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DETAILED SCHEDULING AND UNCERTAINTY MANAGEMENT IN CUSTOMIZED MASS PRODUCTION

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ABSTRACT

Customization has become more and more typical in the field of mass production. Companies are forced to customize products, for selective customers, fashions or important seasons. This requires decreasing lot size and increasing delivery capabilities. Most of these companies use proactive approach to schedule production orders and jobs at shop floor level. To make optimal schedule for shop with automated machine lines is very important but complicated task, because of the very large number of alternative solution in the searching space. Good heuristic and improving algorithms are required to satisfy constraints and to optimize production performances. Another issue, that during the production lead time numerous disturbances may happen. They can be external or internal ones. When modeling the disturbances and uncertainties of production activities a hierarchical model can be built up. Behavior based control (BBC) proved to be successful in process control, to avoid unwanted differences between planned and finished performance. In most cases uncertainty management requires human activities therefore the human expert knowledge can be the only base of successful corrections. To help production control decisions on MES (Manufacturing Execution Systems) level, the real time and aggregate data on user screen windows (Cockpit) are the most suitable tools.

Keywords: Manufacturing Execution System, scheduling, uncertainty management

1. INTRODUCTION

Today, most companies on the field of mass production manufactures hundreds of goods or product choices (called Stock Keeping Units, SKU) for market demands. In many cases SKU items variations are made of different raw materials and components, or requires individual labeling and packaging. It is also typical that the big supermarket centers require very hard delivery due dates. The companies are forced to customize products, for selective customers, fashions or for important seasons. These requirements cause tendency to decrease lot size, to make more flexible production master plans, to develop forecast or supplying and warehousing operations, and to use information technology for more efficient production control methods and uncertainty management.

Most of these companies use proactive approach to schedule production orders and jobs at shop floor levels. To make optimal detailed schedule for automated machine lines is very complicated task. There is a lot of product variants where streams of new products are introduced on a case-by-case basis without the benefit of systematic product portfolio planning or the standardization of materials, parts, components, and processes. In some cases the old products are not realizable ever, and they just accumulate in the product inventory of company.

Relying on forecasts to order parts and products is becoming more and more problematic as volume is growing, markets become more turbulent and unpredictable. As delivering from inventory becomes more expensive and less effective, companies try to become agile and use make "to order," and make “to stock” policy simultaneously, controlling shop floor activities proactively and reactively.

The production (or operation) engineering and management utilize more and more computer integrated application systems. As a result of research and development activities of software industry, four types of large application systems have been developed which offer “turnkey” solutions for the management to support decision making. They are as follows:

- Enterprise Resources Planning (ERP),
- Computer Aided Design and Process Planning(CAD/CAPP),
- Manufacturing Execution Systems (MES),
- Manufacturing Automation (MA).

This paper focuses on MES functionalities whose efficiency is a key factor to remain competitive for mass production companies in the global market.

2. MES FUNCTIONAL COMPONENTS

A Manufacturing Execution System (MES) is a collection of hardware/software components that enables the management to control production activities from order launch to finished goods. While maintaining current and accurate data a MES guides, initiates responds to and reports on plant activities as they occur. MES provides mission-critical information about production activities to decision support processes across the shop floor level of manufacturing management [Barkmeyer, 1999].

Manufacturing Execution Systems are intended to provide plant-wide insight into the production process, informing about the state of manufacturing objects, performance measurement, emergence of unexpected events, and allocation of production costs to products, jobs, or production orders. MES may improve better resources planning and allocation, allows tracking the process execution, and allows promptly making reactions to abnormal events. Product tracking, as the core functionality of a MES system has the main objective to accompany and supervise the manufacturing process. Based on requests from the production management or upper Enterprise Resources Planning (ERP) system, the feedback information from low level Supervisory Control and Data Acquisition (SCADA) systems, and inputs from the operators it has to be in the position not only to know the current state of production and all products, but also to recognize abnormal, deviant or critical states in the production process [Füricht, 2002].

MESA International [www.mesa.org, 1997] identifies eleven functional areas which a MES should fulfill, see Figure 1.

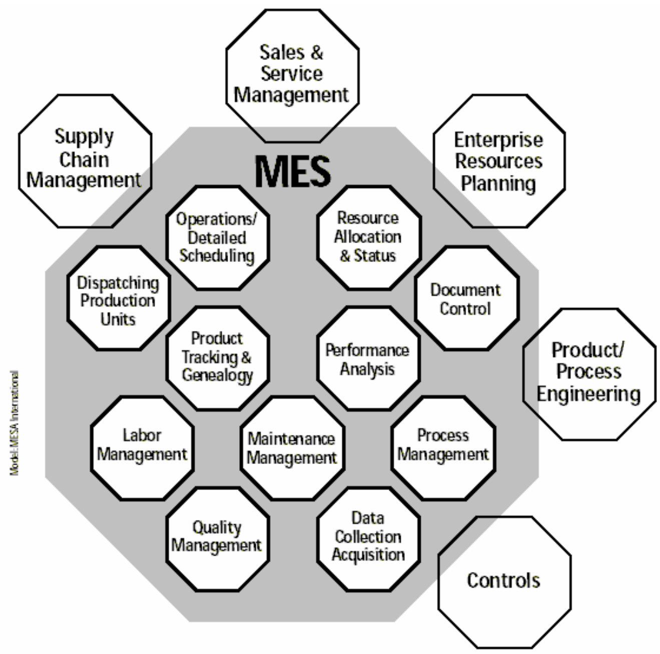

Figure 1. MES functional model

3. SCHEDULING IN CUSTOMIZED MASS PRODUCTION

In CMP - originally coined by Stan Davis [Davis, 1997] - there is wide variety of goods and services increasing the chance that consumers will find products which meet their individual requirements. Using modern Information Technology to customize goods makes it possible that they may cost no more than standard mass-produced goods.

Mass production is starting to give way to mass customization. That is good news for consumers, since a wide variety of goods and services increases the chance that consumers will find products that meet their individual requirements.

At MES level production management initiate *fine* (or *detailed*) schedule to meet the *Master Plan* defined at Enterprise Resources Plan (ERP) level. A fine scheduler must consider the statuses and feasible alternatives on:

- machines, or work places,
- technological routes,
- material types,
- batch sizes and
- product order or job sequences.

A further requirement against the scheduler is to respect the special characteristic of the given manufacturing type such as:

- setup times (depending on the type and order of jobs),
- production intensity (depending on the type of product to manufacture),
- limitation of resources available or
- priority of parallel resources.

The scheduler has to provide a feasible sequence of jobs which meets the management's goal. Obviously, management may declare various goals time by time. The computation time of the scheduling is also an issue – especially with large number of jobs, variants and constraints.

The output of a scheduling engine is a production plan which declares the sequence of jobs, assigns all the resources to them and proposes the starting (release) time of operations. It can not break all the constraints but has to meet the predefined goal(s).

To formalize scheduling problem the notation of [Brucker, 1998] is used here. Let's introduce
$\alpha \mid \beta \mid \gamma$ tuple, where:
α: denotes machine environment descriptors,

β: denotes processing characteristics/constraint,

γ: denotes the parameter list of objective functions.

$\alpha = [\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5]$.

α_1 : Type of resource. ***S***: singe purpose, ***M***: multi purpose.

α_2 : Nature of alternative machines. ***E:*** equivalent, ***Q***: machines of distinct intensity.

α_3 : Precedence and routing. ***F***: Flow shop (each job has an assigned route and machine), ***J***: Job shop (one route for each job but may use different machines) , ***O***: Open shop, (no routing sequence or jobs may have alternative, ***X***: mixed routes.

α_4 Setup cost. ***Su:*** constant, ***SuJ:*** job-dependent, ***SuJJ:*** sequence dependent.

α_5 : Number of resource types per workplaces

α_6 : Number of workplaces.

$\beta = [\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6]$.

β_1 : ***Pr:*** operations can be preempted.

β_2 : ***Pc:*** there is a job precedence which requires a detailed description (e.g. permutation flow-shop, graphs, etc.).

β_3 : ***Re:*** jobs have earliest launch time defined.

β_4 : ***Sp:*** there are special limitations to number of operations, operation times, etc.

β_5 : ***D***: Jobs have *due date* defined.

β_6 : Operations may form sequences. It requires further descriptions.

$\gamma = [\gamma_1, \gamma_2, \gamma_3]$.

γ_1 : Goal. ***Sa:*** Scheduling meet constraints only, ***Op:*** optimal scheduling:

γ_2 : Number of goals to be taken into account.

γ_3 : The nature of goal function, see Table 1 for typical goal functions.

C_{max}	Finishing time of last job to be min. (makespan)
L_{max}	Max lateness to be min.
T_{max}	Max tardiness to be min.
S_{max}	Max square distance of differences to due dates to be min
$\sum(C_i - R_i)$	Sum of throughput times to be min
$\sum L_i$	Sum of lateness times to be min
$\sum T_i$	Sum of tardiness times to be min
$\sum S_i$	Sum of square distance of differences to due dates to be min
$\sum U_i$	Sum of machine utilization to be max
$\sum w_i(C_i - R_i)$	Weighted sum of flow times to be min.
$\sum w_i L_i$	Weighted sum of lateness times to be min.
$\sum w_i T_i$	Weighted sum of tardiness times to be min.
$\sum w_i S_i$	Weighted sum of square distance of differences to due dates to be min.
N_{WIP}	Number of Work In Progress to be min.

Table 1. Typical goal functions for detailed scheduling

4. KNOWN FLOW SHOP MODELS

In discrete manufacturing, batches of goods are produced. Batches can be of very different size, from single product (e.g. special parts, complex, or unique machines) to millions of the same product (simple parts, or mass production of goods). In discrete manufacturing operations are executed on discrete, separated machines. Depending on arrange of machines and transportation devices, manufacturing systems may have linear or nonlinear layout. The execution of the operations for mass production or customized mass production requires the exact predefinition of the routing of the operations. This kind of model is called flow shop model.

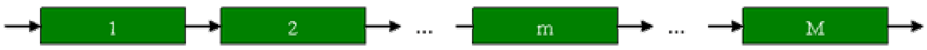

Figure 2. Flow Shop model of manufacturing

There are *M* machines in this structure (*m = 1, …, M*), placed one after the other in the order predefined by the technology. The model is highly influenced by the presence of buffers between machines. If the capacity of the buffer is zero $c_{m,\ m+1}= 0$ then the system is strictly synchronized transfer system. In the presence of buffers machine lines are called asynchronous systems.

In customized mass production we assume automated machine lines with large (practically unlimited) buffer capacity. In this system each product has the same manufacturing route, and each product have to be manufactured on each machine. Production is executed in batches of products, but machines may have different order of jobs to execute (non permutation flow shop).

To extend our model let's define the Extended Flexible Flow Shop (EFFS) model, with machines having concurrent processing ability. Each machine group S_k $(k=1, \dots, K)$ consist of M_k number of equivalent machines.

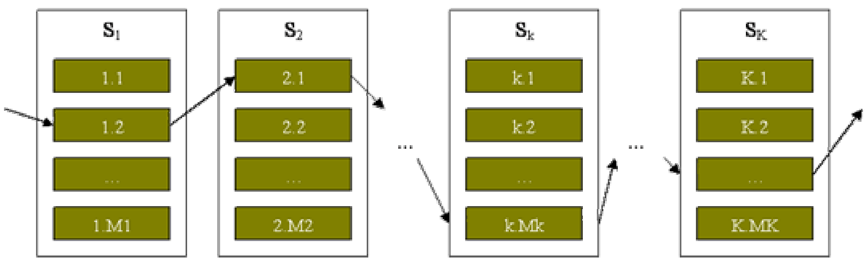

Figure 3. Flexible Flow Shop model

Between consecutive machines unlimited buffer capacity is assumed. Each work piece has to be manufactured on each sequenced machine by selecting one of the machine groups it consists of.

In this model both the selection of machines and the order of the jobs are of great importance. Lots of flexible flow shop models are known in the literature. Most of them use the latest finishing time (*makespan*) of the jobs as goal function of optimization. Only a few of the models deals with the due date which is more important in "Make to Order" manufacturing.

The existing models do not consider the requirements of customized mass production, e.g. aggregate machines, alternative technological routes, and limited availability time of the machines, so the improvement and extension of flow shop models is required.

5. EXTENDED FLOWSHOP MODEL

Manufacturing context, constraints and execution parameters

The discrete manufacturing process examined produces various consumer goods. By means of forecasting tools which considers external orders, market trends, seasonal characteristics a set of internal orders has been created by the production planners. Each order defines the required number of identical products of certain product type, which should be manufactured by the predefined time. The logistical unit is the palette at the shop floor level. Internal orders consist of one or more (i.e. whole number of) palettes. Depending on the product type palettes carry predefined number of identical products. External orders can be considered as the set of palettes to manufacture, where the number of palettes depends on the ordered product quantity, and the capacity of the palettes.

The model being investigated in this paper applies to manufacturing / assembly machine groups (individual machines and/or machine lines). Machine lines perform more manufacturing steps. A job consists of four or less manufacturing steps executed in a predefined order.

Technological steps consist of sequences of elementary operations and can not be interrupted. Consequently steps can be the smallest allocation units during the scheduling. Execution of these steps requires appropriate quantity and type of materials, components. The nature of the flexible manufacturing is that same goods can be manufactured using alternative materials, components, machine groups or technological routes.

In this model, the machining groups can be characterized by:

- various setup times – depending on the order of jobs,

- availability time frames,
- various production rate depending on product type,
- capability for performing a single step or a sequence of steps for a concrete product.

A machine group can work on single job, and on a job a single machine group can work. The buffer between the machine groups is not limited. It is expedient to consider that machine groups may not be available during the whole time frame the scheduling created for. Certain machine groups can be occupied with running jobs which can not be cancelled. Thus the current, confirmed schedules affect the new schedule plans.

Goals and objective functions

The goodness and quality of the schedule can be evaluated using the numeric result of the goal function. Same examples are listed in Table 1. Real manufacturing environments may require various goal functions declared.

A manufacturing process can be characterized by performance indices. The most important three state variables are as follows: 1. stock level, 2. capacity utilization and 3. readiness for delivery. They are usually denoted as the '*production triangle*' [Tóth, T. et. al., 1998]. The goal functions improving the readiness for delivery may be of two kinds:

- due date related and
- without due date related.

Let's deal with due date related functions for jobs J_i *(i=1,…,n).*

Each J_i has a D_i delivery time and R_i earliest start time. Denote C_i the real finishing time.

Lateness: $$L_i = C_i - D_i \,. \qquad (1)$$

Tardiness: $$T_i = \max(0, L_i) \,. \qquad (2)$$

Earliness: $$E_i = \max(0, -L_i) \,. \qquad (3)$$

Let's note G_i a generic goal function of the above. The most widely goal functions can be expressed as follows:

Maximum: $$\gamma = \max(G_i) \,. \qquad (4)$$

Total: $$\gamma = \sum_i G_i \,. \qquad (5)$$

Average: $$\gamma = \frac{\sum_i G_i}{n} \,. \qquad (6)$$

Number of jobs to late: $\gamma = |\{i \mid T_i > 0\}|$. (7)

We can express the priority of the jobs using w_i weights.

Weighted maximum: $\gamma = \max(w_i G_i)$. (8)

Weighted total: $\gamma = \sum_i w_i G_i$. (9)

Weighted average: $\gamma = \frac{\sum_i w_i G_i}{n}$. (10)

Some of the goal functions are not related to due dates. The most widely used ones are as follows:

Maximum Completion Time: $\gamma = \max(C_i)$. (11)

Flow Time of all jobs: $\gamma = max(C_i) - min(R_i)$. (12)

Furthermore for each J_i the flow time can be calculated as:

Flow time: $F_i = (C_i - R_i)$. (13)

We can put F_i into (4) (5) (6) or (8) (9) (10) to declare additional non due date related goal functions. Using the notation defined above the scheduling task this paper deals with can be formalized as:

$$M, Q, F, SuJJ, 1, 4 \mid 0, 0, R, 0, Due, Sp \mid Op, 1, \max C_i \rightarrow \min \quad (14)$$

As you can see solving scheduling tasks are highly depend on the model used.

SOLVING THE SCHEDULING PROBLEM

Each palette is considered as a separate *job*. Solving the problem means scheduling of jobs. There is no predefined batch size of palettes. During the manufacturing a single set-up is used for several palettes, which defines the manufacturing batch size. The number of palettes ordered can be different to that batch size: an order can be split into several batches, and the palettes of different orders can be merged into one batch. The size of the batch may vary dynamically. In our model we expect that the earliest start time of the jobs is defined for the first technological step of the selected technological route. The earliest start time manifests the availability the components to manufacture/assemble.

One of the basic entities of the scheduling task is the execution step. The execution step is a sequence of technological operations which can be executed on a single (multifunctional) machine, and requires no machine change.

A route is the sequence of execution steps. So each execution route includes all but only those technology steps which are required in order that the final product can be produced so that the intersection of different routes is an empty set of execution steps.

The types of execution steps define the manufacturing machine group types. Within each group type there can be various machines, having various manufacturing intensity.

Computer simulation is used to evaluate the schedule. It considers the availability of the individual machines for a given time window and the required setup times between the batches. Using the machine-job assignments the manufacturing time can be calculated. For each job the start and finishing time can be defined. By means of the simulation the goal function can be evaluated. There can be a predefined set of goal functions of which the appropriate one can be selected when running scheduler.

A software application has been implemented to solve (14) under certain limitations. [Kulcsar 2005a, Kulcsar2005b, Kulcsar2006].

MES systems are responsible for execution those schedules, as planned. In the following sections the factors which may result declinations from plan are discussed.

6. UNCERTAINITY MANAGEMENT

During the production activities numerous disturbances may happen. They can be external or internal ones. When modeling the disturbances and uncertainties of production activities a hierarchical model can be set up. It may include the following levels in bottom-up direction:

1. Problem in quality assurance – indicated by the increased waste goods rate.

2. Machine failure – indicated by the machine control and monitoring system

3. Resources utilization issues – indicated by the difference in planned and achieved production descriptor indices.

4. Out of stock error in production – indicated by product tracking data.

5. Supply chain issues and co-ordination problems at the shop floor- indicated by the material management of MES.

6. Daily scheduling issues – indicated by continuous need for rescheduling.

7. Production planning issues leading locked batches, very complex or irresolvable schedules - indicated by the dispatchers.

8. Prognosis problem - indicated by the growth of inventory or Work in Progress (WIP) level.

9. Problems in order management in production planning leading to reduced delivery capability or reduced satisfying level of consumer needs

10. Problems in production/packaging specification, merchandizing – indicated by logistic service.

11. Problems in IT or data consistency - indicated by low readiness of IT services.

12. Problems in investment, marketing, management, organization, scope of authority – indicated by controlling or business performance measurement.

It is very difficult to model how the individual disturbances affect the company. Each kind of problem may require its own corrective action at the appropriate hierarchical level. Furthermore disturbances may happen concurrently thus affecting to each other. Consequently handling uncertainties in the real word is a very complex task. Real-time control of Manufacturing Execution Systems needs the following computer aided tools:

- production data acquisition, observing,
- monitoring, supervising,
- behavior-based control (BBC),
- analysis, evaluation by Human Machine Interface (HMI) – also known as Cockpit Task Management (CTM),
- diagnostic capability and
- learning and prognostic ability.

It is expedient to have a bottom-up approach when developing a system dealing with uncertainties. Behavior based control proved to be successful in robot control. Behavior-based controllers consist of a collection of behavior models, recognition abilities and proposals to correction. Behavior of control system means special processes or control laws that achieve and/or maintain appropriate process goals. For example, 'avoid-obstacles' maintains the goal of preventing collisions; 'go-home' achieves the goal of reaching some home destination etc. Behaviors can be implemented either in software or hardware components; as a processing element or a procedure. Each behavior can take inputs from the sensors of the process (e.g., bar code reader, RFID, camera, position sensor, ultrasound, infrared, tactile sensor, etc.) and/or from human operator observing the process. BBC system recognize the situation and send outputs to the process (e.g. machine stop, feed override, wait command, job execution blocking, new setup, change in allocation, rescheduling tasks etc.). Thus, a behavior based controller is a structured network of such interacting control behaviors. Note that behaviors themselves can have state, and can form representations when networked together. Thus, unlike reactive systems, behavior based systems are not limited in their expressive and learning capabilities [Matratic, 1998]

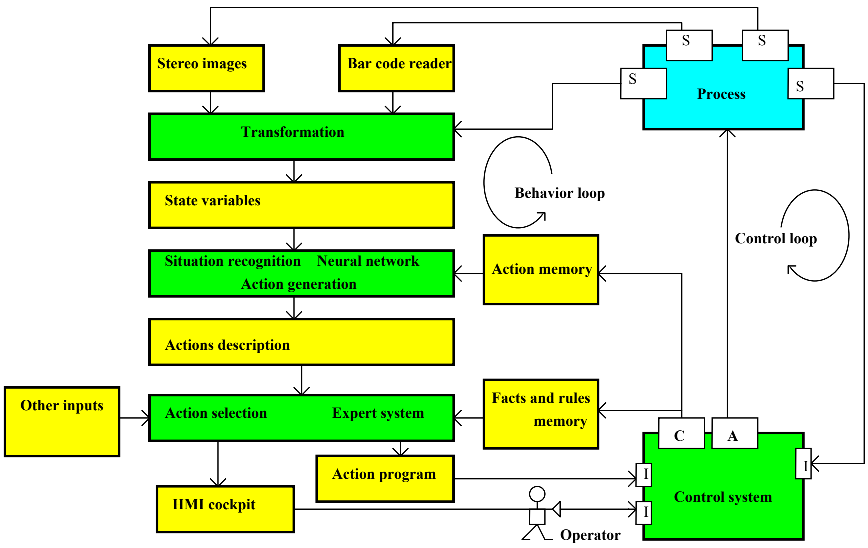

Fig. 4. BBC in process control

The following fundamental principles should be emphasized:

1. Modeling of mass production requires complex model having a large number of parameters.
2. The change in the state of the system can be respected as a behavior. Perspicuity can be increased when behaviors are categorized into discrete categories.
3. Making corrective actions should focus on the level and mode of interactions. Individual behavior categories can be assigned to interaction categories.

BBC is feasible for making some automatic corrective actions. Most of the cases however require human experts to make decision and/or interaction. This requires interactivity thus Human Machine Interface plays an important role besides data aggregation, analysis, computing of management indices and cockpit techniques.

The term Cockpit Task Management originates from error handling in flight control. CTM involves recognizing and coordinating flight crew goals; prioritizing the goals based on importance, urgency, and other factors; and performing tasks to achieve those coordinated and prioritized goals. In order priority required actions are as follows:

- *aviate*: controlling the airplane.
- *navigate*: determining where the airplane is, where to go, and how to get there.
- *communicate*: communicating with air traffic control.
- *manage systems*: configuring and correcting power plant, fuel, electrical, hydraulic, and life support systems.

CTM performance is satisfactory when there are no conflicts among the goals, the goals are properly prioritized, and at least the highest priority tasks are being performed satisfactorily [Funk, 1990].

Customized mass production requires a Human Machine Interface – i.e. cockpit – which becomes the main tool to make real-time interactions at MES level.

Control loop approach

Figure 5. depicts a generic control loop of manufacturing processes. If manufacturing were work without any disturbing then the planned set up dominant and no corrective interaction would be necessary. Unfortunately, processes of real life coupled with disturbing.

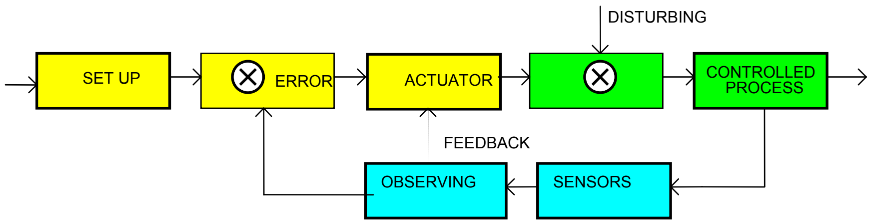

Fig. 5. A generic control loop

Feedback control systems can cope with setup executing and disturbance suppressing tasks at the same time. Architecture of MES systems also follows feedback system paradigm.

Production Information Research Team of Department of Information Engineering of University of Miskolc participates in an industrial project called 'VITAL'. One of the goals of the project is to support uncertainty management by modern IT tools. An important topic of the project is to deal with real-time production control with changes and disturbances. Figure 6. shows an extended process loop applied to production processes.

There are eight new components in this approaches which extend MES functionality.

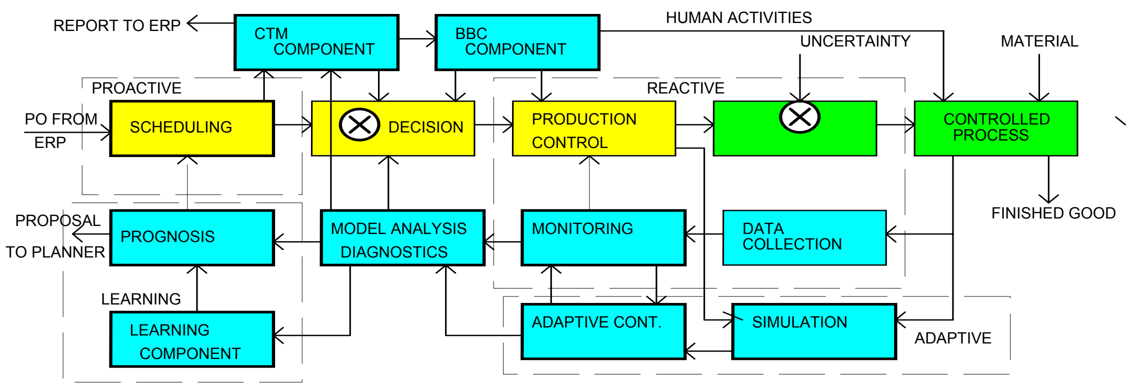

Fig. 6. Uncertainty Management concept for production processes

Monitoring component extends the process observing functions and creates new state variables, aggregate performance indices and event signals.

Model analysis and diagnostic components attempt to recognize reasons and interrelations among variable values. To support the uncertainty management decisions, adaptive, BBC and Cockpit task management algorithms are applied. Rapid simulation can give answers to "*what .. if*" type questions. Learning components have the capability for accumulating system history and for evaluating the effectiveness of corrective actions. Prognostic component can give notion to prepare middle term production planner.

CONCLUSIONS

In this paper, the definition and the common functions of Manufacturing Execution Systems have been overviewed. Some possible extensions of MES systems for customized mass production have also been described. A new scheduling approach to solve extended flexible flow shop scheduling problem in customized mass production has been introduced. Future research work will be carried on investigating some heuristic procedures which can be applied to our scheduling problem and studying effect of change in the machine environment. Uncertainty Management in MES systems has been investigated, which make difficult to plan production processes even middle time horizon. The main tools for managing uncertainties are the fast, real time decision support systems such as BBC and CTM modules.

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