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# Fault-Tolerant Control Design for over-actuated System conditioned by Reliability: a Drinking Water Network Application.

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**Abstract:** An optimal control law synthesis conditioned by the reliability of actuators in the presence of failures is presented in this paper. The aim is to preserve the health of the actuators and the availability of overactuated system both in the nominal situation and in the presence of some actuator failures. The reliability assessment is computed by Bayesian Network since it is well suited to model the reliability of complex systems with simple parameter matrices and also to compute actuators reliability given evidences through the bayesian inference. It is applied on a system to estimate its reliability and those of its components and provide the parameters to synthesize the control laws. The effectiveness and the performances of the developed method are illustrated on a subsystem of a drinking water network.

*Keywords:* Probabilistic model, Bayesian Network, actuator failures, Control allocation, Fault Tolerant System, Drinking water network.

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## 1. INTRODUCTION

Dependability analyses are used to increase the performance, the product quality and the system reliability by improving analytic and material redundancy. In most safety critical systems, particular redundant structures have been used to design engineering systems. Actuator redundancy is often used and since these systems are overactuated therefore several solutions are available to control the system. The main problem in the dependability analysis of a system with several components is to determine the relationship between the performance level of the system and the performance levels of its components. This relationship is usually explained by a Structure Function (SF). The reliability literature develops the properties of binary systems with binary components, where only two states are supposed: "perfect functioning" and "complete failure" (see, for example, Barlow and Proschan (1975)). But such a binary assumption becomes an oversimplification when dealing with real situations, since it is very often found that components and systems can be in intermediate levels. In the recent literature, as in Weber et al. (2010), a growing interest to model the reliability of complex industrial systems by means of Bayesian Networks (BN) has appeared. This modelling method is very relevant in the context of complex systems Langseth (2008). BN are particularly interesting because they are able to compute the reliability taking into account observations (evidences) about the state of some components. For instance, it is possible to estimate the reliability of the system and all

its components knowing that a part of them are out of order.

Drinking water management in urban areas is a subject of increasing concern as cities grow Baumann et al. (1997). Limited water supplies, conservation and sustainability policies, as well as the infrastructure complexity for meeting consumer demands with appropriate flow, pressure and quality levels make water management a challenging control problem. Fault-tolerant control (FTC) is introduced in order to address the growing demand of plant availability. The aim of FTC is to keep plant available by the ability to achieve the objectives that have been specified in faulty behaviour Noura et al. (2009). The FTC is based on material or functional redundancy. For overactuated systems, control allocation is implemented to distribute the objectives over the available solutions to control the system. Recently Khelassi et al. (2010) propose to integrate the reliability of the actuators in the control allocation in order to preserve the health of the actuators and the availability of the system both in the nominal behavior and in the presence of actuator faults. Nevertheless, the SF is not used in this method, therefore the solution minimizes the actuator's failure and contributes to increase the overall system reliability but is not based its optimization. Our proposal consists mainly in formalizing a standard SF model with a BN and demonstrating the usability of this model in FTC problem of overactuated system. The paper is organized as follows: In Section 2, a solution for a reliable control of overactuated systems is presented based on the on-line actuators reliability indi-

cators. Section 3 introduces BN and explains the generic structure and parameters to model reliability of an over-actuated system. Section 4 is dedicated to the illustration of our approach. Finally, conclusions are given in Section 5.

## 2. PROBLEM STATEMENT WITH A SOLUTION CONDITIONED BY RELIABILITY

Various methods have been developed to control large scale systems. Few control approaches are useful to deal with multi scale systems or to coordinate a number of local controllers. Most of large scale systems require to solve control problem associated to different control configurations, also called modes (or paths). Optimizing a sequence of actions to attain or to track a general target is the main topic of control theory. Moreover, in the presence of faults/failures, the configuration structure of the system should be able to improve the robustness and fault tolerant properties of the control scheme. From a general point of view, let us consider a linear process for large scale systems with an overactuated structure described by:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \\ z(t) &= My(t) \end{aligned} \quad (1)$$

where  $A \in \mathbb{R}^{n \times n}$ ,  $B \in \mathbb{R}^{n \times m}$  and  $C \in \mathbb{R}^{p \times n}$  are respectively, the state, the control and the output matrices.  $x \in \mathbb{R}^n$  is the system state,  $u \in \mathbb{R}^m$  is the control input,  $y \in \mathbb{R}^p$  is the system output.  $M \in \mathbb{R}^{l \times p}$  is a known constant matrix used to select the output required to track the reference signal.  $z(t) \in \mathbb{R}^l$  is the controlled output and  $(A, B)$  is stabilizable.  $\text{rank}(B) = k < m$  characterizes the overactuated property of the system. A virtual actuator is computed through a classical controller synthesis and classical control allocation optimization methods can be considered in order to distribute the load to each actuator (see Durham (1993) or Harkegard and Glad (2004)).

As proposed recently by Picasso et al. (2010), another state space representation can be considered such as:

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^m \alpha_i(t) b_i u_i(t) \quad (2)$$

where  $u_i(t)$  is the control variable provided to the  $i^{th}$  actuator and  $\alpha_i(t)$  is an additional input variable which fixed the active actuator or not. The control variables should be designed in order to select a subset of actuators to achieve the main target of the system. In the general case, the management level is used to provide the operational objective, and a global control level *identifies* one of the  $2^m$  values taken by the vector  $\alpha(t) = [\alpha_1(t) \dots \alpha_m(t)]^T \in [0 \ 1]^m$ .

For both representations, an optimal control input  $u = (u_1, u_2 \dots u_m)$  is the solution of a control (re)-allocation problem. From a general point of view, a weighting matrix  $W_u \in \mathbb{R}^{m \times m} \succ 0$  is used to give a specific priority level to the actuators (in fault-free case or failure case) according to multi-objective operational goals see for instance Maciejowski (2002) or Tatjewski (2008).

In order to improve the safety of the system and to keep the set of the actuators available as long as possible, a specific choice of the weighting matrix  $W_u$  has been proposed based on the actuators reliability (Khelassi et al. (2010)).

The weighing matrix  $W_u$  is considered as a key to manage the overactuators and contributes to reliable controllers which improve the system reliability. However in order to perform simultaneously the control law synthesis and to solve the control allocation problem, we proposed to distribute the desired efforts defined by the controller proportionally to the actuator functioning probability according to the on-line observations and their reliability based on the steady-state optimization (Tatjewski (2008)) as follows:

$$\min\{W_u u(t)\} \quad (3)$$

subject to:

$$Qu(t) \leq \Gamma \quad (4)$$

$$z_d(t) = MA^+ Bu(t) \quad (5)$$

$$u_{\min} \leq u(t) \leq u_{\max}, y_{\min} \leq y(t) \leq y_{\max} \quad (6)$$

where  $z_d$  correspond to the desired outputs and  $w_i$  is the actuator  $i^{th}$  functioning probability with:

$$W_u = \begin{pmatrix} w_1 & & 0 \\ & w_2 & \\ & & \ddots \\ 0 & & & w_m \end{pmatrix} \succ 0 \quad (7)$$

For simplicity reasons without any restriction, it is assumed that  $y(t) = x(t)$ .

As a direct consequence, the actuators are utilized in the control strategy proportionally to their ability and necessity of functioning. Let us consider the actuator  $i \in \{1 \dots m\}$  defined as a random variable  $w_i$  with two states  $\{Up, Down\}$  and  $S$  is the system state with also two states  $\{Up, Down\}$ . Its functioning probability is defined by:

$$P(w_i = Up | S = Up) \quad (8)$$

In order to integrate the actuators degradation in the re-configured control allocation strategy,  $W_u$  is re-estimated and changed on-line according to the *a priori* estimation of actuator reliabilities. Therefore, if an actuator  $w_j$  is unavailable, the system is still working because it is an overactuated system, and the functioning probability of each actuator is defined by:

$$P(w_i = Up | w_j = Down \dots S = Up) \quad (9)$$

This paper concerns the on-line synthesis of  $W_u$  according to the reliability of the each component *i.e.* the diagonal matrix values are defined at each sample  $t$ . The following section explains how the Dynamic Bayesian Network model is used to compute (9).

## 3. BAYESIAN NETWORK MODEL

BN is a efficient solution to model the reliability of complex systems because they perform the factorization of variables joint distribution based on the conditional dependencies. The principles of this modelling tool are explained in Jensen (1996). The variable handled by BN are not limited to Boolean random variables contrary to the standard reliability analysis as Fault Tree or Reliability Block Diagram.

### 3.1 Recall of BN characteristics

A BN is a directed acyclic graph (DAG) defined by a set of nodes and a set of directed arcs. A probability

Table 1. Conditional Probabilities Table of node  $g_j$ .

$e_{i+\delta}$	...	$e_i$	$g_j$	
			Available	Not Available
$Up$	$Up$	$Up$	1	0
		$Down$	0	1
		$Down$	0	1
		$Down$	0	1
		$Down$	0	1
		$Down$	0	1
		$Down$	0	1

is associated to each state of the node. This probability is defined *a priori* for a root node and computed by inference for the others. A general inference mechanism (that permits the propagation as well as the diagnostic) is used to collect and to incorporate new information (evidences) gathered in a study. The Bayes' theorem is the heart of this mechanism and allows updating a set of events' probabilities according to the observation of some variables and the prior knowledge of the others. This theorem also is responsible of the strength of this knowledge management tool.

### 3.2 Generic reliability models

A BN model provides an easy solution to model the reliability of complex systems in which the nodes represent the system variables and the arcs symbolize the dependencies or the cause-effect relationships among the variables. Let us consider  $Q$  sets with  $\delta$  components that represent the minimal set of components that guarantee the system functioning, these sets are the success paths. The random variables  $g_j$  with  $j \in \{1 \dots Q\}$  is defined by two states  $\{Available, Not Available\}$  and represent all success paths states. Components are defined as random variables  $e_i$ ,  $i \in \{1 \dots m\}$  with two states  $\{Up, Down\}$ . The availability of a success path is computed by the intersection of the  $\delta$  functioning components  $e_i$ . One minimal success paths is necessary to guarantee the success of the main system mission. The system reliability modelled by variable  $S$  and its states  $\{Up, Down\}$ , is defined from the union of variables  $g_j$  representing success paths validity. This combination respects the logical description of the system SF. Fig. 1 presents the generic BN model structures for any system.

The conditional probability table (Table 1) defines the relation between  $g_j$  and components  $e_i$  in the success path. This path is defined from a logical aggregation as *AND* gates to compute the availability of the minimal success path and the system reliability is defined as a *OR* gate to compute the combination of the minimal success paths (Table 2). In both tables, the parameters in the conditional probability tables (CPT) are equal to 1 or 0 because there is no uncertainty on the combination of components' events leading to the unavailability of the system.

### 3.3 Computation of $w_i$

$W_u$  is estimated on-line according to the estimation of actuator reliability and the observation of actuators out of order. A Dynamic Bayesian Network (DBN) computes the reliability of each component following an exponential distribution Weber et al. (2004). Without any restrictions,

Table 2. Conditional Probabilities Table of node  $S$ .

$g_Q$	...	$g_j$	...	$g_1$	$S$	
					$Up$	$Down$
$Available$		$Available$		$Available$	1	0
		$Not Available$		$Not Available$	1	0
		$Not Available$		$Available$	1	0
		$Not Available$		$Not Available$	1	0
		$Not Available$		$Available$	1	0
		$Not Available$		$Not Available$	1	0
		$Not Available$		$Available$	1	0
		$Not Available$		$Not Available$	0	1

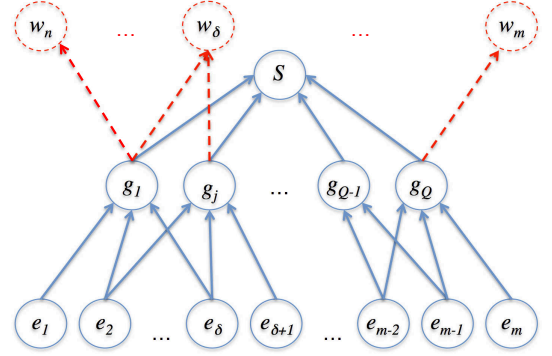


Fig. 1. Generic BN model computing  $w_i$  according to the success paths  $g_j$ .

Table 3. Weight CPT of  $w_\delta$ .

$g_1$	$g_j$	$w_\delta$	
		$Up$	$Down$
$Available$	$Available$	1	0
	$Not Available$	1	0
$Not Available$	$Available$	1	0
	$Not Available$	0	1

we assume that the less the reliability of a component is the less it can be used in the control law and the less its weight should be. Moreover, if a component  $e_\delta$  is involved in only one path  $g_j$ , and if this path is *Not Available*, the component  $e_\delta$  is not used and its weight is equal to zero. Of course, many actuators are involved in several paths and if a component is involved in at least one available path its weight is different from 0. The weight is thus computed by the BN from CPT and Bayes theorem. For instance, as presented in Fig. 1, the CPT of  $w_\delta$  depends of  $g_1$  and  $g_j$  because the component  $e_\delta$  is connected to the paths  $g_1$  and  $g_j$ . The marginal distribution of  $w_\delta$  is computed according to Table 3.

The failure of a component in a path induces the unavailability of the path. Consequently, the control law of all the actuators involved only in the failed paths is no more necessary since it has no effect on the efficiency of the paths. When several paths are in state  $\{Available\}$ , the control of the actuators involved in each path depends on the reliability of each path and the reliability of the component. The value associated to  $W_u$  are weighted by the path availability computed from the reliability of actuators.

## 4. APPLICATION

### 4.1 System description

A drinking water network (DWN) is a network which considers sources (water supplies), sinks (water demand sectors) and pipelines that link sources to sinks. It also contains active elements like pumps, valves. For the study of the DWN reliability, sources, sinks, tanks and pipelines are considered perfectly reliable. Only the active elements are considered not perfectly reliable. The water transport network of Barcelona is used as the case study of this paper. This network covers a territorial extension of 425km<sup>2</sup>, with a total pipe length of 4,470 km. Every year, it supplies 237.7hm<sup>3</sup> of drinking water to a population over 2.8 millions of inhabitants. The network has a centralized tele-control system, organized in a two-level architecture. At the upper level, a supervisory control system installed in the control centre of AGBAR is in charge of controlling the whole network by taking into account operational constraints and consumer demands.

For sake of illustration, the proposed study focuses on a small part of the Barcelona DWN. Five sources of water and one sink are considered (see Fig. 2). To supply the demand corresponding to the sink (demand sector *C100CFE*), 2 out-of 5 sources (*AportLL1*, *AportLL2*, *ApousE12*, *ApouseE3456*, *AportA*) are needed through the DWN. So, from the reliability point of view, a 2 out-of 5 sources, classically noted 2oo5:G, system should be considered and each source is in series with the pipes, the valves and pumps of the DWN which link a source to the sink. Compared to Ocampo-Martinez et al. (2009),

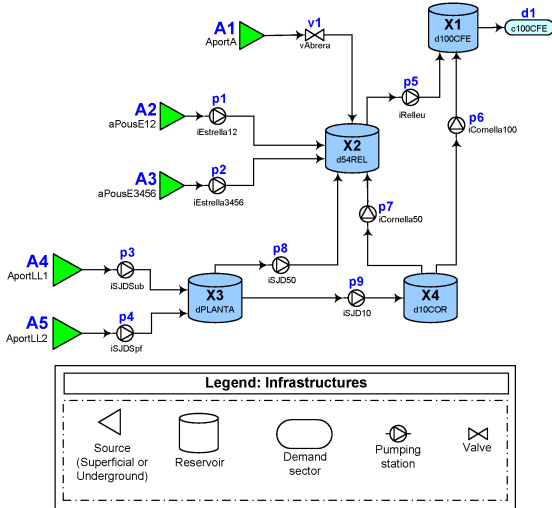


Fig. 2. The considered part of the Barcelona DWN.

the economic cost of the flow through pumps depending to the time of the day based on electricity costs have not considered for simplicity reason. Then, the economic costs of the water according to the selected source (dwell, treatment plant ...) and the electrical costs associated to the pumping weighted by the reliability of the component have been omitted in the steady-state optimization defined in (3).

Table 4. Success paths of considered part of the Barcelona DWN

Path	Component Set
path 1	{ <i>AportLL2</i> , <i>iSJDspf</i> , <i>iSJD10</i> , <i>iCornella100</i> }
path 2	{ <i>AportLL1</i> , <i>iSJDSub</i> , <i>iSJD10</i> , <i>iCornella100</i> }
path 3	{ <i>AportLL2</i> , <i>iSJDspf</i> , <i>iSJD10</i> , <i>iCornella50</i> , <i>iRelieu</i> }
path 4	{ <i>AportLL1</i> , <i>iSJDSub</i> , <i>iSJD10</i> , <i>iCornella50</i> , <i>iRelieu</i> }
path 5	{ <i>AportLL2</i> , <i>iSJDspf</i> , <i>iSJD50</i> , <i>iRelieu</i> }
path 6	{ <i>AportLL1</i> , <i>iSJDSub</i> , <i>iSJD50</i> , <i>iRelieu</i> }
path 7	{ <i>ApousE12</i> , <i>iEstrella12</i> , <i>iRelieu</i> }
path 8	{ <i>ApousE3456</i> , <i>iEstrella3456</i> , <i>iRelieu</i> }
path 9	{ <i>AportA</i> , <i>iRelieu</i> }

### 4.2 BN Synthesis

By considering all the paths from all the sources to the sink, the combination of all success paths should follow the functional requirements. Based on this analysis, the following list of paths is detailed in table 4. Notice that all sources (*AportLL1*, *AportLL2*, *ApousE13*, *ApouseE3456*, *AportA*) are assumed completely reliable and are conserved in the paths. The valve *vAbrera* is also considered perfectly reliable but is not modelled in the BN for the sake of simplification. The reliability distribution of all the components is considered exponential and the failure rates are given in table 5. The BN reliability model is given in

Table 5. Failure rates

Actuator name	Actuator code	Failure rate
<i>iSJDspf</i>	<i>P4</i>	9.5 $10^{-4}h^{-1}$
<i>iSJDSub</i>	<i>P3</i>	6.3 $10^{-4}h^{-1}$
<i>iSJD10</i>	<i>P9</i>	1 $10^{-4}h^{-1}$
<i>iSJD50</i>	<i>P8</i>	5 $10^{-4}h^{-1}$
<i>iRelieu</i>	<i>P5</i>	1 $10^{-4}h^{-1}$
<i>iEstrella12</i>	<i>P1</i>	1.2 $10^{-4}h^{-1}$
<i>iEstrella3456</i>	<i>P2</i>	3.456 $10^{-4}h^{-1}$
<i>iCornella50</i>	<i>P7</i>	5 $10^{-4}h^{-1}$
<i>iCornella100</i>	<i>P6</i>	10 $10^{-4}h^{-1}$

Fig. 3. The nodes on the left part of the figure model the reliability of each active component as a DBN and the availability of the sources. The nodes AND<sub>*i*</sub> model the combination operators between components to compute the reliability of each path from source to sink defined in the Path<sub>*i*</sub> nodes. On the right part, the nodes AvailX define the availability of the sources X through the DWN according to the path availability. The availability of the sink is defined through the node *C100CFE*. Modelling the path, the nodes WiX compute the weight *w<sub>i</sub>* of each actuator X as explained in the previous section. The Table 6 gives the CPT to compute the weight *w<sub>i</sub>* of the component Cornella50. The supply of water through the network should be done by at least 2 sources from all sources. So,

Table 6. Weight CPT of *w<sub>i</sub>Cornella50*

path <sub>3</sub>	path <sub>4</sub>	<i>w<sub>i</sub>Cornella50</i>	
		Up	Down
Available	Available	1	0
	Not Available	1	0
Not Available	Available	1	0
	Not Available	0	1
Available	Available	0	1
	Not Available	0	1
Not Available	Available	0	1
	Not Available	0	1

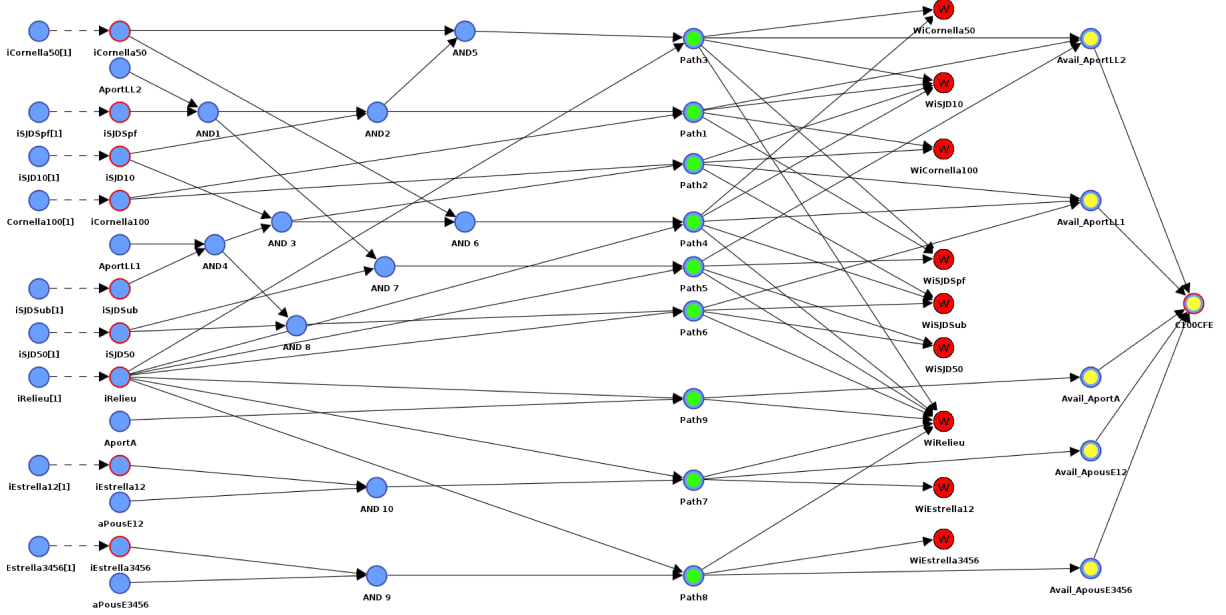


Fig. 3. Reliability and weights computing BN model of the Barcelona DWN.

the combination among the sources availability through the network is a 2005:G system.

#### 4.3 Results and Comments

A simulation has been done with a duration of 3600 hours. It is done under Matlab<sup>TM</sup> for the optimization, the control and the system simulation. The BN part is computed thanks to Bayesialab<sup>TM</sup> a BN dedicated software. At the beginning, a fault-free case is considered. As illustrated in Fig. 4 during the 500 first hours, the measured output is tracking the desired output reference  $z_d$  (3). The steady optimization method generates control inputs which minimize efficiently the criteria under tracking control objective constraints. A first failure is assumed to occur

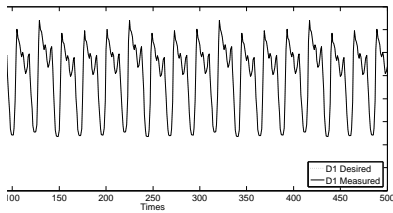


Fig. 4. Desired and measured outputs in fault-free case.

and to be isolated on pump P8 (*iSJD50*) at  $t=1000h$ , and at  $t=2000h$ , a second failure is isolated on pump P5 (*iRelieu*). A Fault Detection and Isolation module is assumed to carry out the failure isolation task. Based on the BN reliability model, the various  $w_i$  parameters are calculated as presented in Fig. 5. Before  $t=1000h$ , the actuators P1 (*iEstrella12*), P2 (*iEstrella3456*) and P5 (*iRelieu*) are used to achieve the water demand  $z_d$ . This solution is computed by the BN and is based on the success paths 7 and 8 (Table 4). This solution is justified by the BN that compute  $w_1$ ,  $w_2$  and  $w_5$  upper to the others  $w_i$  because the actuators P1 (*iEstrella12*) and P2 (*iEstrella3456*) are more reliable than P3 (*iSJDSsub*) and

P4 (*iSJDSpf*) and the actuator P5 (*iRelieu*) is more reliable than P6 (*iCornella100*) (table 5). Moreover, because P1 (*iEstrella12*) and P2 (*iEstrella3456*) are saturated, the actuator P3 (*iSJDSsub*) is used to provide the desired output  $z_d$  as illustrated in Fig. 5. The actuator P3 (*iSJDSsub*) is used because the BN compute  $w_3 > w_4$  (P3 (*iSJDSsub*) is more reliable than P4(*iSJDSpf*)). This solution is based on the path 6 using P8 (*iSJD50*). Unfortunately after  $t=1000$ , the actuator P8 (*iSJD50*) is out of order, therefore the path 6 is unavailable. The path 4 {P3, P7, P9} is then computed by the BN to be the solution to reconfigure the system. Between 1000h to 2000h the components used are P1, P2, P5 and P3, P7, P9 as presented in Fig. 5. After the occurrence of the failure of P5 (*iRelieu*) at  $t=2000$ , the success path 7 and the success path 8 become unavailable. Therefore, the BN compute  $w_1 = 0$  and  $w_2 = 0$  due to the fact that the actuators P1 (*iEstrella12*) and P2 (*iEstrella3456*) can not be used. The system is reconfigured using the path 1 and the path 2 with the components P3, P4, P6 and P9. The BN compute  $w_3 = 1$ ,  $w_4 = 1$ ,  $w_6 = 1$ , and  $w_9 = 1$ , being the only solution to provide the water to the demand sector as highlighted in Fig. 5.

## 5. CONCLUSION

In this paper, we have shown how to define a generic BN that can easily model the reliability of overactuated system. Moreover the functioning probabilities of each actuator is computed with DBN inference. These distributions of probabilities are proposed to be used to define the weighing matrix used to give a specific priority level to the actuators in the re-allocation problem of control. This method provides a control re-allocation that is based on the on-line actuators reliability estimation and the BN provide the reconfiguration solution according to the available success path in the system. The future work is to implement this method to a larger part of the DWN.

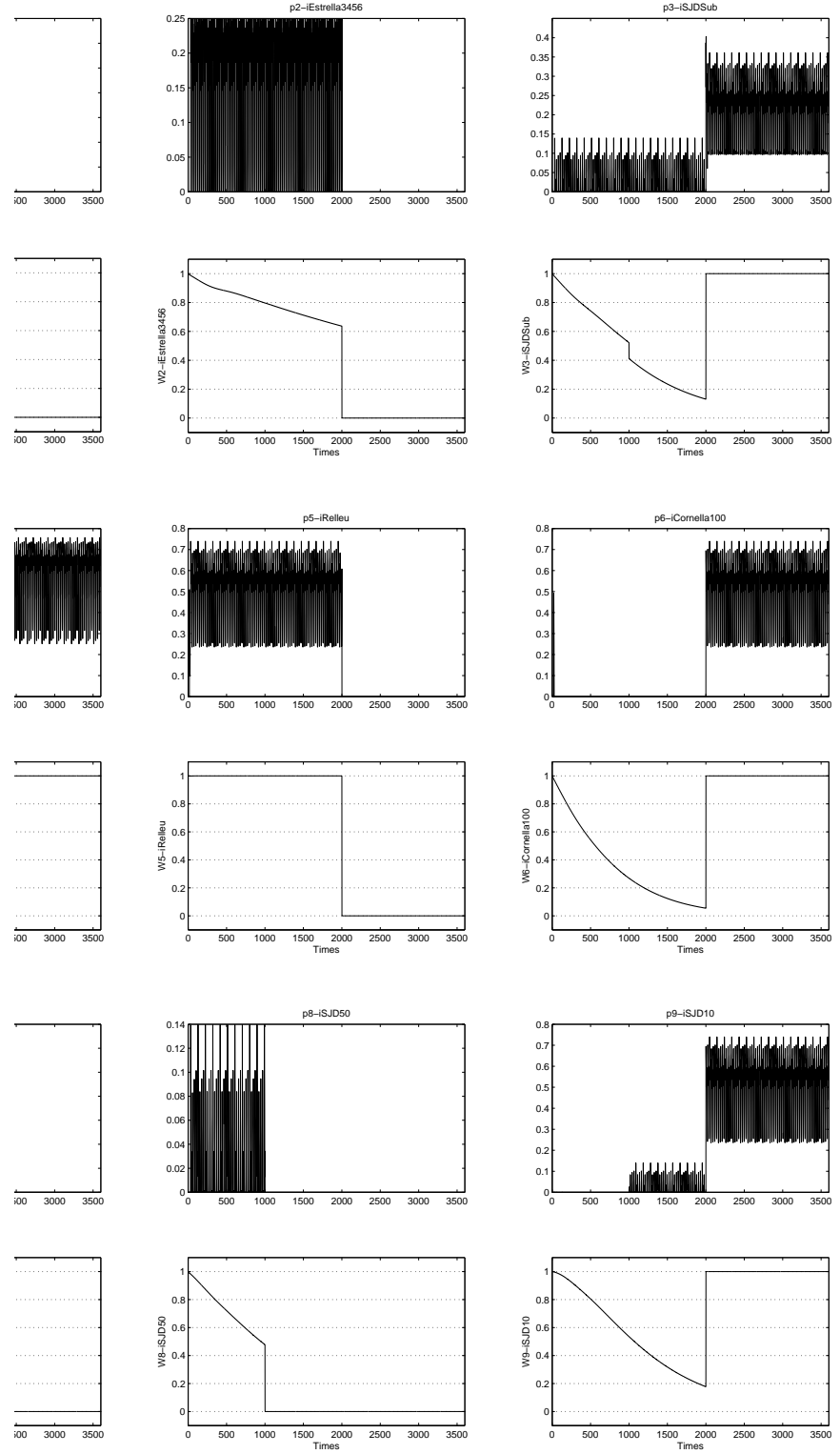


Fig. 5. Controlled output behaviors  $z_i$  (P1..P9) of flow rate and usability indicators  $w_i$  with a failure on P8 (*iSJD50*) at 1000h and another one on P5 (*iRelieu*) at 2000h.



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