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MODELING AND SIMULATION OF INTERACTIONS BETWEEN THE LOCAL COMMAND UNITS AND THE SUPERVISOR OF AN AUTOMATED ASSEMBLY LINE: A CASE STUDY

This article presents a case study concerning the interactions between a set of programmable logic controllers and a central supervisor intended to the control of a automated assembly line. The programmable logic controllers ensure the command of the various production machines of the process. The exchanges are client-server type and are carried out on several occasions during the cycle of the programmable logic controllers. Modeling with the Petri nets formalism and simulation make it possible to evaluate the performances of the studied system and to measure the impact of the supervisor response time to the requests of the programmable logic controllers. The need for limiting the supervisor response time, in order to respect the production targets, is shown.

1. INTRODUCTION

The behavior of a production system is conditioned by the characteristics of the equipment which ensures its control [GRI-01]. Then, the data-processing tools deployed to control the automated production systems constitute a dominating factor of the productivity and must, following the example of the controlled mechanical process, to be the subject of a specific study guaranteeing a better integration of the whole equipment.

The production control functions imply the taking into account of a significant number of treatment activities of matters and information from various controlled process components with an aim of manufacturing products profitably [VEE-94]. The control system design of an automated industrial equipment then poses a large quantity of hardware and software problems. Current control architectures are generally consisted a set of distributed and heterogeneous entities. They are often complex and bring into play a volume of information increasingly more consequent; this evolution is usually accompanied by a questioning of the control methods and of operation of the systems automated by integration of particular requirements applied to the response times.

The case study presented here is undertaken for the account of an automotive equipment supplier, the Livbag company of the Swedish group Autoliv[3]. It applies to assembly lines

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which control is assured jointly by an programmable logic controller set and central equipment (supervisor). The programmable logic controllers are located at the production machine level, constituting the assembly line. They are directly in charge of the command activities in connection with the field equipments (sensors and actuators).

The programmable logic controllers and the supervisor cooperate in order to make possible the process to respect definite rates and to achieve the laid down production targets. The exchanges between these entities are supported by a fieldbus. Thus, the message transmission is the only dialogue mode inside the control system. The communication between the programmable logic controllers and the supervisor is carried out according to a request emission and answer reception sequence. The exchanges are always initiated by the programmable logic controllers and are carried out at several times during the cycle of the production machines. The interaction mode is client-server type.

The message routing, waiting and treatment cumulated delays constitute a response time that is necessary to control and contain in bounds in order to ensure that the control system does not influence significantly the production rates. The study aims to analyze the supervisor reactivity to the requests of the programmable logic controllers and to measure its impact on the production system performances.

The article is approached by a description of the production system and the control architecture in section 2. The modeling stage of the production system and its control is then presented in section 3. It is based on the formalism of the timed coloured Petri nets. The model performance evaluation relates to the message reception buffer occupancy rate and the treatment resource utilization (supervisor). Several configurations are evaluated, they differ by the number of established stations on the assembly line. These various cases imply a request volume variation submitted to the supervisor and thus a more or less significant consumption of the shared resource it constitutes for the programmable logic controllers.

The simulation results summary in section 4 makes it possible to measure the model performances and to evaluate its correlation level, in terms of produced part volume, with the real production system.

Lastly, the section 5 presents a conclusion of the study and makes it possible to establish some prospects for improvement of the production system productivity by reducing the supervisor message processing time.

2. PRODUCTION SYSTEM CONSIDERED

The production system considered is an automated assembly process with several production machines called stations organized in line [Fig. 1]. It's a production resource serie successively visited in the order of their position by the parts to manufacture.

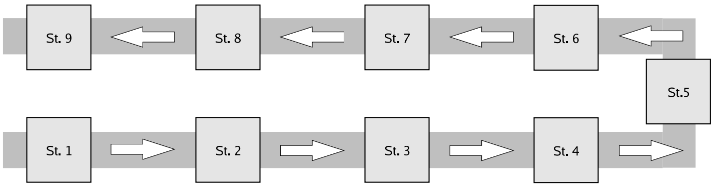

Figure 1: Flow-shop

The circulation on the assembly line proceeds according to the “first in-first out” policy and the part displacement is done by a conveyor. In this serial production mode, also called “flow-shop”, the parts undergo the same operation sequence with an individualized time for each station.

The stations work in an independent way from each other and execute individually their operating program. A station cannot retain and operate more than one part at a given moment. When a station is available (no treatment in progress) and a part is present at its entry, it starts its program execution.

2.1. WORKING CYCLE OF THE STATIONS

During their cycle, the stations execute an operation sequence whose each occurence is of constant duration [TAB. 1]. Only the mechanical treatment is of specific execution time.

Operation	Resource	Duration $_{(ms)}$
Convoying	External	3 000
Identification	PLC	550
Status request	PLC	60
Message evaluation Status search / Data insertion Status sending / Insertion acknowledgment	Supervisor	600
Status analysis	PLC	60
Data transmission	PLC	60
Relaxation	PLC	60

Table 1: Constant duration operations

The parts are assembled by successive mechanical operations by the stations. The product flow coordination is based on a part identification on arrival in a station. Thus, when a production machine deals with part, the programmable logic controller send a request to the supervisor in order to know the part status (good or bad). The response analysis cause the mechanical treatment (good part) or the relaxation (bad part).

At the end of the mechanical treatment of a part, the programmable logic controller once again solicits the supervisor to transmit the assembly results (measurements and various indications).

The mean latency delay noted for a response from the supervisor is 600 ms in the better case. This time covers the message evaluation and treatment by the supervisor and the response sending to the programmable logic controller.

2.2. COMMAND AND CONTROL ACTIVITIES

The programmable logic controllers question and inform the supervisor in a regular way to condition and coordonate their actions. These exchanges proceed at the production rhythm.

Then, the supervisor has a data centralization function it enriches by the information transmitted by the programmable logic controllers and that it can give back.

In the considered production system, the command activities are completely done by the programmable logic controllers. The notion of local command is then evoked.

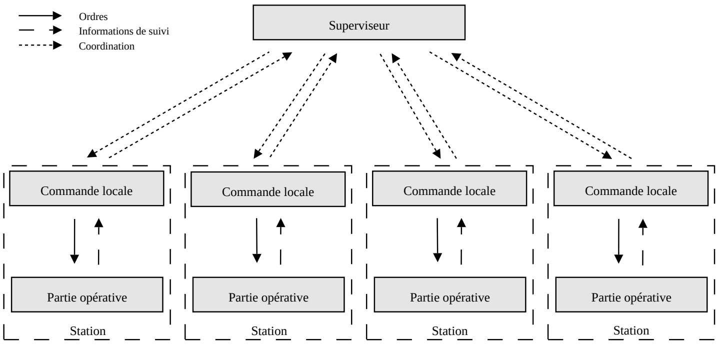

Figure 2: Command and control architecture

The supervisor ensures the production system control and is a central entity of the command and control system [Fig. 2]. So, the structure implementes a centralized control and a distributed command.

2.3. INTERACTIONS BETWEEN THE PROGRAMMABLE LOGIC CONTROLLERS AND THE SUPERVISOR

The communication between the programmable logic controllers and the supervisor are client-server type. In the context of the considered command and control architecture the programmable logic controllers are the clients and the supervisor is the server.

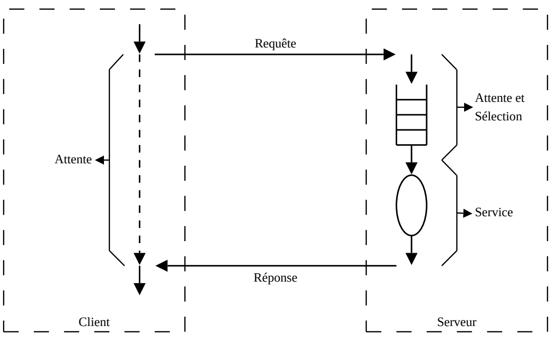

Figure 3: Client-server interactions

During an exchange, the programmable logic controller send a request to the supervisor. The message supporting the request is placed in a communication buffer. The supervisor manages the message selection and execute the treatment in adequacy with the message parameters.

The latency time in the communication buffer is variable. At the end of the treatment, the supervisor establishes a response message that it transmits to the programmable logic controller [FIG. 3]. The cumuled delays corresponds to the supervisor response time. The selection policy of the messages stored in the communication buffer is "first in-first out" type.

The control architecture implementation described implies frequent exchanges between the programmable logic controllers and the supervisor. The rate of these exchanges is conditionned by the rhythm of successive treatments of the parts by the various stations.

A request sending by a programmable logic controller causes a freezing situation of their cycle. The activity restart is triggered by the response reception coming from the supervisor.

3. SYSTEM MODELING

This work concentrates on the study of the interactions within the control system. Response time to a request is quite important because of its influence on the station cycle time. Also, the corresponding operations have the highest priority level of the task set executed by the supervisor.

The model describes architecture supporting the interactions between the local command units and the supervisor of an assembly line. It is primarily founded on the independent working of the various production machines and their access to a common treatment resource that is a central supervisor. The established model mainly applies to describe data flows related to the control activities which determine the behavior of an assembly line.

The model was established according to the timed coloured Petri nets formalism using the software Design/CPN. The Petri nets interest for the design and the evaluation of production systems has often been emphasized [DES-95, DIC-93, PRO-94, SIL-98, ZIM-96]. The timed coloured Petri nets are a wide type of the classical Petri nets.

The behaviour of the data processing system used in computer-integrated manufacturing and robotics is very often based on timed mechanisms making it possible to define the duration of the activities. The timed extensions of Petri nets are highly suitable models for the formal study of these mechanisms [JUA-00]. Thus, the timed Petri nets are often used for the system performance analysis, and more particularly, in the case of manufacturing processes but are often criticized because of the proportions which they can take when the number of products or stations implied is important.

The Petri nets colouring makes it possible to reduce the size of a model and to obtain a more compact representation of the systems including of distinct components having identical behaviors. Except the mechanical treatment that is not taken into account by the model, the production machines of the assembly line have the same working sequence. So, colouring is appropriate for modeling the studied production system of production.

3.1. MODELLED BEHAVIOUR

The model implements three main elements that are the stations set, the communication buffer and the treatment resource. Functions of the produced parts counting is also implemented.

The communication buffer size is fixed according to the number of stations declared in the model. It makes it possible to have a capacity sufficient for all the configurations evaluated in order not to lead to a saturation situation in accordance with the modelled real system.

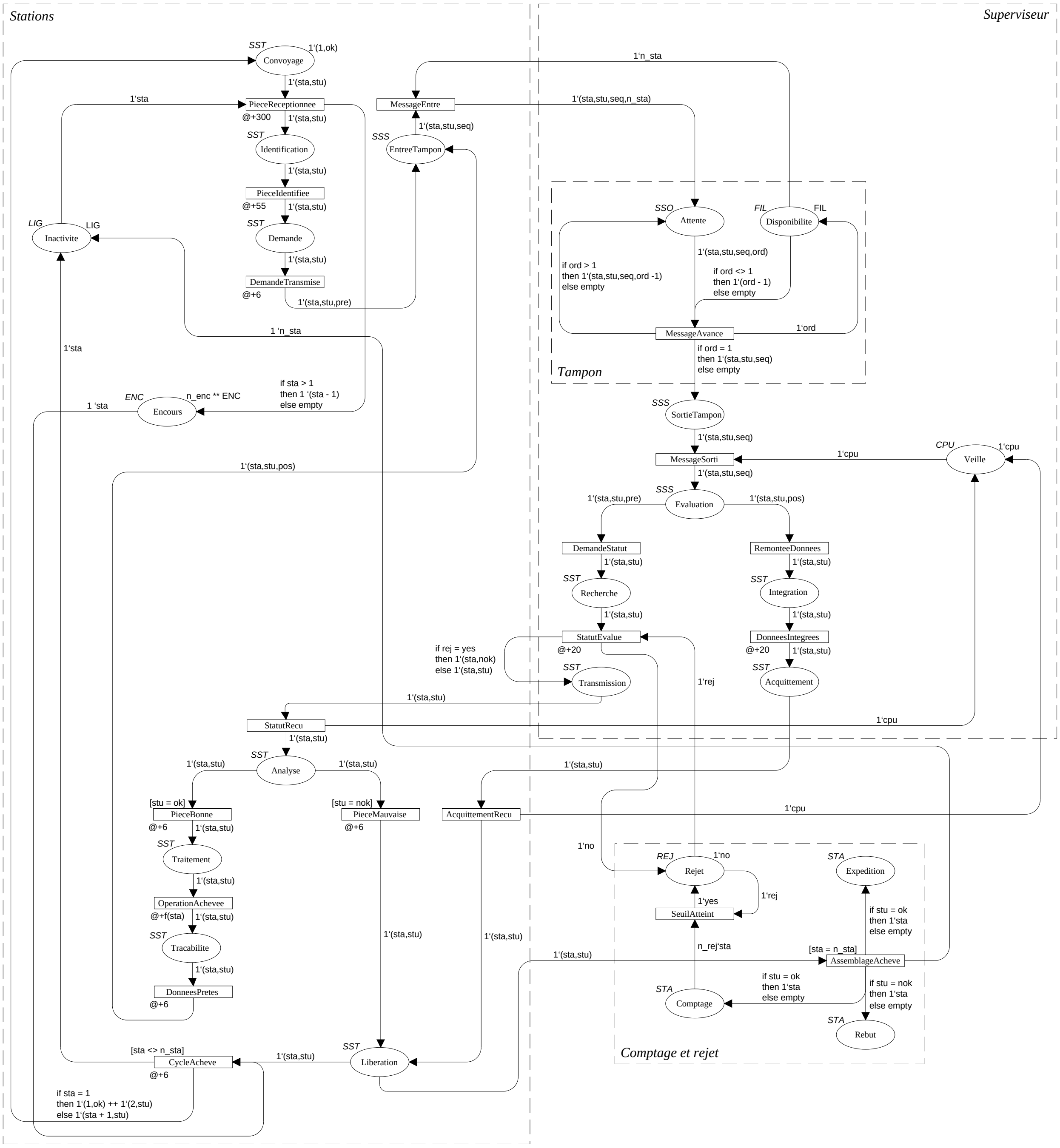

Figure 4: Petri net of the studied system

The time sampling rate is generally selected quite higher than the main time-constant of the controlled process [OGA-87]. The time quanta appointed for the modelled activities temporization is 10 ms. This period is defined according to the characteristics of the programmable logic controllers whose cycle time is around 60 ms.

The message propagation on the fieldbus is very fast compared with the modelled system. Only the latency delays in the communication buffer and messages treatment are significant. As, within the framework of our study, we consider that the message transmission is instantaneous.

The cycle station operations are integrated into the model in the form of places, the described sequence takes into account the operations of routing (place *Convoyage*) and identification (place *Identification*) of the part, status request send to the supervisor (place *Demande*), response analysis emitted by the supervisor (place *Analyse*), mechanical treatment of the part (place *Traitement*) and data transmission (place *Tracabilite*).

The transitions correspond to the events that make the token circulation symbolizing the system evolution and the situation of the stations and the supervisor. The temporization of some transitions (notation "@+<delay>") makes it possible to maintain the presence of the tokens in the places located upstream during the specified time. It allows to specify the execution time of the operations.

Colouring is primarily used to distinguish the various stations as well as the various positions of the communication buffer. For the stations, the colors apply according to their number and order on the assembly line. The part moving from a station to another is modelled by incrementing the token color number, except in the case of the treatment by the last station (end of assembly). The station availability is managed by a specific place (place *Inactivite*) guaranteeing the exclusivity of its execution to the treatment of only one part, the presence of a token of color x indicates that the station x is inactive. The place *Inactivite* is initialized according to the number of declared stations.

The communication buffer is modelled by a place (*Attente*) in which the token, representing the situation of a station having emitted a request. The colors are affected according to the order in the buffer. Each token rotation symbolizes and advance and its color number is decreased. The advance in the communication buffer is done by the treatment of the most advanced token.

The treatment resource is represented by a single place (*Veille*). The token in this place indicates the supervisor availability. A message arrival in the communication buffer implies the token leaving from the place *Veille*. The supervisor stops his activity when it completes the message treatment and when the communication buffer is empty.

3.2. MODEL SETTINGS

The evaluated configurations differ by the number of stations. They correspond to nine cases for which the assembly line consists of 2, 3, 4, 5, 10, 15, 20, 25 and 30 stations.

The model is primarily intended for the system evaluation in its initial state with response times to the requests emitted by the programmable logic controllers which are in conformity with the mean time measured on real production systems. The temporization of the Petri net places is mainly defined with readings taken on several assembly lines.

However, the simulation work implements configurations that are is not effective in the workshops. The mechanical processing time cannot be given by measurements. Then, these durations were generated using a pseudo-random generator. The generation takes account of the maximum and minimal bounds noted on the existing assembly lines where the mechanical times are between 1 100 and 8 500 ms.

Consequently, the model settings are based on the number of declared stations and the message treatment time by the supervisor.

4. SIMULATION RESULTS

The simulation operations are declined in two stages. The first phase related to the study of existing production systems (2 to 15 stations) and must allow the model checking by comparing the obtained results with readings taken from real configurations. The second phase, on the one hand, is intended to evaluate the extension possibilities of the station number and, on the other hand, to measure the potential profits brought by the message processing time reduction.

The model running time corresponds to a manufacturing period of 75 mn sampled every 10 ms (450 000 clock steps). It covers the phases of rise in rate and normal production of the assembly lines. The rise in rate is a transient regime and the stationary regime applies to the situation of normal production.

The transition from transient to stationary regime is cause by the working start of the last station (taken into account of the first part). It is related to the station number and differs according to configurations. However, for homogenity reasons, we study the stationnary regime on the 360 000 last clock steps corresponding to 60 mn of production.

4.1. EXISTING SYSTEMS

The simulation results for existing systems show an increase in supervisor activity rate. This value lead to the activity rate in stationary regime.

Config.	Rate (%)	Config.	Rate (%)
2 st.	28,083	5 st.	56,493
3 st.	36,791	10 st.	95,964
4 st.	46,926	15 st.	99,996

Table 2: Supervisor activity in stationary regime

The supervisor activity lies between 28 % and 100 % according to the configurations [Tab. 2]. The message treatment resource reaches saturation point for the configurations with 10 and 15 stations.

Config.	Mini	Mean	Maxi	Config.	Mini	Mean	Maxi
2 st.	0	0,049	1	5 st.	0	0,242	3
3 st.	0	0,119	2	10 st.	0	1,269	5
4 st.	0	0,149	2	15 st.	0	5,079	10

Table 3: Message number in the communication buffer in stationary regime

Except in the case of the configuration with 10 and 15 stations, the message mean number in the communication buffer remains quite lower than 1 [TAB. 3]. Also, many supervisor inactivity moments exists for the configurations with 1, 3, 4 and 5 stations.

By neglecting the fieldbus propagation delays, the supervisor response time to a request is an addition of the staying time in the communication buffer and the treatment time by the supervisor [TAB. 4].

The interactions between the stations and the supervisor occur twice during their working cycle (case of a good part). The simulation results concerning the supervisor response times are close to measurements obtain from the real production systems.

Config.	Mini$_{(ms)}$	Mean $_{(ms)}$	Maxi $_{(ms)}$	Config.	Mini$_{(ms)}$	Mean $_{(ms)}$	Maxi $_{(ms)}$
2 st.	600	609,952	760	2 st.	600	609,952	760
3 st.	600	790,967	1 200	3 st.	600	790,967	1 200
4 st.	600	786,688	2 400	4 st.	600	786,688	2 400
5 st.	600	852,650	2 920	5 st.	600	852,650	2 920
10 st.	600	1 391,994	7 200	10 st.	600	1 391,994	7 200
15 st.	600	3 650,287	33 180	15 st.	600	3 650,287	33 180

Table 4: Supervisor response time in stationary regime

During its execution, the model makes it possible to obtain production volumes similar to those noted on the real assembly lines [TAB. 5].

Config.	Simul.	Real syst.
2 st.	391	384
3 st.	372	–
4 st.	372	–
5 st.	369	–
10 st.	324	–
12 st.	261	271
15 st.	220	–
18 st.	184	204

Table 5: Production volumes for existing configurations

4.2. PROSPECT

The second phase of simulation relate to configuration of 20, 25 and 30 stations which, although they were never implemented, can meet a constant need to increase the number of operations necessary to the part manufacturing.

Config.	Mini	Mean	Maxi
20 st.	2	9,100	15
25 st.	6	13,507	20
30 st.	8	16,691	23

Table 6: Message volume in the communication buffer in stationary regime

The simulation results show a permanent supervisor activity during the stationary regime indicating the systematic message presence in the communication buffer waiting for a treatment [TAB. 6].

Config.	Mini $_{(ms)}$	Mean $_{(ms)}$	Maxi$_{(ms)}$
20 st.	680	6 058,531	44 930
25 st.	680	8 700,545	77 930
30 st.	680	10 618,110	101 980

Table 7: Supervisor response time in stationary regime

The supervisor mean response time [TAB. 7] grows in a significant way and does not allow to obtain quantities of produced parts in accordance with the productions targets [TAB. 8].

Config.	Qty
20 st.	159
25 st.	122
30 st.	99

Table 8: Production volumes for extended configurations

We have simulated the behaviour of assembly lines with a reduced message treatment time to 200 ms. The results show that significant productivity profits can be obtain [TAB. 9].

Config.	Qty	Gain
2 st.	421	7,673 %
3 st.	420	12,903 %
4 st.	419	12,634 %

Config.	Qty	Gain
5 st.	416	12,737 %
10 st.	385	18,827 %
15 st.	342	55,455 %

Config.	Qty	Gain
20 st.	332	108,805 %
25 st.	325	166,393 %
30 st.	313	216,162 %

Table 9: Production volume with reduced message treatment time to 200 ms

5. CONCLUSION

The study presented in this article applies to the control system of an automated assembly line. The aim is to estimate the impact of the supervisor response time to the requests emitted by the programmable logic controllers of the local command on the performances of the controlled process.

The described quantitive analysis enables to know a priori the behaviour of the assembly lines for various configurations according to a supervisor message treatment time.

The modeling and simulation of the production system show that the performances are strongly conditioned by the supervisor reactivity. The freezing situations for the stations are frequent and result in a productivity loss. Also, the message treatment time reduction is a significant factor of productivity improvement.

The production profits obtained by the message treatment time reduction grows quickly with the number of stations.Thus, it appears necessary to analyse the possibilities of optimizing the supervisor reactivity by placing temporal constraints.

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