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Production Process Efficiency Analysis: an approach based on Colored Petri Nets

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Abstract: The purpose of this paper is to analyze the overall equipment efficiency (OEE) of the machines in the production process, with the objective of measure the quality and efficiency of the process and the used resources (machines). For this analysis the present work shows the Colored Petri Nets for the modeling the flow data in Factory Information System (FIS). The obtained net represents the necessary information flow for data acquisition from machines. This data will be processed to calculate the performance indexes. Using a colored net is shown how to obtain the necessary code for the FIS implementation. The simulation of the proposed model is also presented in this paper.

1. INTRODUCTION

The competitiveness of the market requires of the production systems more flexibility to process the orders in the minimum time, a competitive production costs that will impact directly in the final price of the product and also a good quality of the product. The performance measurement is the first step to analyze a process in order to understand how the system is working, what are the errors more often and why they occur, what is the impact of these errors in the quality of the final product and also to find out where the efficiency can be improved.

To be able to calculate such index, it is necessary to have a Factory Information System (FIS) responsible to acquire the necessary data, organize the information and calculate the desired performance indexes. According to Dicesare et al. (1993), the FIS is a central component of any manufacturing system, because it supports the operational system and also the tactical and strategic decisions. The FIS is a memory of the manufacturing system, containing valuable data about the produced pieces as well the quality and efficiency of the process.

Based on the data extracted from the system is possible to calculate some performance indexes in order to evaluate if the performance of the production systems is satisfactory event to improve it (De Ron and Roonda, 2005). Dicesare et al. (1993) describe the manufacturing information system as a difficult system in modeling perspective, because of the variety of information types, and also in the time that this information should be stored. The modeling of the information system should be done based on the data that wants to extract from this model.

In this context, the present paper purposes a model based on Colored Petri Nets (Jensen, 1992), to specify the data flow in the system, making possible the analysis of the production process, using performance indexes. Based on these indexes, it is shown how they can be used to understand the system and identify points where the efficiency of the system can be improved.

This paper is organized as follows: section 2 presents the necessary theoretical backgrounds necessary to understand the presented approach; section 3 presents the FIS structure and describes the elements of the system; section 4 describes the modeling of FIS using Colored Petri Nets; section 5 describes the simulation of the proposed model; finally, section 6 presents the conclusions and future works using our approach.

2. THEORETICAL BACKGROUNDS

To understand this paper, the necessary theoretical backgrounds are the Colored Petri Nets Theory, and the meaning of performance indexes. The Colored Petri Nets Theory is necessary to understand the dynamic behavior of the model, and the performance indexes are necessary to find the place where the improvement should be applied to have a better efficiency in the production system.

2.1. Colored Petri Nets

Petri Nets are a theory developed for describing and representing discrete event systems. High level nets such as Colored Petri Nets (CPN) are being used extensively for many different practical purposes. They provide a graphical representation as well as defined semantics which allow formal analysis (Jensen, 1992). The capability of representing and working with more information than classical PN make them attractive for representing manufacturing systems, where larger quantities of information travel through the net.

According to Jensen (1992), a generalized CPN is defined as a 9-tuple: CPN = (Σ,P,T,A,N,C,G,E,I), where Σ is a finite

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state of non-empty types, called color sets; P is a finite set of places; T is a finite set of transitions; A is a finite set of arcs; N is a node function, defined from A into PxT U TxP; C is a color function, defined from P into Σ; G is a guard function; E is an arc expression function and I is an initialization function.

The set of color sets determine the types, operations and functions that can be used in the net inscriptions. The places, transitions and arcs are described by three sets P, T and A which are required to be finite and pair wise disjoint. The node function maps each arc into a pair where the first element is the source node and the second the destination node. Adjacent nodes have to be of a different kind; a place and a transition. The color function C maps each place, p, to a color set C(p); each token on p must have a token color belonging to C(p). The guard function maps each transition, t, to an expression of type Boolean. The arc expression function E maps each arc a, into an expression type C(p(a)); and the initialization function I maps each place, p, into a closed expression type C(p). More details about the formalism can be obtained in Jensen (1992).

2.2 Performance Indexes

According to Chakravarthy et al. (2007), Overall Equipment Efficiency (OEE) has been an established metric for measuring the manufacturing performance of tools mainly in semiconductor manufacturing operations. Sheu (2006) describes that OEE was originated from Japan in 1971. After that Nakajima introduces this index in US, it gained a lot of attention as the ultimate performance index, able to analyze equipments in the process (Pomorski, 1997) (Gaboury, 2001).

This index represents the percentage of the ideal effectiveness of the equipment, and based on OEE comparison it is possible to identify the bottleneck inside of a productive system. This capability in translate the real efficiency of the equipment inside of the production system, considering the efficiency of the equipment in relation to his nominal specification, and also considering the context influence, make this performance index as the most complete to understand where the improvement actions should be applied.

To calculate OEE index, it is necessary establishes the states in which an equipment can be. In SEMI (2001), six main states of manufacturing equipment are defined. The states are described as follows.

1) Nonscheduled state: equipment is not scheduled to be utilized in production, such as unworked shifts, weekends, and holidays (including startup and shutdown);

2) Unscheduled down state: equipment is not in a condition to perform its intended function due to unplanned downtime events, e.g., maintenance delay (maintenance is waiting for personnel or parts), repair, change of consumables or chemicals, and out-of-spec input;

3) Scheduled down state: equipment is not available to perform its intended function due to planned downtime events. This state includes the following activities: production test, preventive maintenance, and setup;

4) Engineering state: equipment is in a condition to perform its intended function but is operated to conduct engineering experiments. The engineering state includes activities as: process engineering, equipment engineering, and software engineering;

5) Standby state: equipment is in a condition to perform its intended function but is not operated. The standby state includes the following activities: no operator available (including breaks, lunches, and meetings), no items available (including no items due to lack of available support equipment), and no support tools.

6) Productive state: equipment is performing its intended function. The productive state includes activities as: regular production (including loading and unloading of units), work for third parties, rework, and engineering runs done in conjunction with production units;

In Chakravarthy et al. (2007), the following definition of overall equipment efficiency OEE is given:

OEE = theoretical production time for effective units/total time

The OEE is built up by means of availability efficiency (AE), operational efficiency (OE), rate efficiency (RE), and quality efficiency (QE)

OEE = AE * (OE * RE) * QE

with

AE = equipment uptime/total time

OE = production time/equipment uptime

RE = theoretical production time for actual units/production time

QE = theoretical production time for effective units/theoretical production time for actual units

3. FIS STRUCTURE

3.1 Operational Management

Measurement, data collection, and information portrayal on performance are essential activities in managing any enterprise system. As information portrayed is converted into information perceived, decision makers at all hierarchical levels are then able to define and carry out actions upon their respective management domains, i.e. the core system being managed (Figure 1). The purpose is to drive performance over time towards desired conditions. Growing recognition of the fundamental importance of management systems has led, in recent decades, to considerable attention regarding design, implementation, and use of measurement systems. Figure 1, extracted from Sousa et al. (2005), shows the process of enterprise management.

3.2 Factory Information Systems

According to De Ron (2005), in literature it is clear the importance of measuring performance of processes in order to enable improvement activities based upon these measures. A Factory Information System (FIS) is used to manage and control manufacturing operations. The FIS may communicate with and connects the many other computer based systems used to support the factory. It is, therefore, the entity that binds the functions of process control, equipment maintenance, production scheduling, product accounting, and performance reporting into a consolidated interactive system for manufacturing control (Gaylord, 1987).

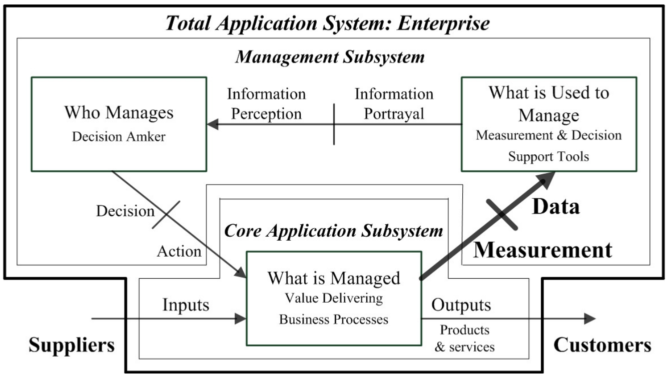


Figure 1: The enterprise management process

According to Harhalakis and Vernadat (1993), FIS is a central component of any manufacturing system in the sense that it provides support to its two other fundamental subsystems: the physical system (or operational system, i.e. where the physical actions take place using enterprise resources) and the decision system (i.e. where strategic and tactical decisions are made). FIS is a subclass of information systems that are responsible for the acquisition, processing, storage and availability of data related to a manufacturing system. The manufacturing system may be a single device, such as a machine-tool, a flexible cell, made up of a number of machine-tools, a robot and a controller, or an entire factory.

The information processed by a FIS is typically received in the form of signals from the manufacturing system. The processing of this information has the objective of calculating production indexes to allow performance evaluation. For a factory information system, as described above, to be successful, some points must be properly observed:

1) Acquisition of the required data for the calculation of the production indexes must be performed accurately and in real-time. By accurately, it is understood that not only correct information must be given as input, but the correct information which relevantly represent what is to be measured and calculated.

2) Processing of the data must be continuously made. This processing is the activity of gathering the relevant information for the calculation of a determined production index. As long as accurate information is available, the correct information processing algorithm must be adequately selected and programmed so that the correct production index is calculated.

3) Data storage for the retrieval of both the information and the production indexes is mandatory. This information may be used for a number of different applications, ranging from maintenance planning to fault diagnostics.

3.3 FIS Conceptual Design

In order for the information flow model to be created, a conceptual architecture for a FIS was conceived. This architecture is composed of the following subsystems:

1) Data Acquisition Module (DAM): the data acquisition module is the piece of hardware which is to be attached to any industrial equipment, such as a programmable logic controller (PLC), a robot controller (RC), a computerized numerical controller (CNC) of a machine-tool or a set of simpler devices such as sensors in a manufacturing cell. The DAM has basically two main goals. The first one is to automatically receive signals from the before mentioned devices or an operator interface attached to it, which is described next. The second one is to send these signals to the acquisition interface, in order for them to be processed and stored.

2) Operator Interface (OI): the operator interface is another piece of hardware which, when required, is attached to the DAM so that an operator of a manufacturing equipment may be able to input information which is relevant for the FIS. The OI should be composed of a small keyboard and a display, as well as a dedicated processor and a communication channel to the DAM. Examples of information, which could be input by the operator through the OI, are the start and end of a setup cycle for a determined product or the start and end of a duty cycle for a machine.

3) Acquisition Interface (AI): the acquisition interface is a program to be run in a computer directly connected to one or more of the DAMs through a proper communication channel. The communication channel may be a serial interface or a more sophisticated industrial networking protocol, such as CAN or a flavor of industrial Ethernet. The acquisition interface checks for consistency of the signals received and automatically forward them to the information storage unit.

4) Information Storage Unit (ISU): the information storage unit is the place where all information received by the AI is stored. The use of a database management system (DMS) is highly recommended, as a vast amount of data must be stored with integrity. The ISU also records the indexes calculated by the information processing unit, which is discussed next. As the amount of information grows, it is a good practice for one to have a rotation policy for all data stored, so that it is either deleted or kept in permanent storage media.

5) Information Processing Unit (IPU): the information processing unit is the computer program which reads the data stored in the ISU and processes it in order to generate the production indexes for performance evaluation. The IPU, once the indexes are calculated, sends them for storage in the

same ISU. Indexes like OEE and TEEP may be calculated, as well as any other which uses the data stored in the ISU. The IPU must exhibit two main behaviors for its calculations. The first one is time-triggered, so that performance indexes may be timely calculated. The second one is event-driven, so that alarms and special situations are correctly treated.

6) Information Access Unit (IAU): the information access unit is the outside connection of the FIS system to other systems that could benefit from the information available in it. The IAU, through a proper software connection, like a TCP socket or an OPC data requisition, responds to information requests. The IAU, in this sense, opens the possibility for the information of the FIS system to be used, for example, by a maintenance planning system, an user interface designed to display the FIS information either locally or through the Web and a fault diagnostics system.

Another important part of the FIS system not directly involved with its routine execution is the one involved with its configuration. The FIS Configuration Tool (FISct) should support the following minimal requirements:

1) Allow the configuration of the DAMs. This configuration should allow the user to specify how many DAMs there are and which signals are acquired by each DAM. This configuration should automatically generate the proper database structure for the data acquisition.

2) Allow the configuration of the IPU. The user should specify how the different signals acquired by each DAM are to be used in the calculation of pre-defined performance indexes. This configuration should also automatically generate the proper database structure for the indexes storage.

The structure of a FIS system, as conceived, is depicted in Figure 2.

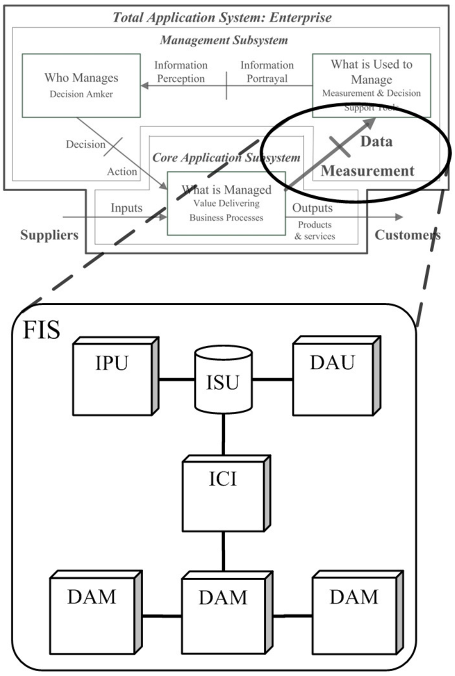
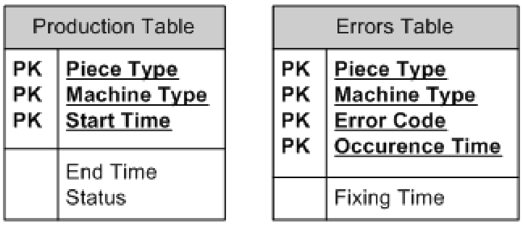


Fig 2: FIS Architecture

3.4 Data Organization

The data provided by FIS-Data Acquisition Device should be stored in an organized way, to make possible the calculation of all the necessary performance indexes. The purposed data model is shown in Figure 3.



Production Table	
PK PK PK	Piece Type Machine Type Start Time
	End Time Status

Errors Table	
PK PK PK PK	Piece Type Machine Type Error Code Occurence Time
	Fixing Time

Fig 3: Database description

The first table shown in the figure 3, makes possible the tracking of each produced piece in the system. There are stored information about the machine that produced a piece, the production start time, the production end time and also in status if the piece was successful produced, or if it was a piece damaged in the process. This model also described a table named Errors, where the information about error occurrence is stored.

Error code represents the reason for stops, occurrence time represents when the machine stops, and fixing time that is the time when the machine restarts.

Table 1: Possible values for Production Status

Status	Description
IN PROCESS	The piece is inside of the machine
DEFECT	The piece was processed but is damaged
FINISHED	The piece was successfully finished

4. FIS DATA FLOW

The Colored Petri net represented in Figure 4, is a conceptual model proposed to show how the operations in the plant should be monitored by a data acquisition device, to provide enough information to calculate the performance indexes described in the section 2.2.

The color sets are: *machines*, that represent the set of machines in the system, each one with a different code; *pieces*, that represent the different types of pieces that the plant can produce; *errors* that represent the expected possibility of errors and pauses in the process, and *pieces x machines* that represents the production process where a piece is produced by a machine.

The place *Idle machines* represents the machines that are available to start to produce a piece. The place *Production order* represents how many pieces of each type should be produced. When the transition *Production start* is fired, a message is sent to the FIS-Monitor System, and a record is created in the production table with the correspondent piece type, and machine type, the status is filled out with *In Production* and Start time with the actual time stamp.

In the place *processing*, it is possible that an error occurs. If the error occurs, the transition *error occurs* is fired and a message is sent to the monitor system, that create a record in the table errors and the piece type and machine code are filled out and also error code is filled out with *In Investigation*. After that, the machine should be repaired and the process should start again. One of the possibilities is recovery the piece that stops in the middle, firing the transition *process restart 1*.

When this transition is fired, a message is sent to the monitor system that will update the record with the correspondent piece and machine that has an empty Fixing time, filling out the fixing time with the actual timestamp. Now the error code is also known and also will be updated according with the code entered by the operator in the FIS-Data Acquisition Device. With this evolution, the system restart in the normal mode and the error will stay registered in the table errors.

Other possibility of evolution is possible in case of the damage in the piece when the process stops. In this case the transition *Process Restart 2* is fired, the fields fixing time and error code is filled out exactly in the same way of *Process Restart 1*. The only difference is that the record in production table with the correspondent Piece type and Machine type, will be updated filling out the field End time with actual time stamp and the status with *defect*. A new token will appear in the place production order to maintain the ordered quantity, and a token will appear also in *scrap* indicating that the machine damaged one piece.

The machine will also go back to idle machine's place and will be ready to start the production of a new piece. Lets restart from the point where the token is in the place *processing*, there is also a possibility of the piece is successfully produced, and then the transition process finished is fired. This transition will send a message to the monitor system that will fill out the record in the production table, with the End time equal the actual time stamp and the status as *produced*. After that the transition *count* will be fired, this transition will just release the machine, to be used in the production of a new piece, and put the produced piece in an output buffer, the place *counted*. After all the production order processing the number of tokens in the place *counted* is equal the number of good pieces produced.

5. SIMULATION OF THE MODEL

To perform the simulation of this model in a computational environment was also necessary to add a *colorset* COMMRESOURCE, to control the TCP/IP connections. This flow is represented by the places *IdleConnection* and *TCPConnection* and the transitions *StartComm* and *StopComm*. This part can connect the CPN Tools (Jensen,

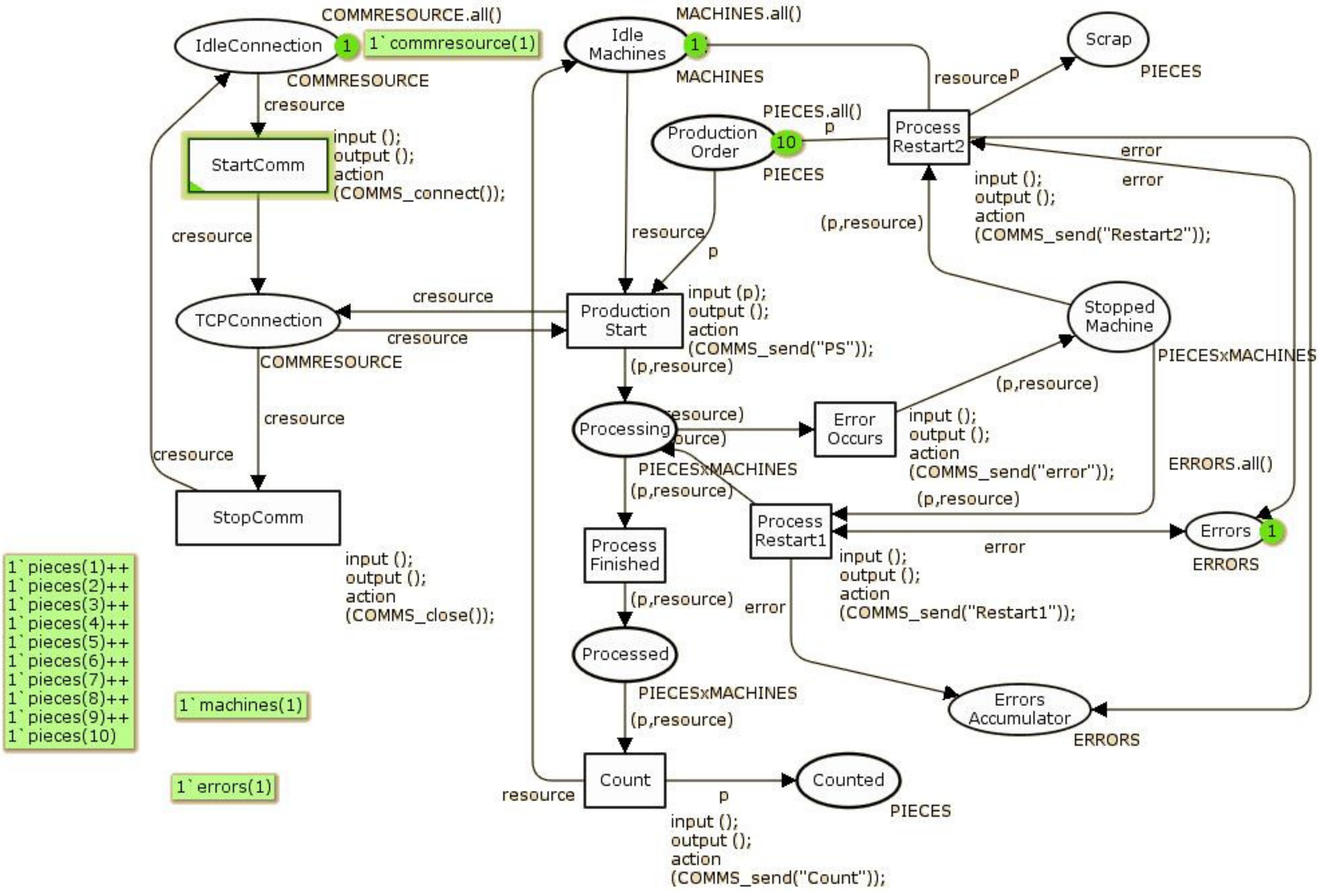


Fig 4: Model of the FIS Data Acquisition Equipment

2006), that is a computational tool used for modeling, with the FIS-Monitor using TCP/IP protocol.

CPN Tools has a communication library that allows connections using a network connection and TCP/IP protocol, to send and receive messages. In the application level, a small protocol was created to identify the main transition points in the network. Receiving these messages the FIS-Monitor is able to calculate the performance indicators. The protocol with the meaning of the messages is shown in the Table 2.

Table 2: Communication Protocol

Message	Meaning
PS	Production Start
error	Error occurrence
Restart1	Production Restart but the piece that was being produced has defects
Restart2	Production Restart and the piece that was being produced is OK
Count	A piece was successfully produced

The simulation was successfully performed using the FIS-Monitor and the model in CPN Tools to simulate the Dataflow. The main goal of the simulation was to be sure that the data collected from the Dataflow was sufficient to calculate the performance indexes, and this goal was reached.

6. CONCLUSION AND FUTURE WORKS

It is possible to conclude that the purposed model is able to acquire the necessary data and calculate the performance indexes. These indexes are important elements to analyze the system, identifying bottlenecks and improve the efficiency of productive processes. The Colored Petri nets approach keeps the model clear and simple even when the FIS is operating with multiple machines and multiple products.

The Overall Equipment Efficiency is a good performance index to compare the efficiency between machines, but to understand the plant and identify problems, it is necessary to divide the meaning of this index in small pieces. These pieces are all performance indexes and can translate better different aspects of the production system. As future work the purposed FIS should be enhanced to calculate other index described in Hansen (1993), than can be used to analyze other aspects of the system, as error frequency, and the impact of programmed maintenance in the system performance.

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