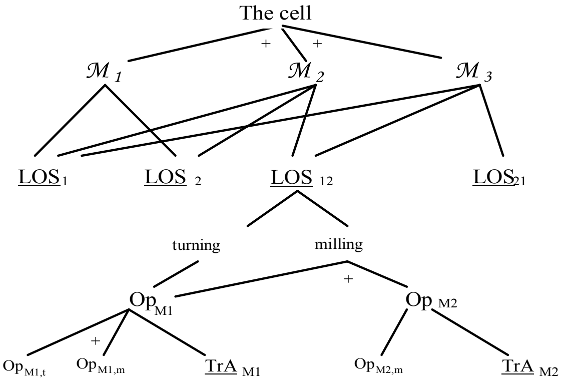

Figure 4: An extract of the functional model of the machining cell.

3 DETERMINATION OF ACCESS TRANSFERS

In order to determine TrA, a first step consists in listing symmetrical transfers between MCA representing both source and destination areas. Then it is necessary to refine these transfers until obtaining elementary transfer operations.

Once Access Transfers are determined, it is necessary to identify elementary transfers which compose them. If there is a direct accessibility between two MCA then $Tr_{MCA\_source \rightarrow MCA\_destination}$ corresponds to an elementary transfer. If not, it is necessary to refine the transfers between the Characteristic Areas until obtaining elementary transfers. The possible paths are then established and those which are redundant are linked together with a logical OR. For example:

$$Tr_{IN \rightarrow M_1} = AND\ (TrE_{R_3}^{IN \rightarrow Z_1}, TrE_{CV}^{Z_1 \rightarrow Z_2}, TrE_{R_1}^{Z_2 \rightarrow M_1}).$$

Due to increasing complexity of FMS, it could be difficult to identify all the elementary transfers which compose Access Transfers. That is why we propose to determine them from the Operational Accessibility Graph (OAG) (Berruet et al., 2000), a graph which represents the FMS plant. The OAG formalizes all the accessibilities between the characteristic areas more precisely than informal specifications provided in the functional requirements.

To build an OAG, a partition of all elementary operations is carried out and the concept of node is introduced to simplify the modeling process. This concept is defined in the following.

A **node** consists of an elementary operation or some elementary operations. This regrouping is governed by rules about the operations taxonomy (Berruet et al., 2000; Toguyéni et al., 2003). The nodes form OAG entities and allow relating the operations using accessibility relations.

Based on this definition, several nodes are defined: storage, machining, assembly, link, and transfer nodes. The nodes are then linked together using accessibility relations in order to build the OAG.

3.1 The Operational Accessibility Graph

The Operational Accessibility Graph (OAG) is a directed graph where nodes are subsets of **operations** performed by the resources of the system and the arcs represent the **accessibility relations** between operations (Toguyéni et al., 2003). The OAG represents all the flexibilities of an existing plant or a plant being designed. It is obtained following these steps:

1st *step- Identification of elementary operations of the* FMS*:* in this step elementary operations of machining, storage (passive, active), and transfer are identified.

2nd *step- Regrouping the elementary operations:* the elementary operations carried out on the same area and the equivalent elementary transfer operations are gathered. A partition of all the operations is thus obtained.

3rd *step- Building the graph:* a node is associated with each operations subset established in the previous step. The nodes of the OAG are thus obtained. Then these nodes are connected with respect to the accessibility between operations. The OAG structure is then determined.

The method is applied to the illustration example (Figure 3).

1) The elementary machining operations are already identified ($Op_{M1,t}$, $Op_{M1,m}$, $Op_{M2,m}$) and the elementary transfer operations ($TrE_{R_1}^{M_1 \rightarrow Z_2}$, $TrE_{R_1}^{Z_2 \rightarrow M_1}$, $TrE_{R_2}^{M_2 \rightarrow Z_4}$, $TrE_{R_2}^{Z_4 \rightarrow M_2}$, $TrE_{R_3}^{IN \rightarrow Z_1}$, $TrE_{R_3}^{Z_1 \rightarrow OUT}$, $TrE_{CV}^{Z_1 \rightarrow Z_2}$, $TrE_{CV}^{Z_2 \rightarrow Z_3}$, $TrE_{CV}^{Z_1 \rightarrow Z_5}$ $TrE_{CV}^{Z_5 \rightarrow Z_3}$, $TrE_{CV}^{Z_3 \rightarrow Z_4}$, $TrE_{CV}^{Z_4 \rightarrow Z_1}$, $TrE_{CV}^{Z_3 \rightarrow Z_6}$, $TrE_{CV}^{Z_6 \rightarrow Z_1}$).

It is necessary to add the following storage operations:

- Storage IN and storage OUT which are passive;
- Storage Z_1, storage Z_2, storage Z_3, storage Z_4, storage Z_5 and storage Z_6 which are active.

2) Concerning the regroupings:

- One gathers $Op_{M1,t}$ and $Op_{M1,m}$ in a complex operation on M_1.
- Linking operations are: Link Z_1, Link Z_2, Link Z_3, Link Z_4, Link Z_5 and Link Z_6.
- The functions fulfilled by the elementary transfer operations are all distinct. There is no regrouping of transfers.

3) Table 1 summarizes the correspondence between the nodes and the operations which compose them. The resulting OAG is represented in Figure 5.

Note: on Figure 5, storage nodes IN and OUT, link nodes as well as machining nodes correspond to characteristic areas of the cell. The subset formed only by storage nodes and machining nodes corresponds to main characteristic areas.

The obtained model is used to calculate the elementary transfers as shown in the following.

3.2 A Procedure for Determination Elementary Transfers

Based on the OAG, the following procedure is proposed in order to calculate Access Transfers.

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Beginning of the procedure:
1st Step: determination of Access Transfers associated with machining nodes
  For each machining node of the OAG:
    - determine the paths which connect it with the others machining nodes and the input of the cell;
    - determine the paths which enable unloading parts onto other machining nodes and the output of the cell;
    The obtained paths are linked with a logical OR;
  End For;
2nd Step: determination of elementary transfers which compose the Access Transfers:
  Do again for each identified path in the previous step
    If the path relates two successive nodes of the OAG
    Then the path is an elementary transfer
    If not determine the paths which compose it
      The redundant transfers are linked with a logical OR; do not consider the paths which go over a transfer node twice and those that contain intermediary machining nodes;
  Until all the obtained paths are elementary.
End of the procedure.
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Table 1: The correspondence between nodes and operations.

N1	N2	N3	N4	N5	N6	N7	N8
Storage IN	$\mathrm{TrE}_{R_3}^{IN\to Z_1}$	Link Z_1	$\mathrm{TrE}_{CV}^{Z_1\to Z_2}$	Link Z_2	$\mathrm{TrE}_{R_1}^{Z_2\to M_1}$	Machining M_1 $Op_{M1,t}$ $Op_{M1,m}$	$\mathrm{TrE}_{R_1}^{M_1\to Z_2}$
N9	N10	N11	N12	N13	N14	N15	N16
$\mathrm{TrE}_{CV}^{Z_1\to Z_5}$	Link Z_5	$\mathrm{TrE}_{CV}^{Z_2\to Z_3}$	$\mathrm{TrE}_{CV}^{Z_5\to Z_3}$	Link Z_3	$\mathrm{TrE}_{CV}^{Z_3\to Z_4}$	Link Z_4	$\mathrm{TrE}_{R_2}^{Z_4\to M_2}$
N17	N18	N19	N20	N21	N22	N23	N24
Machining M_2 $Op_{M2,m}$	$\mathrm{TrE}_{R_2}^{M_2\to Z_4}$	$\mathrm{TrE}_{CV}^{Z_3\to Z_6}$	Link Z_6	$\mathrm{TrE}_{CV}^{Z_6\to Z_1}$	$\mathrm{TrE}_{CV}^{Z_4\to Z_1}$	$\mathrm{TrE}_{R_3}^{Z_1\to OUT}$	Storage OUT

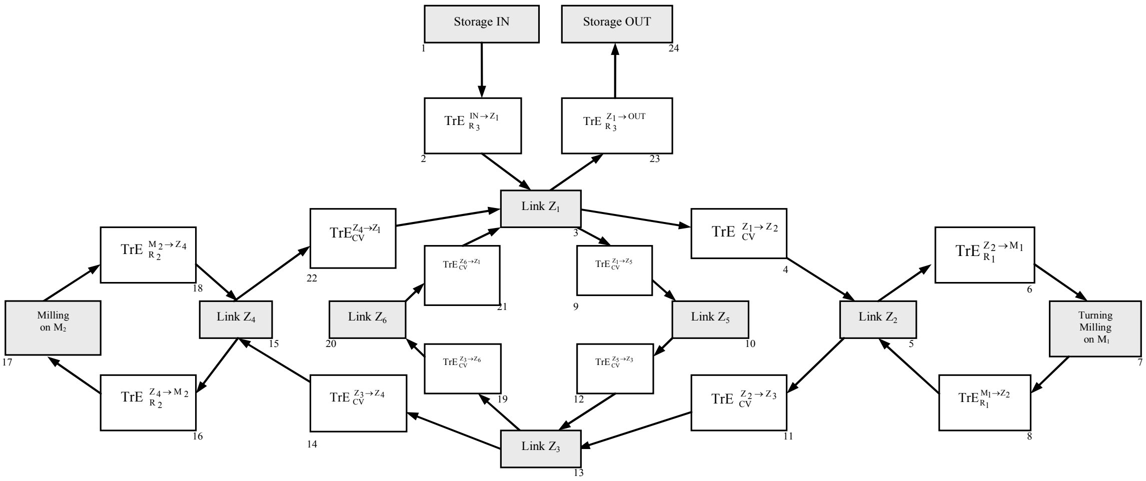

Figure 5: The OAG of the illustration example.

For each machining node, the access paths which are associated with it, added with machining operations carried out on this node, are linked with logical AND. This regrouping is an aggregate operation.

For the illustration example, the access paths calculated in the first step of the procedure for the machining area M_1 are the following: OR $(Tr_{IN \to M_1}, Tr_{M_2 \to M_1})$ and OR $(Tr_{M_1 \to M_2}, Tr_{M_1 \to OUT})$. The following elementary transfers are then obtained using the second step of the procedure.

$Tr_{IN \to M_1} =$ AND $(TrE_{R_3}^{IN \to Z_1}, TrE_{CV}^{Z_1 \to Z_2}, TrE_{R_1}^{Z_2 \to M_1})$; $Tr_{M_2 \to M_1} =$ AND $(TrE_{R_2}^{M_2 \to Z_4}, TrE_{CV}^{Z_4 \to Z_1}, TrE_{CV}^{Z_1 \to Z_2}, TrE_{R_1}^{Z_2 \to M_1})$; $Tr_{M_1 \to M_2} =$ AND $(TrE_{R_1}^{M_1 \to Z_2}, TrE_{CV}^{Z_2 \to Z_3}, TrE_{CV}^{Z_3 \to Z_4}, TrE_{R_2}^{Z_4 \to M_2})$; $Tr_{M_1 \to OUT} =$ AND $\{TrE_{R_1}^{M_1 \to Z_2}, TrE_{CV}^{Z_2 \to Z_3}$, OR [AND $(TrE_{CV}^{Z_3 \to Z_4}, TrE_{CV}^{Z_4 \to Z_1})$, AND $(TrE_{CV}^{Z_3 \to Z_6}, TrE_{CV}^{Z_6 \to Z_1})$], $TrE_{R_3}^{Z_1 \to OUT}\}$.

Finally, $TrA_{M_1} =$ AND [OR $(Tr_{IN \to M_1}, Tr_{M_2 \to M_1})$, OR $(Tr_{M_1 \to M_2}, Tr_{M_1 \to OUT})$].

4 CONCLUSIONS

In this paper our modeling method dedicated to FMS *mode handling* is extended. The FMS functional model is obtained by a modular and hierarchical decomposition leading to the elementary machining and transfer operations. For large scale systems, it is difficult to obtain all possible redundancies of a plant. So we propose to determine aggregate operations associated with machining areas from the plant model represented by the OAG. The aggregate operations are generic concepts which depend only on the plant and not on production goals. Such method enables to generate automatically aggregate operations for an existing system or a system being designed. The proposed modeling steps are then illustrated through an example of a manufacturing cell.

Further works aim at implementing the proposed method within the information system *CASPAIM_soft* (Ndiaye et al., 2002).

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