Application of measurement-based AHP to product-driven system control

William Derigent[1], Alexandre Voisin[1], André Thomas[1], Sylvain Kubler[2], Jérémy Robert[2]

[1]Université de Lorraine, CRAN, UMR 7039,2 avenue de la forêt de Haye, Vandoeuvre-lès-Nancy, 54516 Cedex, France. {firstname.lastname}@univ-lorraine.fr
[2]University of Luxembourg, Interdisciplinary Centre for Security, Reliability & Trust, 4 rue Alphonse Weicker L-2721 Luxembourg.{firstname.lastname}@uni.lu

Abstract. This paper presents an application of the measurements-based AHP to define a two-stage algorithm for product-driven systems control, in case of an unexpected event. This algorithm is made of two stages: the first one aims to define which kind of strategy the product should adopt (*wait, react by it self* or *switch back to centralized mode*) while the second one helps to choose the most appropriate resource able to fulfill the product requirements. The methodology is detailed on a simple case study.

Keywords: Product-driven systems, resource allocation, measurement-based AHP

1 Introduction

PDS (Product Driven Systems) can provide reactive solutions to unexpected events and significantly improve robustness and adaptation of local decisions on the shop floors. The products processed by a PDS are considered as intelligent in the sense of [1], i.e "linked to information and rules governing the way [they are] intended to be made, stored or transported and capable to support or influence these operations" (for more information about intelligent products, the reader is advised to read the comprehensive review made by [2]). Products can thus make real-time decision in unexpected situations according to production status. [3] suggested that performance of product-driven control depends highly on the nature of the local decisions. Indeed, when nothing happens, the initial production plan is followed, while products stay silent. However, in case of unexpected events (in this paper, resource breakdowns), the product has only 3 choices:

- *Wait and do nothing:* the product waits and does nothing until the resource is repaired;
- *React by itself (distributed mode)*: the product tackles the emergency by itself;
- *Switch back to centralized mode*: the product switches back to the centralized control to ask the higher level to globally optimize the re-scheduling.

adfa, p. 1, 2011.

It is thus vital, at first, to be able to correctly select and switch from a strategy to another when appropriate. The product thus executes the following two-stage algorithm:

1) **Stage 1 : Select the strategy to use (wait, react by itself or ask for help);**
2) **Stage 2 [only in the "react by itself" strategy]:**
   a) Evaluate and rank the resources than could respond to its needs;
   b) Select the most appropriate alternative among the ordered list of resources, using consensus strategy or negotiation protocols with other products/resources.

This two-stage algorithm is the subject of this paper. However, in this paper, the point 2b) – resource selection – is not detailed.

The problem of *strategy switching* (stage 1 of the algorithm) is addressed in [4], where a complete solution dedicated for mixed planning and scheduling is described. Under an unexpected event, they consider three different strategies: hierarchical (centralized) strategy, negotiated heterarchical (decentralized) strategy and non-negotiated heterarchical strategy. In their experiments, they compare the performances of each strategy on the makespan for a particular FMS platform, and conclude that the second strategy is the best for this system.

The problem of *resource evaluation and selection* (stage 2 of the algorithm) has been treated extensively via several theories and methods (goal programming, stochastic approaches, …). One interesting way to handle this problem is to employ Multi-Criteria Decision Making (MCDM) algorithms [4]. [6] argue that MCDM algorithms suit well to production activity control because they are interfaced with the human operator and can handle conflicting objectives that can arise in task reallocation (such as minimizing the lead time vs. the production costs). They can also support qualitative and quantitative criteria. [6] use indicators related to 3 criteria (*Lead Time, Quality* and *Cost*) and 7 indicators (like *Running Time*, *Move Time*, *Setup Time*, …) to evaluate resource via the ELECTRE method [7] defines the concept of 'potential' associated with a resource-machine as the basis for reassignment of tasks in case of breakdowns. This potential is a value between 0 and 1, evaluated by means of three criteria (*Time*, *Cost* and *Reliability*). Each criterion comprises a certain number of indicators (among them, *Upstream Storage Cost* or *Reliability*). In the present work, the Analytic Hierarchy Process (AHP) [8] is chosen as a MCDM technique. This choice is based on the simplicity and flexibility of AHP among multi-criteria decision making (MCDM) techniques. Indeed, AHP allows to rank a set of alternatives, here the finite set of resources, via the use pairwise comparisons matrices (see section 2 for further explanations). Each alternative receives a 'potential' value (or *weight*). The 'potential' concept is closed to the concept of 'potential field' used for product/resource interaction, for dynamic product routing and task allocation in FMS [9,9]. When arriving at a location *d,* the product uses the value of each resource potential field to select the resource the most suitable from its situation.

From this short state-of-the-art, some remarks can be done: 1) Even if the performances of the different execution strategies have been studied, the question of when switching from a strategy to another one is still an issue 2) Resource evaluation is related to the production context (location of the product, required operation, resource queue at time *t*, machine states, …). This very specific choice should be based on human knowledge, which makes MCDM techniques the most suitable ones because they are flexible, capable of handling a wide range of information, and overall interfaced with the human operator. In this regard, AHP, via its hierarchical structure, seems to be a very convenient alternative. However, it needs some adaptation to be able to handle dynamic data originating from the shop floor.

The rest of this document is organized in 3 sections. Section 2 introduces the mathematical background, needed to structure the different stages of the methodology. The AHP process as well as its adaptation for PDS are described. Section 3 presents in details both stages of the algorithm. Finally, in section 4, an illustration of the proposed algorithm is done on a small case of study. Finally, some conclusions are provided.

2 Adaptation of AHP to PDS

AHP is a simple but cumbersome process, which is time-consuming mainly because the pairwise comparisons. Hence, when a breakdown occurs, each product being manufactured may need to find an alternative resource, autonomously, which is not possible with the classical AHP methodology. The main idea is then to modify the last level of the AHP structure, when alternatives are compared to each other, to use measurements made on resources. Indeed, all the other levels (criteria and sub-criteria) are the same for all the products, and supposed to be fixed by the human operator before the breakdown occurs (each week for instance). It represents the global context, which is supposed to be the same for all products. However, the choice of alternatives is highly contextual and the preferences of one product may not be similar to the ones of another product. As a result, *Product preference functions* are introduced to transform parameters measured on resource into a preference scale. A product preference function is defined for each criterion as in equation 1:

$$f:\quad \mathbb{R} \mapsto [0;1] \\ x \mapsto p \tag{1}$$

Where :

- x, the value measured on a resource;
- p is the corresponding preference value between 0 and 1.

For each resource A_i, a preference value p_i is obtained, corresponding to the preference for **a given criterion** for **the considered product**. This value is then used to build the pairwise comparison matrix (PCM) of the resources as in equation 2:

$$PCM\ final\ level = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{matrix} A_1 & A_2 & \cdots & A_n \\ \end{matrix} \begin{bmatrix} 1 & \frac{p_1}{p_2} & \cdots & \frac{p_1}{p_n} \\ \frac{p_2}{p_1} & 1 & & \frac{p_2}{p_n} \\ \vdots & & 1 & \vdots \\ \frac{p_n}{p_1} & \frac{p_n}{p_2} & \cdots & 1 \end{bmatrix} PCM\ final\ level = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{matrix} A_1 & A_2 & \cdots & A_n \\ \end{matrix} \begin{bmatrix} 1 & \frac{p_1}{p_2} & \cdots & \frac{p_1}{p_n} \\ \frac{p_2}{p_1} & 1 & & \frac{p_2}{p_n} \\ \vdots & & 1 & \vdots \\ \frac{p_n}{p_1} & \frac{p_n}{p_2} & \cdots & 1 \end{bmatrix} \tag{2}$$

3 Description of the proposed algorithm

3.1 Stage 1: strategy switching

From a product's perspective, the objective of this first stage of the algorithm is to determine which actions should be undertaken at time *t*. In a first attempt, two parameters have been considered as relevant for strategy switching, i.e *Residual Slack Time (RST)* and *Event Duration (ED)*. The *RST* is the difference between the latest possible completion time of product production (the date which will not delay the completion of the overall command), and the earliest possible completion time. The *ED* is an estimated duration of the event causing the breakdown, given by the human operator when the breakdown is detected. It can change over time. Figure 1 depicts different zones depending on the *RST* and *ED*: in zone 1 (*Wait and do nothing*), the *RST* is high and estimated *ED* low, the ratio *RST/ED* is far above 1. After recovery, the failed resource would still have time to produce the item. In zone 2 (*React by itself)*, the ratio *RST/ED* is approximately 1, meaning the *ED* is equal to the *RST*. The product can be done on time, but a slight additional problem could result in important delivery delays. When the ratio is really under 1, which corresponds to zone 3 (*Switch back to centralized*), the product needs to ask for help. The limits between each zone is clearly an issue, that is solved in this paper via the use of the AHP methodology combined with product preference functions.

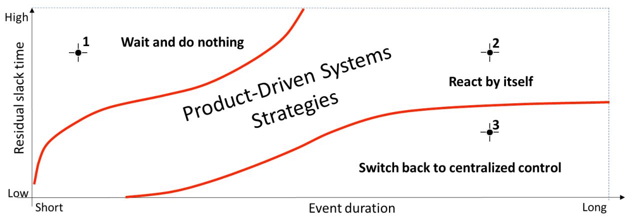

Fig. 1. Different strategy domains according to Residual Slack Time and Event Duration

The proposed AHP structure is presented figure 2 (a). The Goal is to select the most appropriate strategy, and this choice is based on two criteria which are: the ratio *RST/ED* (also named *Product Ratio*) and the *ED duration*. The different alternatives are the candidate strategies (*Centralized, Wait, PDS*). Two product preference functions are defined for each criterion (figure 2(b)).

3.2 Second stage: resource evaluation

In this second stage, the resource evaluation is done via AHP as well. The AHP structure is shown figure 2(c). Part of the parameters of this structure have been selected from the literature. However, to emphasize on the importance of quality and sustainability, two more criteria *machine precision* and *power consumption* have been added to the structure. For each parameter, product preference functions are defined and presented figure 2(d). For the sake of simplicity, we consider only one type of product, hence only one type of preference function has been considered for each criterion

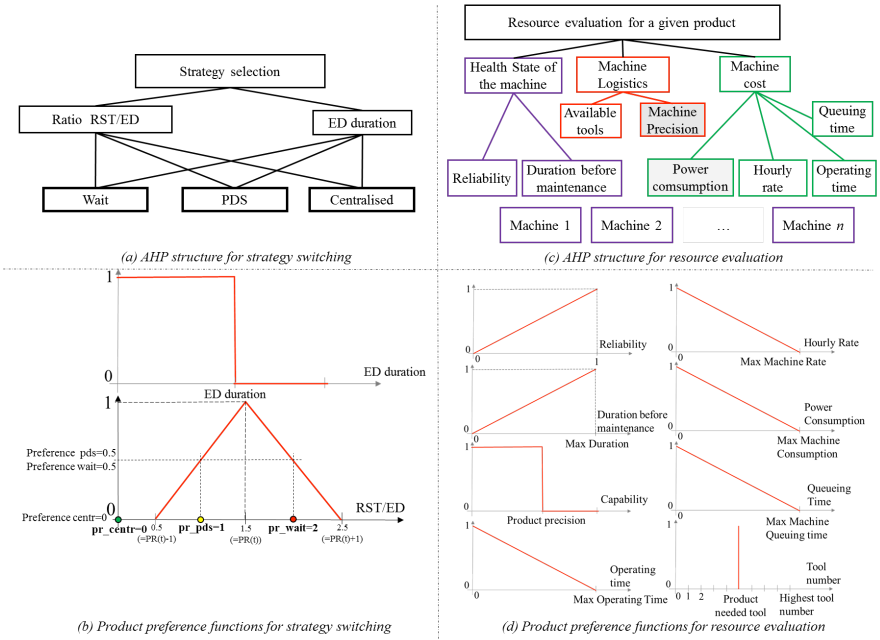

Fig. 2. AHP structures & product preference functions

4 Case study

In our scenario, a breakdown occurs at time *t* in the shop floor, composed of intelligent products and resources. Products affected by this breakdown have to decide or not to react by themselves or with the help of the centralized control (*1st stage of the algorithm*). To do so, the following values have been assessed by experts: the time needed to react autonomously (defined as *pds_time*) is 10 min, to setup a centralized response (defined as *centr_time*) is 20 min; PDS is ideal when the product ratio is equal to 1 (this value is referred to as *pr_pds*), whereas centralized control is rather to be used when the product ratio is near 0 (*pr_cent*). If the product ratio is equal or above 2, the wait strategy should be preferred (value of *pr_wait*). In our case, the product ratio is equal to 1.5 at time *t*, with a *RST* of 15min and a assessed *ED* of 10min. If an autonomous reaction is required, each concerned product then decides to evaluate and select a resource among the 3 available machines. Each of these machines is supposed to send every 15 minutes the information needed for the 2nd stage of the algorithm (as depicted in the extract shown figure 3). The AHP is then launched with the information available at time *t*. The length of our experimentation is 480 minutes (8 hours). In this experiment, the product is supposed to require a machine precision of 5mm, and the tool number 3.

INFORMATIONS FOR MACHINE 1						*MTTF :=*	*300*	*h*
Time (min)	Fiability	Duration before maintenance (h)	Power consumption (kW)	Available tool	Queuing time (min)	Operating time (min)	Hourly Rate (€/h)	Machine Precision (mm)
0	0,71	1,5	0	5	0	30	40	1
15	0,71	1,5	0	5	0	30	40	1
30	0,71	1,5				30	40	

Fig. 3. Example of information obtained for machine 1

4.1 Algorithm 1st stage: Strategy selection.

As explained earlier, this part of the algorithm uses the AHP structures and the preference functions plotted figures 2 (a) & 2(b). In a first step, the weights of the criteria are defined. Then, the weights of the alternatives are determined and finally, all these are aggregated.

a) Determination of criteria weights

The two concerned criteria are *RST/ED (or Product ratio – PR)* and *ED*. The expert gives a stronger importance to the criteria *Product Ratio* than the criteria *ED*, and defines the following 2x2 PDM, which leads to the weights expressed in equation (3):

$$\begin{matrix} & PR & ED \\ PR & \multicolumn{2}{c}{\multirow{2}{*}{}} \\ \end{matrix} \quad \begin{matrix} PR \\ ED \end{matrix} \begin{bmatrix} 1 & 2 \\ 0.5 & 1 \end{bmatrix} \Rightarrow \begin{matrix} PR \\ ED \end{matrix} \begin{bmatrix} 2/3 \\ 1/3 \end{bmatrix} \tag{3}$$

b) Determination of the weights of alternatives via product preference functions for each criteria

Then, for each criterion, alternatives' values are transformed into preference via the preference functions shown figure 2(b). As an example, let consider the criteria *PR* (*RST/ED*). The product ratio at time *t* is 1.5. By replacing 'product ratio' by 1.5, it is then possible to use the *PR* product preference function to compute the preference associated with the 3 alternatives which are 'Wait', 'PDS' and 'Centralized'. Because preferences of 'PDS' and 'Wait' are equal, both strategies are equally preferred before 'Centralized'. Via the use of a 3x3 final level PCM, the weights are determined. The same kind of process is done with the criteria *ED*, by using the values *pds_time*, *centr_time* and the product preference function associated to *ED.*

c) Aggregation and ranking of alternatives

For a given *PR* and *ED*, it is then possible to compute the weights of alternatives and rank them. For the example expressed above, the final weights are: w_{wait}=0.25; w_{pds}=**0.75**; w_{centr}=0. This result means that, for this given situation, the PDS strategy should be used.

4.2 Algorithm 2nd stage: Resource evaluation

As explained earlier, this second part of the algorithm uses the AHP structure and the preference functions detailed figures 3 (c) & 3(d). The steps are similar to the ones of the first part of the algorithm.

a) Determination of criteria weights

The expert has attributed the same importance to all the criteria of a given level. Indeed, the computed weights for the 3 criteria of level 1 are all equal to **0.33**, the weights of the 2 sub-criteria related to the 'Health State of the machine' and 'Machine logistics' are equal to **0.5**, and the 4 sub-criteria of 'Machine cost' are all equal to **0.25**.

b) Determination of the weights of alternatives via product preference functions for each criteria

The process is the same than the one described earlier. For each criterion of level 2, the corresponding product preference function is used to transform the alternative's value into a preference. The alternative's values are taken from the data sent by the resource itself. Once done for all criteria, the resulting PCM is constituted and weights computed. Note that these weights depend on the instant $t_{,}$ when the breakdown occurs.

c) Aggregation and ranking of alternatives

The aggregation of the different levels allows the computation of the weights of the alternatives. As said previously, the weights of each machine are time-dependent, as shown in figure 4, plotting the evolution of each alternatives's weight over the 480min of our scenario. Obviously, at a certain time, a decision should be done by consensus or negotiation between products (step 2b of the algorithm).

5 Conclusions and future works

In this paper, a two-stage methodology to handle resource breakdowns has been presented. The proposed method is based on AHP coupled with product preference functions, that make possible to compute easily and on-the-fly the weights of the different alternatives. The theoretical foundations of this work and the tools needed to proceed to experimentation has been done, and a first experiment on a very simple scenario has been conducted. The future works will consist in first analyzing more precisely the results obtained with this scenario and then proceed to tests on a real production system like the TRACILOGIS Platform[1], based in Epinal, France.

[1] For more information, visit http://www.tracilogis.uhp-nancy.fr/

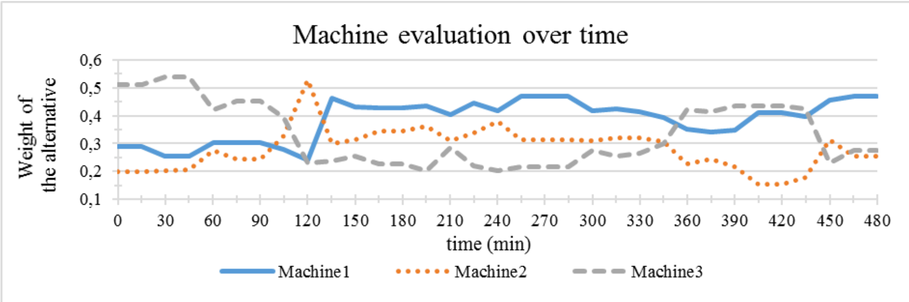

Fig. 4. Machine evaluation over time

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