

PRODUCT & RESOURCE DRIVEN CONTROL OF ALLOCATION AND ROUTING PROCESSES IN FMS

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ABSTRACT: *This paper deals with the heterarchical control of flexible manufacturing systems, more particularly on coupling dynamic task allocation and dynamic routing controls, with a focus on the latter. After presenting our major assumptions, we introduce the concept of semi-heterarchy, a key element in the proposed architecture based on active decisional entities, which can be products or resources. Dynamic allocation algorithms for such active products and/or resources are presented, and a stigmergic approach to routing control is then proposed. The proposed approach automatically searches for and finds efficient routing paths for active products whose routing has been perturbed. The proposed routing control model is based upon a functional architecture with two levels: a virtual level in which virtual active products evolve stochastically in accelerated time, and a physical level in which physical active products evolve deterministically in real time. A virtual level path exploration is triggered when a perturbation is diagnosed in the transportation system, and the active products follow the best paths detected on this virtual level. The data used in the simulation on the virtual level is then updated to reflect the real state of the transportation system. We illustrate the model's adaptive capabilities through several simulation scenarii using NetLogo software, and present an on-going real implementation taking place at the AIP-PRIMECA Center in Valenciennes, France.*

KEY-WORDS: *stigmergy, dynamic routing, active product, manufacturing control, flexible manufacturing system*

INTRODUCTION

This paper addresses the issue of production process control in flexible manufacturing systems (FMS), in which heterarchical relations exist between some decisional entities.

First we introduce the global assumptions on which our proposal relies. Then, we present a brief state-of-the-art of the literature and explain the objective of our study. Next, we define what we mean by heterarchy. Since the task allocation control has already been studied (Sallez et al., 2004), we focus here on our innovative approach to routing and the integration of this approach within the procedures for production process control.

1. GLOBAL ASSUMPTIONS

To situate our study in the overall domain of FMS, it is very important to introduce the main assumptions on which our study is based and on which our model relies.

1. *the topology of the FMS transportation system* is assumed to be associated to a strongly connected, directed graph, in which nodes can be both resources and disjunction points, and arcs are the parts of the system that require no decisions during the routing process since the product can only move in one direction towards the next node. Routing times are assumed to be non-negligible compared to production times and non necessary constant. Resources are also assumed to be flexible, meaning that the same operation type can be executed on several resources, with the possibility of different processing times.

2. *Products and production resources* are assumed to be decisional entities. Usually, these products and resources are considered to be passive entities: they never communicate, decide nor act during production process. However, current technology (e.g., RFID, smart cards, embedded systems, wifi, infrared communication) has recently led to some new activities involving "active" decisional entities, in which products and resources are able to act in accordance with the real state of the

production system. This new ability can be embedded in the product or resource itself (McFarlane et al., 2002). In this paper, products and resources that can be taken as decisional entities are denoted AP (active products) or AR (active resources).

3. The studied production control system must control the production process in real time. Consequently, its *inputs* are assumed to be information about planned manufacturing orders optimized over the long term (what to do and when?), coming, for example, from an ERP (enterprise resource planning) system. The *controlled production process* is assumed to be composed of several activities, involving mainly the execution of manufacturing orders using production resources and the routing of products within the production system. Given this assumption, dynamic production control systems must deal with many issues: dynamic scheduling/task allocation (who undertakes the tasks required for each manufacturing order?), tool and inventory management, reconfiguration/preparation of resources, transportation system management, performance indicator updating, and so on.

4. The structure of the production control system is assumed to be non-centralized (i.e., no central data management system can be identified) and to have a non fully hierarchical control structure (this concept will be described more precisely later).

2. STATE-OF-THE-ART AND OBJECTIVES

This section provides a brief state-of-the-art of the literature in the domain of production control systems that are non fully hierarchical. Most research developments in this context focus on distributed or decentralised dynamic control of one of the issues mentioned above: dynamic task allocation/scheduling. See, for example, studies by Aissani et al. (2008), Bousbia et al. (2005), Cavalieri et al.(2000), Lastra and Colombo (2006), Maione and Naso (2003), Tharumarajah (2001), Wong et al.(2006), Duffie et Prabhu (1996) and Baker (1998). Our initial work in this domain led us to propose a dynamic allocation process based upon an heterarchical product-driven and resource-driven control of dynamic scheduling (Sallez et al., 2004). However, in order to apply concepts relevant to this domain in a real FMS, dynamic scheduling is not sufficient; several other process controls must also be developed (e.g., tool management, inventory level control, routing process control).

We are currently working on producing a semi-heterarchical control for a real FMS (AIP-PRIMECA Cell). This is why we must then now integrate all the previously introduced process controls into our model. Since, from the product point of view, the product alternatively searches for services among the available production resources (transformation) and the available transportation resources, we choose to begin by

integrating routing process control with our previously designed allocation process control. This new model for routing process control, and its integration with our previous model, is described in this paper. The next section defines precisely what we mean by heterarchy, which is important since it is a key concept for the designing of the new control structure.

3. HETERARCHY

In our opinion, heterarchy can be formalized by using graph theory. A directed graph composed of nodes representing decisional entities and arcs representing the master-slave interaction of a decisional entity (master) with another entity (slave) is called "influence graph". Since each node can be considered both a master and a slave, no hierarchy can be identified. The graph is thus considered to be strongly connected, which defines a heterarchy. This formalisation is consistent with the initial heterarchy concept developed by (McCulloch, 1945). Figure 1 illustrates the difference between hierarchy and heterarchy graphically.

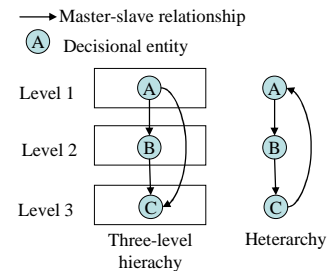


Figure 1. Hierarchy and heterarchy.

Thus, hierarchy and heterarchy are both relevant to the structure of a system composed of several decisional entities (cf. figure 2). Based on these two concepts, different structures can be formed, ranging from fully hierarchical (no heterarchical relationship) to fully heterarchical (no hierarchical relationship). We use the term "semi-heterarchical" to refer to a structure that can not be assimilated to a fully heterarchical system while it contains at least one sub-graph that is fully heterarchical.

4. PROPOSED CONTROL STRUCTURE

A production control system is designed to determine in real time the list of each successive task (operation, date) that an active resource AR has to realize, taking into account both allocation and routing issues. Thus, the two processes that must be controlled are the dynamic allocation process (DAP) and the dynamic routing process (DRP).

The proposed semi-heterarchical control structure is shown in Figure 3. In this structure, allocation is controlled prior to routing.

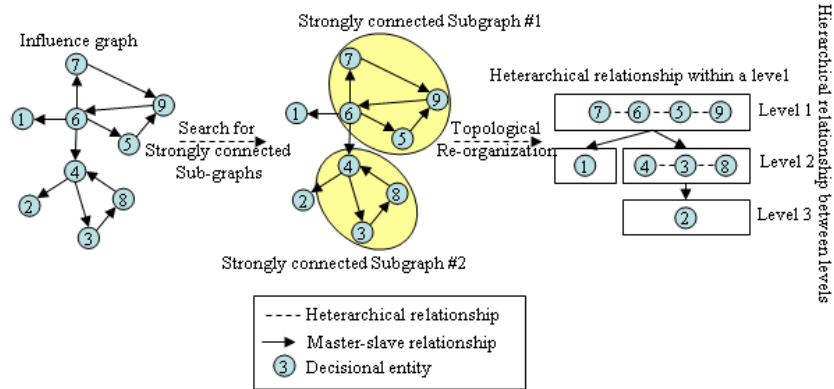


Figure 2. Hierarchy and heterarchy as building blocks of a system composed of decisional entities.

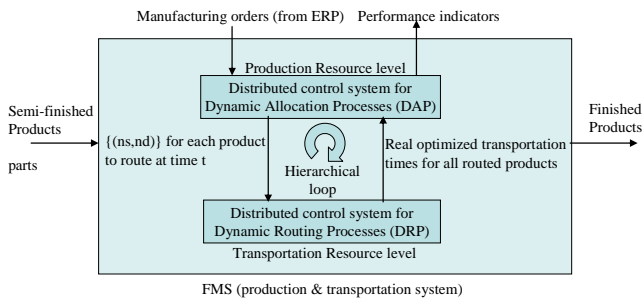


Figure 3. Proposed semi-heterarchical control structure.

Inputs to the DRP control system are assumed to be composed of the set of couples (ns, nd) – where ns is the active resource source node and nd the active resource destination node – that concern one or more products at a given time t. This information is defined by the DAP control system. Outputs from the DRP control system are the optimized real transportation times for routed products. This information will be used by the DAP control system to improve its allocations. Relationship between DAP & DRP control systems is then hierarchical.

Meanwhile, the global structure is partially heterarchical since each of the two control systems is fully heterarchical: no hierarchy can be identified in any of the individual control subsystems (decisional entities) and there is neither centralized data management nor centralized processing capability. A fully heterarchical structure in which the DRP and DAP cooperate to optimize allocation and routing jointly is possible, but such a structure generates new issues that are currently being studied and have yet not been published. The following provides the control algorithm supported by our previous control structure model.

5. PROPOSED CONTROL ALGORITHM

Our initial research dealt with a theoretical heterarchical DAP control (Sallez et al., 2004). Here, we improve on this theoretical control model, by combining it with the DRP control in a more global control algorithm, which allows the hierarchical articulation of the two control systems. This new approach is fully reactive since it assumes that manufacturing orders have

been planned and optimized using a wider time horizon window. Since our goal is to validate our model on real embedded systems, a real-time programming approach was used (e.g., reduction of the number of loops and non-blocking states).

The following are the main notations used in our model.

Let $N = \{n_i\}$ be the set of considered nodes n_i (active resources – AR) or disjunction points in the transportation system) and $X = \{x_j\}$ be the set of active products – AP. Both AR and AP are decisional entities. For each AR, an input zone exists where an AP waits for a task (i.e., operation to be executed) and an output zone where an AP waits to be transferred. Figure 4 illustrates these notations and shows the two decisional entities AR and AP.

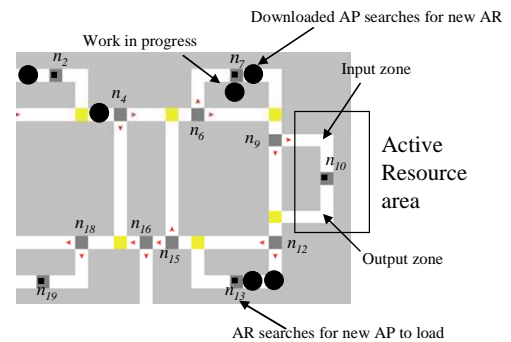
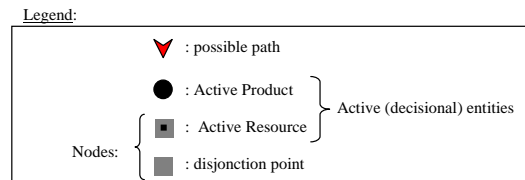


Figure 4. Notations and decisional activities.

The main algorithm (below) features the two kinds of decisions made by AR and AP:

- When an operation is completed by AR n_i on AP x_j
- AP x_j is downloaded by AR n_i in its output zone
- AR n_i decisional algorithm is triggered
- AP x_j decisional algorithm is triggered

These two decisional algorithms are described in the next two sections.

5.1. Active Resource decisional algorithm

When an AR has finished an operation on AP x_j , it downloads x_j to its output zone if space is available (pre-conditions). Then the AR analyzes its input zone, if several AP are available, it chooses the “best” next x_k . The algorithm responsible for this decision has two steps:

1. AR n_i identifies next AP $x_k = g(D)$
2. AR n_i loads AP x_k

In this algorithm, the function g depends on evaluating a criterion D that is defined according to the global objective assigned to the control system. The choice for the best criterion to achieve this objective is still an open issue. However, D is usually based upon such information as shortest processing time, shortest remaining time/tasks or first-in first-out to name a few. The best product to load is the one that proposes the best value for D through mono-criterion (min or max) or multi-criteria analysis.

Steps 1 & 2 are supported by the DAP heterarchical control system.

5.2. Active Product decisional algorithm

When an operation is completed on an AP, the AP enters the output zone of the AR that has executed the operation. It must then choose (decide) an AR for the next operation (service). To do so, the AP uses the following 3-step algorithm:

1. x_j identifies the next operation to execute
2. x_j reserves the “best” destination $n_d = f(D', M)$
3. x_j moves from current node resource n_s to n_d

The f function depends on two parameters: the criterion D' used to optimize the operation and the method M used to gather information. The best choice for criterion D' is, like the choice for D , open to debate, but this criterion is usually based upon such information as next available time, shortest remaining number of operations to proceed and/or transfer time, for example. In a heterarchical context, one of the most usual methods chosen for M is based upon the contract-Net protocol (Smith, 1980), but a blackboard system could also be used.

A global performance objective must be defined and “translated” into specific local criteria sets (D, D'). For example, one may minimize delivery delays by fixing $(D, D') = (\text{Shortest Slack Time}, \text{Shortest Next Available Time})$. But this “translation” is still an open issue: some contradictory sets may lead to bad global performances. This point is currently under study.

Steps 1 & 2 are supported by the DAP control system while step 3 is supported by the DRP control system.

5.3. Looping DAP and DRP control systems

The input for the DRP control system is then the set of couples (n_s, n_d) . After the routing operation has been executed, $\tau_{nd}^*(n_s)$, denoting the minimal real-time to go from AR n_s to the destination AR n_d , is then updated by the DRP control system. This value is sent back to the DAP control system each time the D' criteria must be estimated. As a result, the real state of the transportation system can be taken into account when determining the “best” AR n_d . The hierarchical loop between the two control systems is then pointed out.

The following section underlines the innovative aspect of our approach and describes in detail the DRP control system, its simulation and its validation on a real FMS cell. The validation of the coupling of the two control systems will be presented in another paper.

6. THE DRP CONTROL SYSTEM

6.1. Concept of stigmergy

To make the DRP adaptive and robust, our approach is based on the concept of stigmergy. The term “stigmergy” describes the mechanism used during ants foraging activities (Theraulaz & Bonabeau, 1999). Ants find food and carry it back to the nest, simultaneously laying down a pheromone trail. Other ants, detecting the pheromones, follow the trail back to the food source. As more ants bring food to the nest, they each reinforce the chemical trail on the path they follow. Since pheromones tend to evaporate over time, the more attractive trails accumulate more pheromones and thus have an advantage over the other trails. Over time, due to the natural reinforcement of the ants, only the shortest trail remains.

Several researchers (Dorigo and Stützle, 2006; Parunak et al., 2001; Brückner, 2000; and Hadeli et al., 2004) have applied the stigmergy concept to solve optimization problems or specific situations in manufacturing control systems. A more detailed discussion about these works is available in (Berger et al., 2006). In most stigmergic applications (e.g., ants searching for food), time is not really considered and attempts cost the user nothing; only the final solution is taken into account. However, in a production context, time inefficiency is prejudicial to the system: for example, if too many solutions are tried before finding the right one (e.g., too many shuttles are used to try paths), the overall performance quality rapidly deteriorates, for instance, in terms of completion time. Consequently, a model is needed that will identify satisfactory solutions quickly in order to accelerate the convergence of algorithms as much as possible. In response to this need, we propose an original functional two-level—physical and virtual—architecture for the heterarchical control of DRP. A close approach was used

by (Qiu, 2005) via the introduction of virtual production lines in a semiconductors manufacturing context.

6.2. Modelling approach

Figure 5 shows the proposed architecture with its two levels and the intermediary Data Space (DS) that memorizes the information for both levels:

- The Virtual Level (VL), where Virtual Active Products (VAPs) move, is an informational domain in which everything is simulated in accelerated time as quickly as possible;
- The Physical Level (PL) represents the real world, in which Physical Active Products (PAPs) move in real-time.

A node n_i (disjunction point or AR) has three components: a virtual image (in the VL), a data memorization and processing structure (in the DS), and a physical infrastructure (in the PL). Since VL works in accelerated time, adaptation time becomes physically short. On the VL level, lots of VAPs can be used to discover new paths, which helps to keep the number of PAPs circulating on the PL level low. The virtual entities (VAPs) make decisions based on stigmergic principles, which include stochastic decision-making and allow adaptive behavior to deal with unexpected perturbations. VAP travel history is used to update the pheromones (i.e., routing data). From a logical point of view, VAP move within a model of the existing routing network in the PL, which contains PAPs. At the PL level, PAP routing decisions are made deterministically with “best efforts”, based upon the optimized results of the VL level.

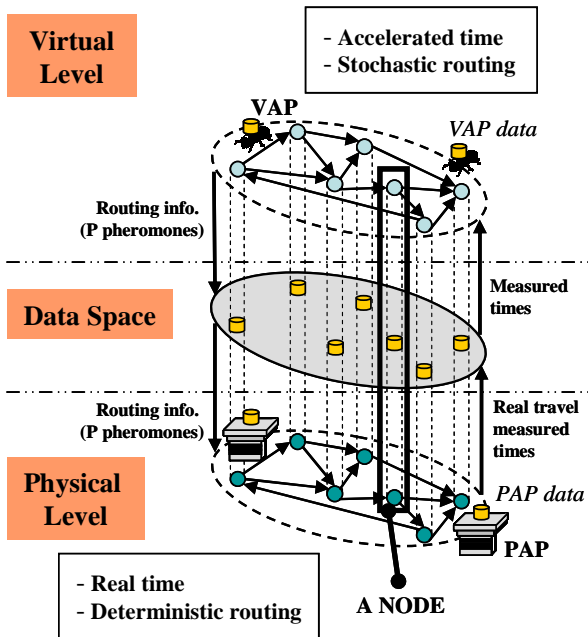


Figure 5. The two levels architecture.

The following section introduces the notations used in this model, which is then described more precisely.

6.3. Notations and variables

The variable $v_{n_i}^w$ denotes the w^{th} neighbour of n_i and V_{n_i} , the set of the neighbors of n_i : $V_{n_i} = \{v_{n_i}^w / \exists \text{arc } n_i \rightarrow v_{n_i}^w\}$, $w \in \{1 \dots \text{card}(V_{n_i})\}$. $N = \{n_i\}$ and V_{n_i} thus describe then the topology of the FMS, including the transportation system. A possible path between node n_i and node n_j is written $u_{ij} = [n_i \dots n_j]$ and corresponds to the ranked list of successive nodes to be visited in order to travel from n_i to n_j .

Variables:

- $t_{n_i}(v_{n_i}^w)$ and $t_{n_i}^*(v_{n_i}^w)$ are, respectively, the travel time (measured by a PAP) and the reference time (for a VAP) between a node n_i and its w^{th} neighbor.

- P_{n_i} is the pheromone matrix. Columns of P_{n_i} correspond to all possible destination nodes n_j from n_i and rows contain all existing neighbor nodes $v_{n_i}^w$. In analogy to biological systems, this matrix characterizes the pheromone rate on the different arcs $n_i \rightarrow v_{n_i}^w$. The value $P_{n_i}(v_{n_i}^w, n_j)$ is associated to the preferred path from the current node n_i to destination node n_j , when choosing the possible intermediate neighbor node $v_{n_i}^w$. Consequently, the following expression is true:

$$\sum_w P_{n_i}(v_{n_i}^w, n_j) = 1, \forall (n_i, n_j) \in N^2$$

In this paper, the best path is considered to be the path on which the PAPs spend the least time.

Figure 6 gives an example of the use of the above variables. Let a PAP be set on current node $n_i = n_3$, coming from the source node n_1 with the destination node $n_j = n_8$. In this example, the best neighbor is n_4 since $P_{n_3}(v_{n_3}^1 = n_4, n_8) = .95 > P_{n_3}(v_{n_3}^2 = n_5, n_8) = .05$. PAP will then travel from n_3 to n_4 , keeping its destination node n_8 in mind. When arriving at n_4 , the time spent $t_{n_3}(n_4)$ is reported to node n_3 via node n_4 and is used by the node n_3 to determine whether or not a perturbation (e.g., bottleneck, slow down, break down) has oc-

curred between n_3 and n_4 by comparing $t_{n_3}(n_4)$ with $t_{n_3}^*(n_4)$.

$\tau_{n_i}^*$ is the minimum time vector. $\tau_{n_i}^*(n_j)$ thus denotes the minimum measured time to move from node n_i to any possible destination node n_j . This variable is updated every time a lower time is clocked, according to a mobile time window (not described in this paper).

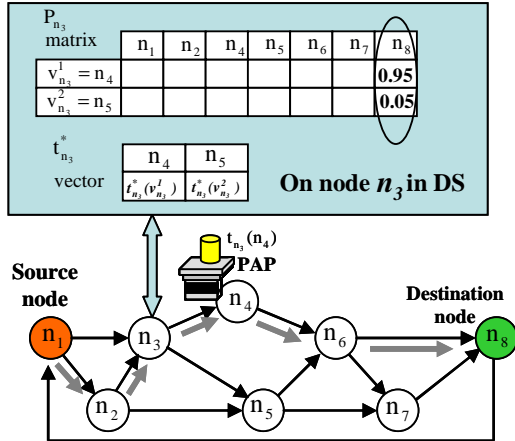


Figure 6. Variables illustration.

$h_{vap}(n_i, n_j)$ is the history table. Each VAP traveling between nodes n_i and n_j updates its history table $h_{vap}(n_i, n_j)$, which is used to store the nodes reached and the corresponding arrival dates:

$$h_{vap}(n_i, n_j) = ([n_i, n_k, n_m, \dots, n_u, n_j], [d_i, d_k, d_m, \dots, d_u, d_j])$$

where d_i is the arrival date at node n_i .

Based on the previous notations, the time spent to travel from n_i to n_j is $\tau_{n_i}(n_j) = d_j - d_i$.

6.4. Model of the routing process control

Nominal routing process control

At a given time, a PAP begins to travel from its AR source node ns to its AR destination node nd . The pair (ns, nd) is provided by the DAP control system. The current node is designated nc , thus $nc = ns$ when the PAP begins to move. The values of $P_{nc}(v_{nc}^w, nd)$ are used to choose the next neighbor node nn . This choice is deterministic since the neighbor with the greater P value is always chosen $nn = \tilde{V}_{nc}^{nd}$ where:

$$\tilde{V}_{nc}^{nd} \in V_{nc} / P(\tilde{V}_{nc}^{nd}, nd) = \max_{w \in \{1, \dots, card(V_{nc})\}} P_{nc}(v_{nc}^w, nd)$$

During the real move on the arc $nc \rightarrow nn$, the real elapsed time $t_{nc}(nn)$ is measured. When the PAP

arrives at node nn , it moves backwards $t_{nc}(nn)$ to node nc . A local perturbation is detected on the arc $nc \rightarrow nn$ if $|t_{nc}(nn) - t_{nc}^*(nn)| > \epsilon$, where ϵ is a fixed threshold parameter.

VAP exploration

When a perturbation is detected, a VAP exploration is triggered. At each time interval T, a VAP is generated on node ns and is assigned the nd destination node.

On a current node nc , the VAP must choose the next neighbor node nn . Since both luck and diversity are important adaptation mechanisms in natural biological systems, the choice of nn is not deterministic (as is true for PAP) but stochastic. The different $P_{nc}(v_{nc}^w, nd)$ are then assigned the probability to reach, from nc and to the destination n_j , the neighbor v_{nc}^w . However, if $P_{nc}(v_{nc}^w, nd)$ is negligible, v_{nc}^w will rarely be chosen. To ensure diversity, a minimum value α is introduced, making the relation:

$$Prob(nn = v_{nc}^a) = \max \left(\frac{P_{nc}(v_{nc}^a, n_j)}{\sum_w P_{nc}(v_{nc}^w, n_j)}, \alpha \right) = \max(P_{nc}(v_{nc}^a, n_j), \alpha)$$

since $\sum_w P_{nc}(v_{nc}^w, n_j) = 1$

which corresponds to the probability of node v_{nc}^a being chosen as the next neighbor (denoted nn).

After reaching node nn , the passage date d_{nn} is then stored in the history table h_{vap} . Because the move is virtual, this date is calculated by adding the time reference $t_{nc}^*(nn)$ to the last date in history table.

Then the node nn becomes the new current node nc , and the VAP continues to travel to the destination node nd , iteratively.

Finally, when the VAP reaches the destination node, the routing is finished and the history table is reported to the node nd .

The search for the "best" alternative path

Like biological ants, which lay down a pheromone trail when returning to the nest, every time a VAP reaches its destination node nd , the information contained in its history table h_{vap} is forwarded to each visited node to update pheromone matrices. In our approach, this coefficient updating process is based upon a reinforcement law.

When the forwarded information reaches node nc , $\tau_{nc}(nd)$ and the minimal time $\tau_{nc}^*(nd)$ are compared. If $\tau_{nc}(nd)$ is less or equal to the minimal time $\tau_{nc}^*(nd)$ and

if nn was the neighbor node used to travel from nc to nd , $P_{nc}(nn,nd)$ is reinforced:

$$P_{nc}(nn,nd) \leftarrow P_{nc}(nn,nd) + r * (1 - P_{nc}(nn,nd))$$

With $nn \in V_{nc}$

Coefficients $P_{nc}(no,nd)$ for the destination nd of the other neighbors no are negatively reinforced through a process of normalization:

$$P_{nc}(no,nd) \leftarrow P_{nc}(no,nd) - r * P_{nc}(no,nd)$$

With $no \in V_{nc}$, $no \neq nn$

The “best” path emerges when all the P_{nc} coefficients at the reached nodes nc are superior to a fixed threshold Ω (0.95 in our study). As shown in figure 10a, this state is reached after a transient period (Zone A). The path is declared “best” after a verification/check period (Zone B), which is indispensable to be sure that the found path is good enough. This last period is finished when a fixed number of VAPs have reached the destination node nd .

7. SIMULATION OF THE DRP CONTROL SYSTEM

7.1. Short description of the simulation tool

The proposed control model is naturally distributed, meaning there is no central memorization and processing system. This property influenced our choice of an agent-based parallel modeling and simulation environment. With NetLogo (Wilensky, 1999), each modeled entity can be described as an independent agent interacting with its environment. All agents operate in parallel on a grid of patches (i.e., a cellular world), and each agent can read and modify some of the attributes linked to the patches in its proximity. The behavioral rules defined for the agents make it possible to describe agent-environment interaction, which is very important when simulating the stigmergic process.

In the following case study, both the physical and virtual levels are simulated. Figure 7 shows our simulator’s interface. An applet is available at url: <http://www.univ-valenciennes.fr/sp/routing/>

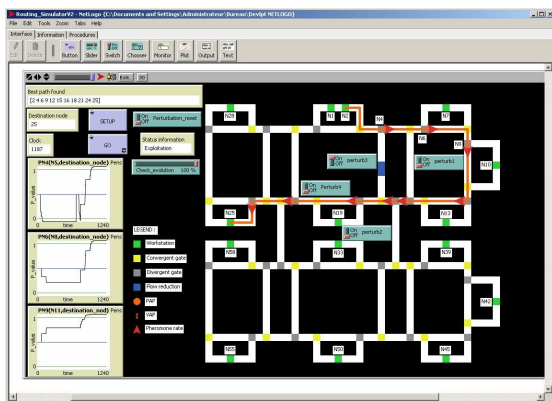


Figure 7. Simulator interface.

7.2. Case study

The proposed approach is currently applied to an FMS built around a conveyer network based on a one-way conveyer system with divergent transfer gates that allow PAPs to be routed toward the different workstations. This FMS, shown in figure 8, can be characterized as follows:

- 15 workstations (nodes in medium grey with a black square inside),
- 24 divergent transfer gates (nodes in medium grey), where a routing choice between two adjacent arc must be made,
- 24 convergent transfer gates (nodes in grey with cross bars).

The FMS is divided into two parts – upper and lower – connected by two arcs $n_{16} \rightarrow n_{36}$ and $n_{61} \rightarrow n_{22}$.

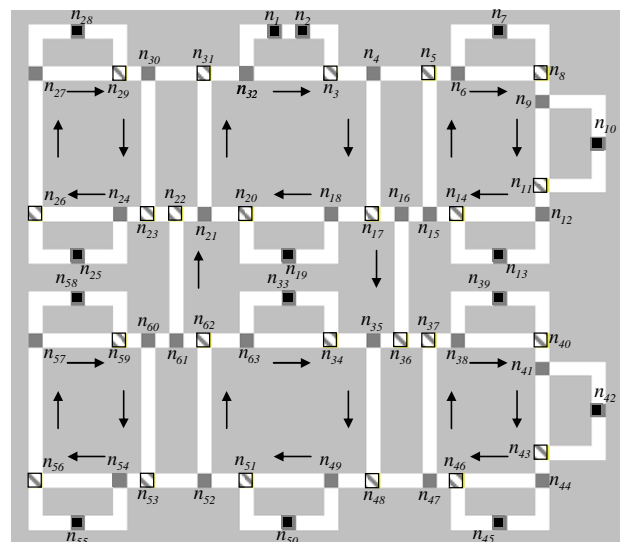
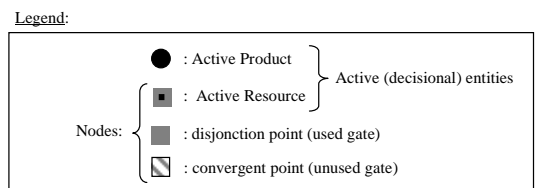


Figure 8. FMS conveying/resource network.

7.3. Results

Several scenarii are presented, pointing out the different capabilities of our model with respect to self-adaptation to perturbations. These scenarii are summarized in table 1.

* Scenario 1: In the first scenario, the impact of a perturbation on an arc that can be by-passed is studied. n_2 and n_{19} are the source and destination nodes, respectively. Qualitative & quantitative results are presented.

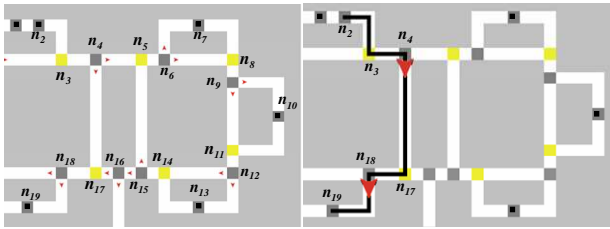
Qualitative results

Figure 9a shows the beginning of the initialization phase. Arrows (near divergent transfer gates) represent

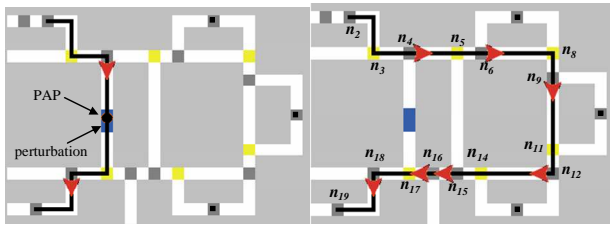
the pheromone rate corresponding to the adjacent arcs. Their size is proportional to the pheromone rate (initial values set to 0.5). The VAPs travel randomly along the different arcs, and the path $[n_2, n_3, n_4, n_{17}, n_{18}, n_{19}]$ emerges through reinforcement. At each divergent transfer gate, the bigger arrows indicate the better arcs. The best path is then traced (in black), cf. figure 9b.

Figure 9c indicates the presence of a perturbation on the arc $n_4 \rightarrow n_{17}$, affecting traffic fluidity on this arc. (The flow reduction is shown in dark grey).

When a PAP (black disc) takes a longer time on this trajectory than expected, a new VAP exploration is triggered via n_4 .



Figures 9a, 9b. Initial state; “best” path found.



Figures 9c, 9d. Perturbation triggered; alternative path.

The VAPs travelling on the arc $n_4 \rightarrow n_{17}$ perform poorly, thus the appeal of this path decreases. The decreased appeal of this perturbed path consequently increases the appeal of an alternative path $[n_2, n_3, n_4, n_5, n_6, n_8, n_9, n_{11}, n_{12}, n_{14}, n_{15}, n_{16}, n_{17}, n_{18}, n_{19}]$ (figure 9d), even though this path was originally not the best. This dynamic response is a classic display of the natural routing reconfiguration capacity of the stigmergic approach.

Quantitative results

Figure 10 shows the evolution of some of the P_{n_i} coefficients. Please note the change that occurs after the perturbation at date $d=350$ (in simulated time). Figure 11 shows more precisely the evolution of the coefficient $P_{n_4}(n_{18}, n_{19})$ for a perturbation occurring at $d=902$ and for its resolution at $d=1472$. After the perturbation has been resolved, the coefficient $P_{n_4}(n_{18}, n_{19})$ again converges to 1.

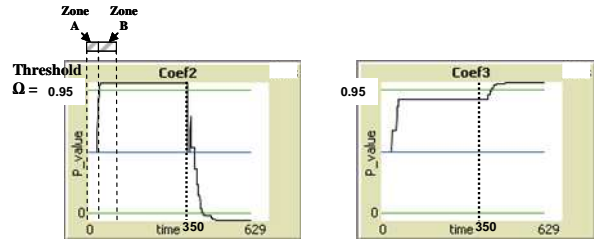


Figure 10a. $P_{n_4}(n_{18}, n_{19})$. Figure 10b. $P_{n_6}(n_9, n_{19})$.

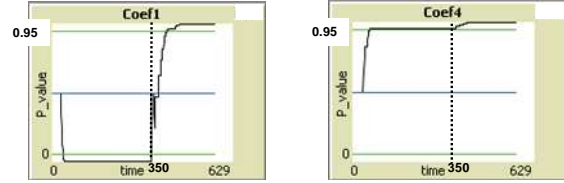


Figure 10c. $P_{n_4}(n_6, n_{19})$. Figure 10d. $P_{n_9}(n_{12}, n_{19})$.

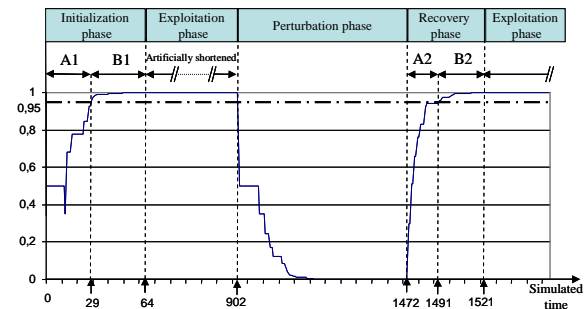


Figure 11. Evolution of $P_{n_4}(n_{18}, n_{19})$.

* **Scenario 2:** In the second scenario, a perturbation is introduced on arc $n_{16} \rightarrow n_{36}$. This arc is an obligatory bridge to travel from the upper to the lower section of the FMS and it can't be by-passed. Please note that, after the perturbation, that the alternative path found is the same as the initial path (cf. table 1). This is possible because the minimum reference time $\tau_{n_{10}}^*(n_{39})$ was constructed using a mobile time window, built with the 20 last measured times. In this context, the previous “good” performance of $\tau_{n_{10}}^*(n_{39})$ is forgotten and the new longer time becomes the reference time.

* **Scenario 3:** Nodes n_2 and n_{25} are the source and destination nodes, respectively. In the event of a perturbation on the arc $n_{20} \rightarrow n_{21}$, the initial simple path becomes:

$[n_2, n_3, n_4, n_5, n_6, n_8, n_9, n_{11}, n_{12}, n_{14}, n_{15}, n_{16}, n_{36}, n_{37}, n_{38}, n_{40}, n_{41}, n_{43}, n_{44}, n_{46}, n_{47}, n_{48}, n_{49}, n_{51}, n_{53}, n_{54}, n_{56}, n_{57}, n_{59}, n_{60}, n_{61}, n_{22}, n_{23}, n_{24}, n_{25}]$.

Scenario	Source node	Destination node	Initial path	Perturbed arc	Alternative path identified
1	n_2	n_{19}	$n_2, n_3, n_4, n_{17},$ n_{18}, n_{19}	$n_4 \rightarrow n_{17}$	$n_2, n_3, n_4, n_5, n_6, n_8, n_9, n_{11},$ $n_{12}, n_{14}, n_{15}, n_{16}, n_{17}, n_{18}, n_{19}$
2	n_{10}	n_{39}	$n_{10}, n_{11}, n_{12}, n_{14},$ $n_{15}, n_{16}, n_{36}, n_{37},$ n_{38}, n_{39}	$n_{16} \rightarrow n_{36}$	$n_{10}, n_{11}, n_{12}, n_{14}, n_{15}, n_{16}, n_{36}, n_{37}, n_{38}, n_{39}$
3	n_2	n_{25}	$n_2, n_3, n_4,$ $n_{17}, n_{18}, n_{20},$ $n_{21}, n_{22}, n_{23},$ n_{24}, n_{25}	$n_{20} \rightarrow n_{21}$	$n_2, n_3, n_4, n_5, n_6, n_8, n_9, n_{11}, n_{12}, n_{14}, n_{15},$ $n_{16}, n_{36}, n_{37}, n_{38}, n_{40}, n_{41}, n_{43}, n_{44}, n_{46},$ $n_{47}, n_{48}, n_{49}, n_{51}, n_{52}, n_{53}, n_{54}, n_{56},$ $n_{57}, n_{59}, n_{60}, n_{61}, n_{22}, n_{23}, n_{24}, n_{25}$

Table 1. Scenarii description.

8. ELEMENTS FOR A REAL IMPLEMENTATION

Given the promising results of the simulation, we decided to test our model on a real implementation, respecting the assumptions introduced in section 1.

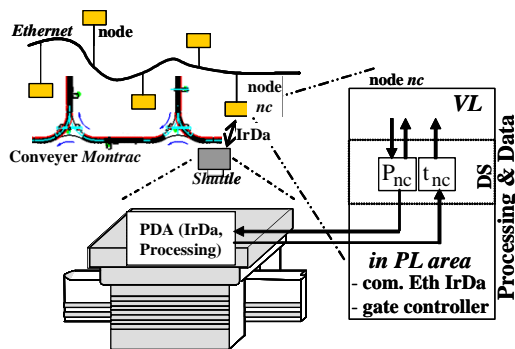


Figure 12. Schematic representation.

Three types of equipment were used:

- A Conveyor system Based on Montrac technology (Montech, 2007), this system is a monorail transport system using self-propelled shuttles to transport materials on tracks;
- Node instrumentation, (figure 12):
 - o a “gate controller” which works to oversee the transfer gate and to help avoid collisions;
 - o a DS containing P_{nc}, t_{nc} , the two variables required by the PL;
 - o two data communication systems (*Ethernet* for node-to-node interaction, and *IrDA* for node-to-shuttle communication (esb-101 Clarinet system (Clarinet System, 2007))); and
 - o a data processing system, supported by a Wago 750-841 controller (Wago, 2007), which is shared by the VL and PL.
- Shuttle instrumentation This instrumentation is based on a data processing system embed-

ded in a PDA device (including an IrDA communication) (figure 13).

Infra-red technology was chosen because of:

- its low energy consumption for a high transfer rate (more than 100 Kb/sec),
- its short range, which enables geographical node localization, and
- its light-based physical layer, which is naturally robust to electromagnetic noise.

The communications between node and product were successfully validated, and Wago programs are now under development.

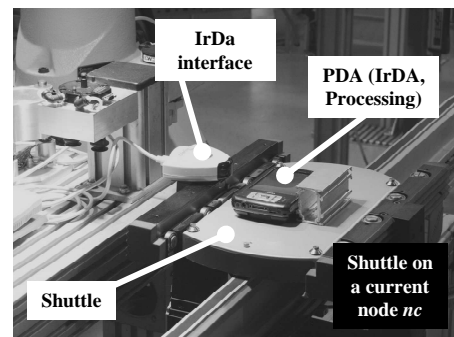


Figure 13. Real implementation.

The flexible assembly cell of the Valenciennes AIP-PRIMECA center is being used as experimental support (figures 13, 14).

9. CONCLUSION AND PROSPECTS

The results described above illustrate the advantages of our approach. First, the PAPs are able to determine the best path from the departure node to the destination node without any centralized control. Second, they are able to surmount perturbations by seeking out new paths that bypass the perturbation but still lead to the desired destination.

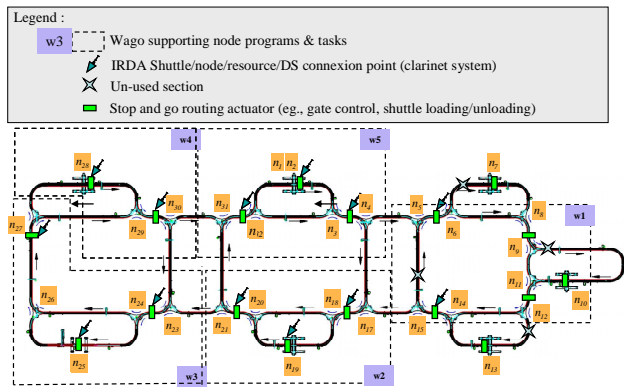


Figure 14. AIP cell case study.

Other simulations under studies but not described in this paper highlight the fact that the alternative found path converges towards the optimal path.

The main advantage of our approach is that none of the assumptions on which the system is based relies on the usual simplifications, such as unlimited stock capacity, no possibility for jamming, unlimited reliability of the transportation system, and so on. Our proposal should lead to more realistic and deployable real-time control systems.

The main perspective for future research is to study the different ways to link our DRP model with the DAP distributed control system introduced in the part 4.

REFERENCES

- Aissani N., Trentesaux D., Beldjilali B., Use of Machine Learning for Continuous Improvement of the Real Time Manufacturing Control System Performances, *International Journal of Industrial and Systems Engineering* (to appear, 2008)
- Baker A.D, A Survey of Factory Control Algorithms That Can Be Implemented in a Multi-Agent Heterarchy: Dispatching, Scheduling, and Pull, *Journal of Manufacturing Systems* 17(4), 1998, p. 297-320.
- Berger T., Sallez Y., Tahon C., Bio-inspired approach for autonomous routing in FMS, *Manufacturing the Future: Concepts, Technologies & Visions*, A.R.S. pro literatur Verlag, ed. by V. Kordic, 2006, p. 101–124.
- Bousbia S., Anli A., Trentesaux D., Grislin E., Agile scheduling of flexible manufacturing systems of production, *17th World Congress – IMACS 05*, CD-Rom, (Paris, 2005), paper # T6-R-00-0316, 8p.
- Brückner S., Return from the Ant synthetic ecosystems for manufacturing control, Thesis Humboldt-University of Berlin, June 2000.
- Cavaliere S., Garetti M., Macchi M., Taisch M., An experimental benchmarking of two multi-agent architectures for production scheduling and control, *Computers in Industry*, vol. 43, 2000, p. 139-152.
- Clarinet System, Network Connectivity for Mobile Devices, <http://www.clarinet.com>, 2007
- Dorigo M., Stützle T., *Ant Colony optimization*, The MIT Press, 2004.
- Duffie N.A., Prabhu V., Heterarchical control of highly distributed manufacturing systems, *international Journal of Computer Integrated Manufacturing*, vol. 9, n°4, 1996, p. 270-281.
- Hadeli T., Valckenaers P., Kollingbaum M. & Van Brussel H., Multi-agent coordination and control using stigmergy, *Computers in industry*, vol. 53, pp. 2004, p.75-96.
- Lastra J.L.M, Colombo A.W., Engineering framework for agent-based manufacturing control, *Engineering Applications of Artificial Intelligence*, vol. 19, 2006, p. 625–640.
- McCulloch W. S., Heterarchy of values Determined by the Topology of Nervous Nets, *Bull. math. biophys.*, vol. 7, 1945, p. 89-93.
- McFarlane D., Sarma S., Chirn J.L., Ashton K., The intelligent product in manufacturing control and management. *15th triennial IFAC world congress*, Barcelone, Spain, 2002.
- Montech Technology, Conveyor systems, <http://www.montech.com>, 2007
- Maione G., Naso D., A soft computing approach for task contracting in multi-agent manufacturing control, *Computers in Industry*, vol. 52, 2003, p. 199–219.
- Parunak H.V.D., Brueckner S., Sauter J., ERIM's Approach to Fine-Grained Agents, *Proceedings of the NASA/JPL Workshop on Radical Agent Concepts (WRAC'2001)*, Greenbelt, MD, Sept. 19-21, 2001
- Qiu R.G., Virtual Production Line Based WIP Control for Semiconductor Manufacturing Systems, *International Journal of Production Economics* 95(2), 2005, pp. 165-178.
- Sallez Y., Trentesaux D., Berger T., Tahon C., Product-based and resource-based heterarchical approaches for dynamic FMS scheduling, *Computer and Industrial Engineering*, vol. 46, 2004, p. 611–623.
- Smith R. G., The contract net protocol: High level communication and control in a distributed problem solver, *IEEE Transactions on Computer*, vol. C29, n°12, 1980, p. 1104-1113.
- Tharumarajah A., Survey of resource allocation methods for distributed manufacturing systems, *Production, Planning & Control* 12(1), 2001, p. 58-68.
- Theraulaz G. & Bonabeau E., A brief history of stigmergy. *Journal of Artificial Life*, vol. 5, No 2, 1999, p. 97-116.
- Wago system, innovative connections, <http://www.wago.com>, 2007
- Wilensky U. <http://ccl.northwestern.edu/netlogo/>. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL, 1999.
- Wong T.N., Leung C.W., Mak K.L., Fung R.Y.K, Dynamic shopfloor scheduling in multi-agent manufacturing systems, *Expert Systems with Applications*, vol. 31, 2006, p. 486–494.