Application of the Digraph Method in System Fault Diagnostics

Emma M Kelly & Lisa M Bartlett

Department of Aeronautical & Automotive Engineering,
Loughborough University, UK.

Overview

- Fault diagnosis is an important facet of engineering applications.
- Introduce the application of the digraph method to determine the likely causes leading to a system malfunction.
- A description of digraphs and their application in fault diagnostics is provided.
- A simple example is used for demonstration purposes.

Introduction to Digraphs

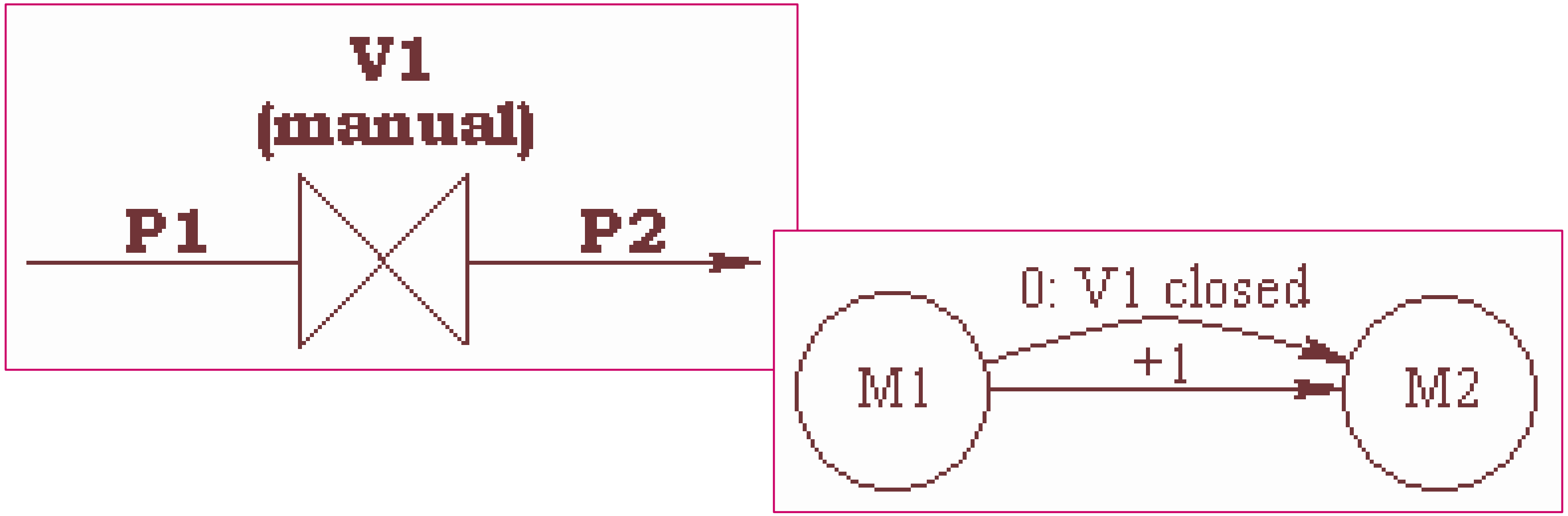
- Qualitative causal model which illustrates the cause and effect behaviour in a system.

- Digraphs comprise:
  i. Set of nodes, representing system process variables.
  ii. Nodes are connected by edges (lines) illustrating the inter-relationships which exist between process variables.

Introduction to Digraphs

- Examples of process variables include:
  - Mass flow.
  - Pressure.
  - Signals from sensors.
  - Temperature.
- Process variable deviations are represented through one of five discrete values:
  - +10/-10: large high / large low.
  - +1/-1: moderate high / moderate low.
  - 0: normal.

An Example of a Simple Digraph



- M1: mass flow at location 1 - independent variable.
- M2: mass flow at location 2 - dependant variable.
- Two arcs:
    - ‘+1’ signed - normal.
    - ‘0: V1 closed’ signed - conditional.

Digraph Development

1) Define system to be analysed.

2) Compile list of system component failures.

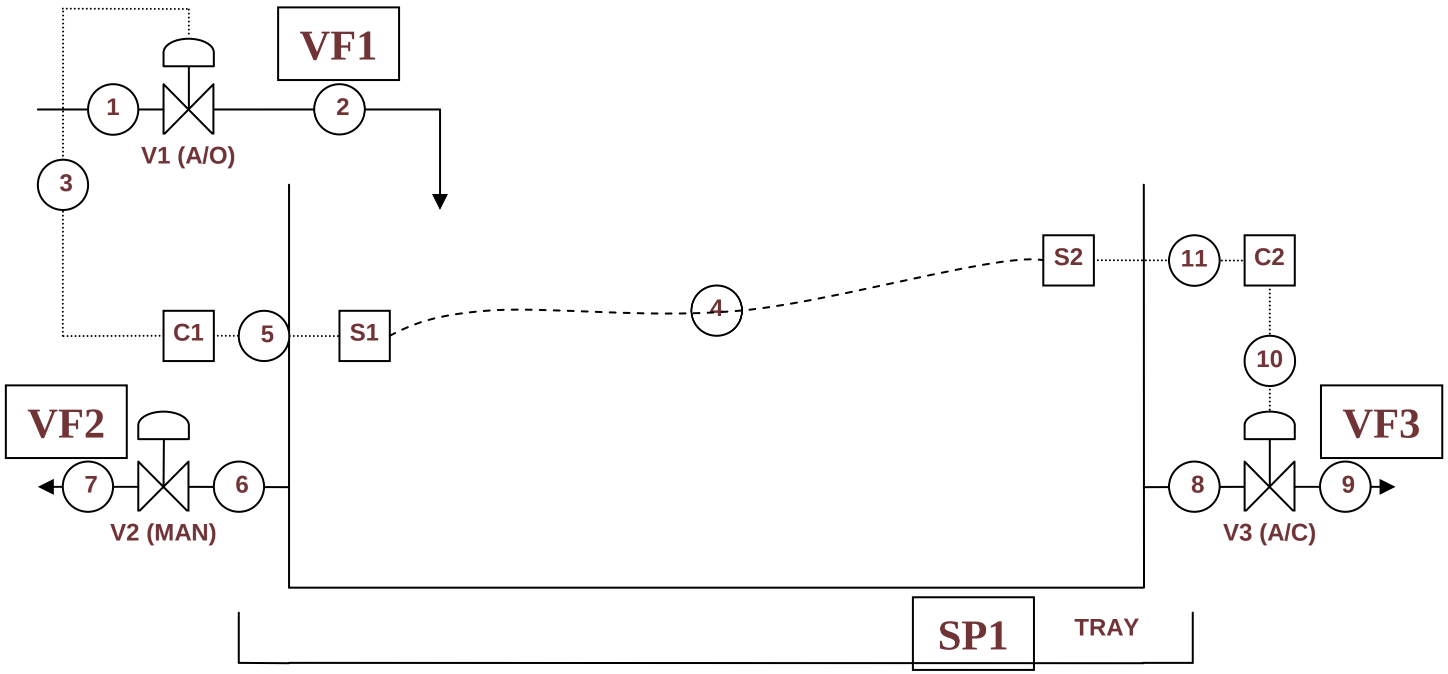
3) Separate system into sub-units.

4) Identify control loops, if present.

5) Generate digraph models for the sub-units.

6) Form system digraph by connecting any common variables from the sub-unit models.

The Water Tank System



- Three valves: V1, V2, V3.
- Two level sensors: S1, S2.
- Two control units: C1, C2.
- Six pipe sections: P1, P2, P6, P7, P8, P9.

The Water Tank System

- System information obtained from the flow sensors, VF1-3 and tray sensor, SP1.
- Flow sensors detect flow or no flow.
- Tray sensor detects presence or absence of water.
- Two operating modes are specified.

Operating Mode	VF1	VF2	VF3	SP1
ACTIVE	Flow	Flow	No Flow	No Water
DORMANT	No Flow	No Flow	No Flow	No Water

System Scenarios

- Sixteen scenarios developed from the potential sensor readings.

Scenario	VF1	VF2	VF3	SP1
1	F	F	F	W
2	F	F	F	NW
3	NF	F	F	W
4	NF	F	F	NW
5	NF	NF	F	W
6	NF	NF	F	NW
7	NF	NF	NF	W
8	NF	NF	NF	NW

Scenario	VF1	VF2	VF3	SP1
9	F	NF	F	W
10	F	NF	F	NW
11	F	F	NF	W
12	F	F	NF	NW
13	NF	F	NF	W
14	NF	F	NF	NW
15	F	NF	NF	W
16	F	NF	NF	NW

Component Failure Modes

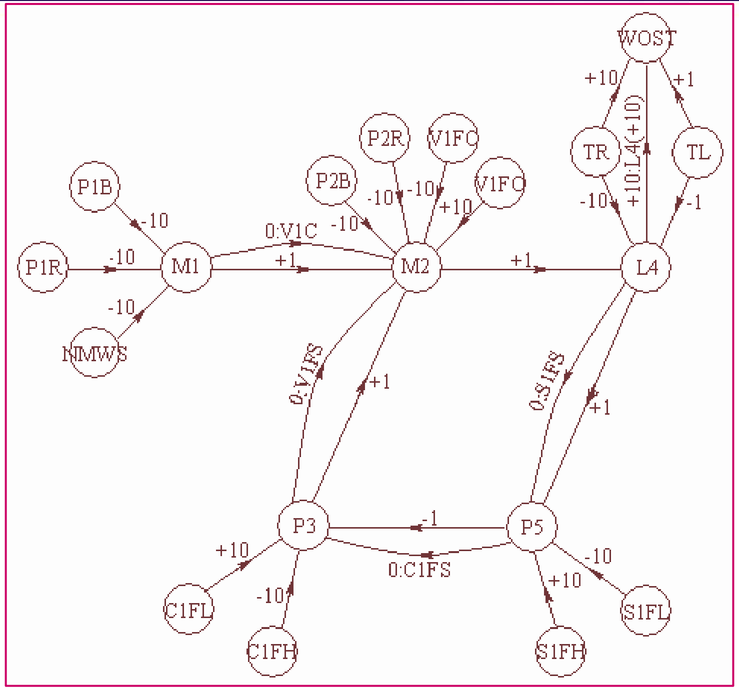
- Failure modes considered which could affect the functionality of the water tank system.

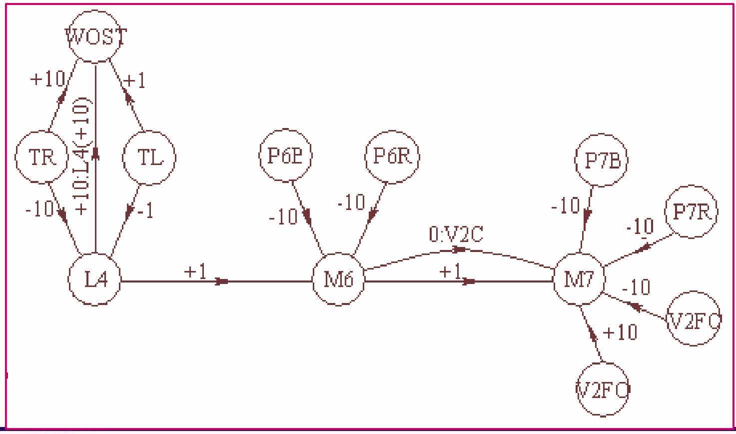
Code	Component Failure	Code	Component Failure
P_iB(1-2, 3-4, 5-6)	Pipe P_i is blocked	P_iR(1-2, 3-4, 5-6)	Pipe P_i is ruptured
$V_iFC(1 \leq i \geq 3)$	Valve V_i fails closed	$V_iFO(1 \leq i \geq 3)$	Valve V_i fails open
C_iFH $(1 \leq i \geq 2)$	Controller C_i fails high	C_iFL $(1 \leq i \geq 2)$	Controller C_i fails low
S_iFH $(1 \leq i \geq 2)$	Sensor S_i fails high	S_iFL $(1 \leq i \geq 2)$	Sensor S_i fails low
TR	Water tank ruptured	TL	Water tank leaks
NMWS	No mains water supply	WOST	Water in overspill-tray

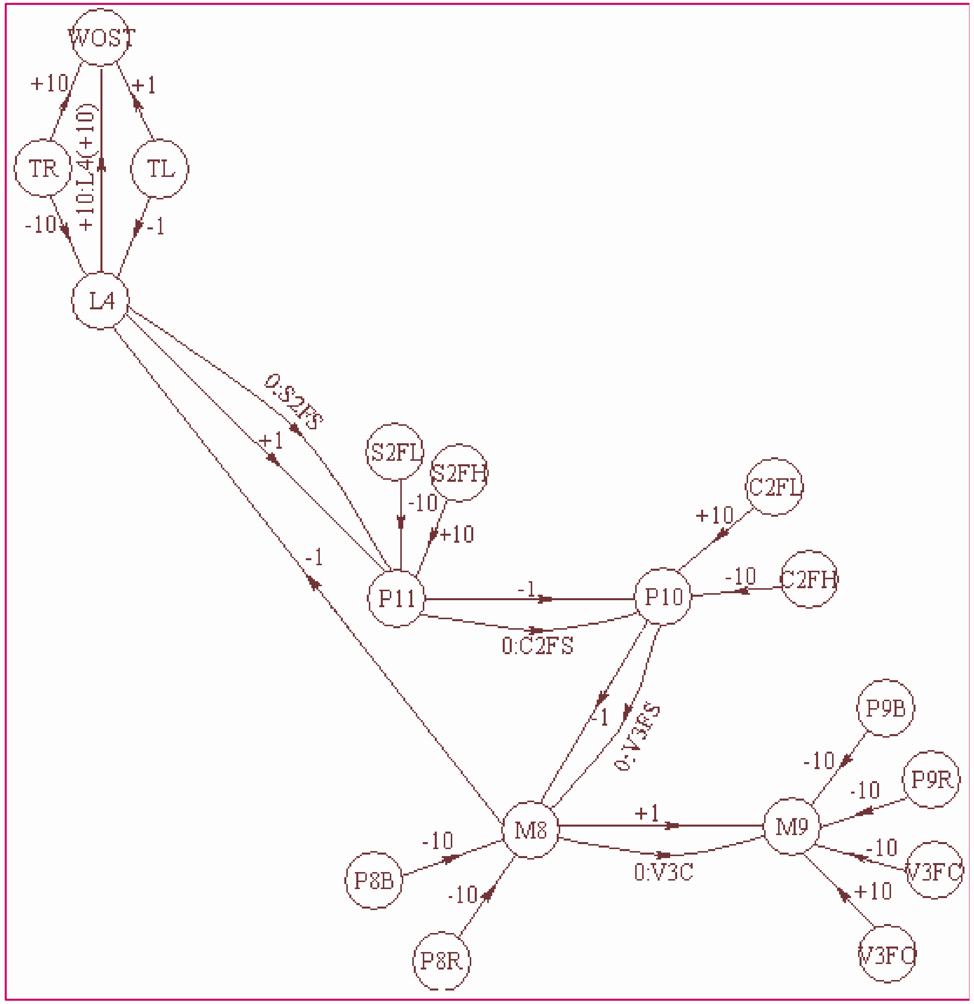
Water Tank System Digraph Development

- Three assumptions:
  i. Given a pipe rupture, flow sensor registers no flow.
  ii. Tank rupture volume loss >> tank leakage.
  iii. System is in steady state.
- Unit digraph models developed for the three water tank valves.
- Each unit digraph considers:
  - Component functions.
  - Effects of failure modes.

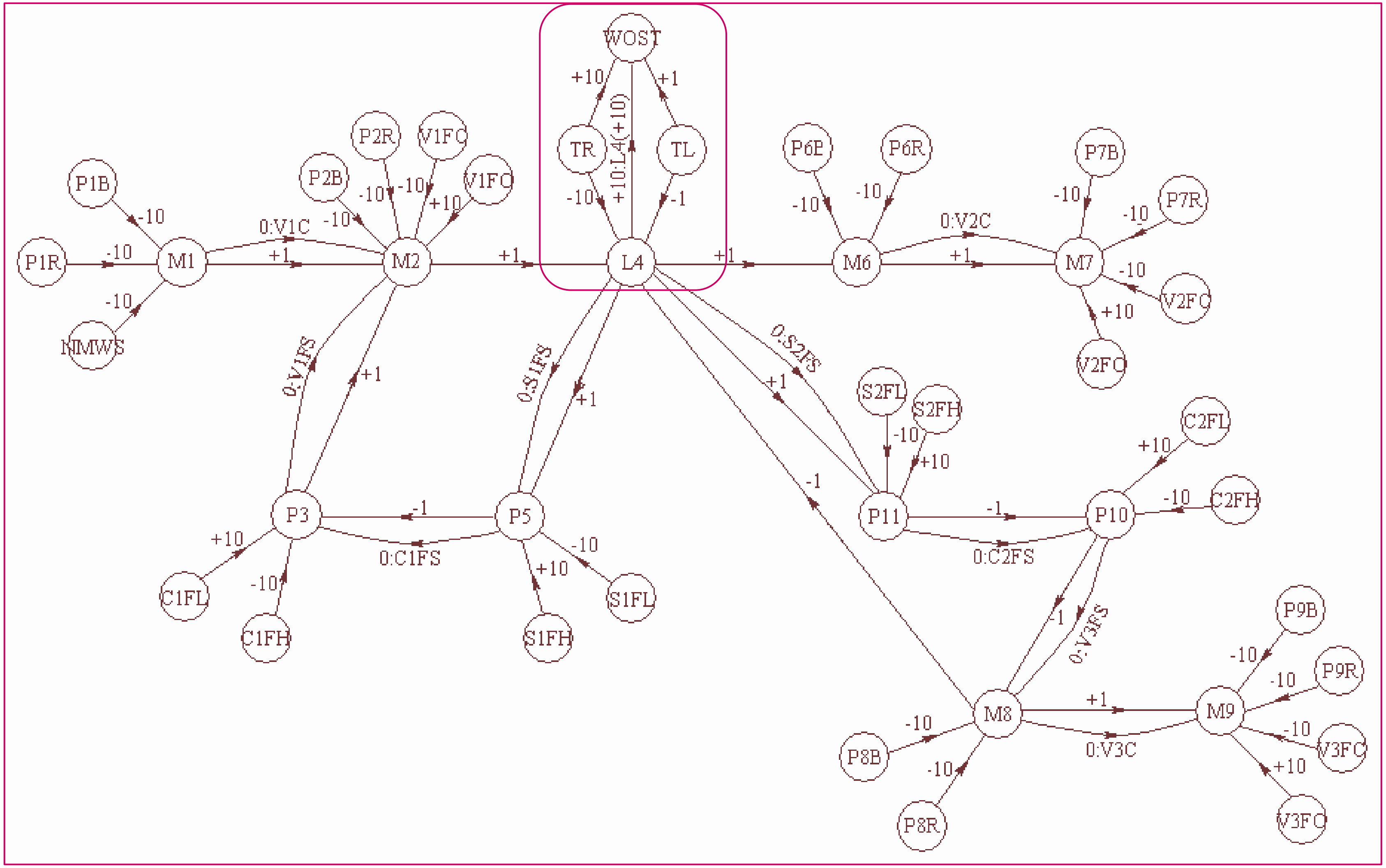
Water Tank System Unit Digraphs







Water Tank System Digraph



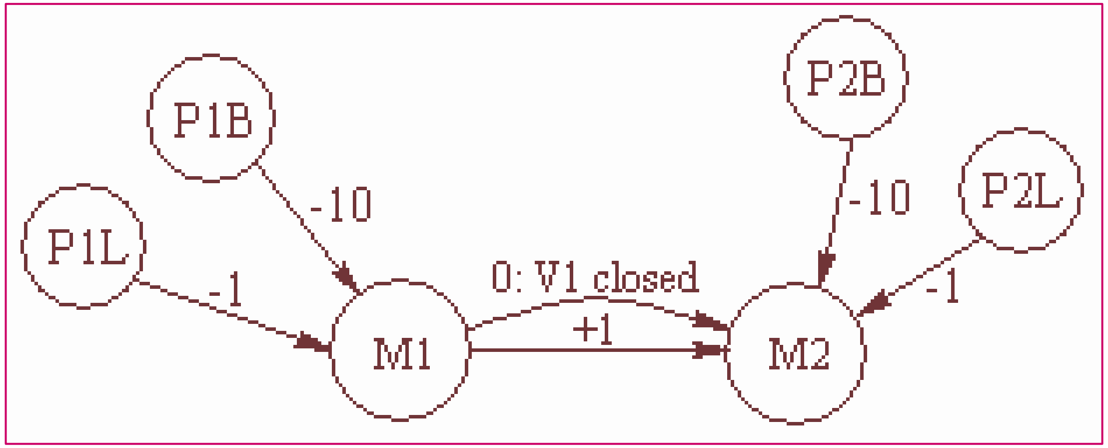
Digraphs in Fault Diagnostics

- Diagnostics is based on comparing retrieved sensor readings with those expected.

- Given the presence of a deviation, diagnosis involves:
  - Noting the location of the given deviation.
  - Determine the component failure modes which may have contributed to the deviation.

- Fault diagnosis is conducted through a process of back-tracing.

Digraphs in Fault Diagnostics: Back-tracing



- Deviation noted after valve. Expect flow, no flow registered.
- Commence back-tracing from noted large, negative disturbance:
  - M2(-10) → P2B.
  - M2(-10) → M1(-10) → P1B.

Water Tank System Diagnostics

Two methods considered:

1) Analyst is required to fully back-trace through the digraph until a point is reached where no further back-tracing can be conducted.

2) Non-deviating sections are flagged. Back-tracing from a deviating node ceases once a flagged section is reached.

Diagnostics of a Faulty Scenario

- Example used to demonstrate diagnostic capability of water tank system digraph.

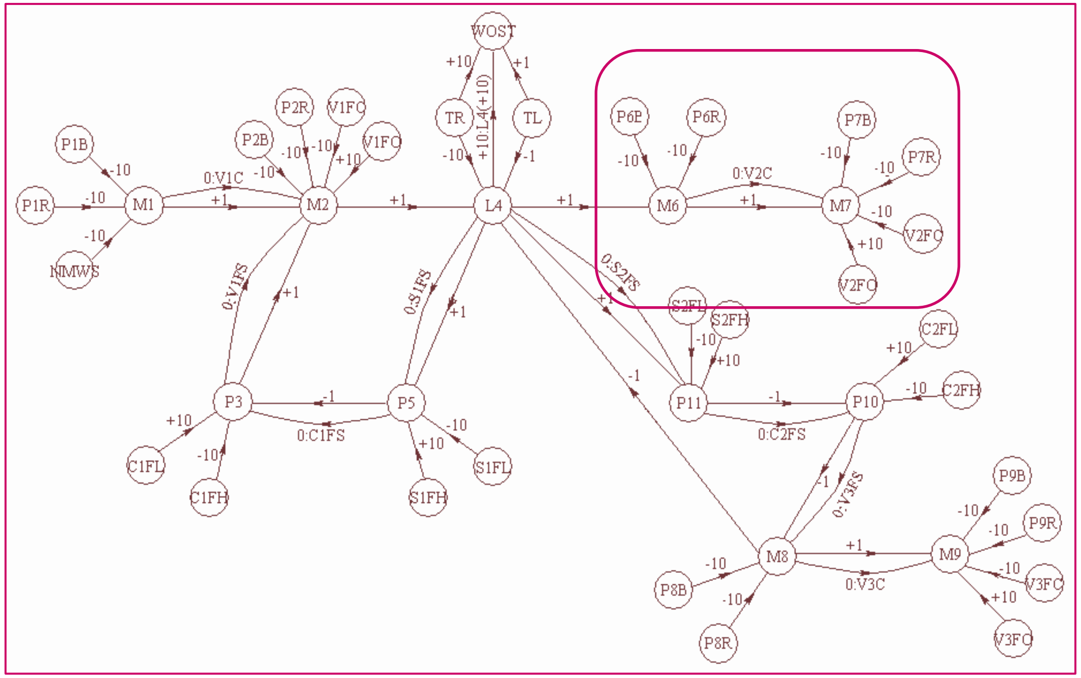
- Water tank assumed to be in the ACTIVE mode.

- Sensor readings retrieved reveal scenario ‘FS16’.

Operating Mode	VF1	VF2	VF3	SP1
ACTIVE	Flow	**Flow**	No Flow	No Water
‘FS16’	Flow	**No Flow**	No Flow	No Water

Fault Diagnostics of ‘FS16’

- Deviation only noted by VF2, flag sections of system digraph incorporating:
  - V1 and control loop one.
  - V3 and control loop two.
  - Overspill tray.

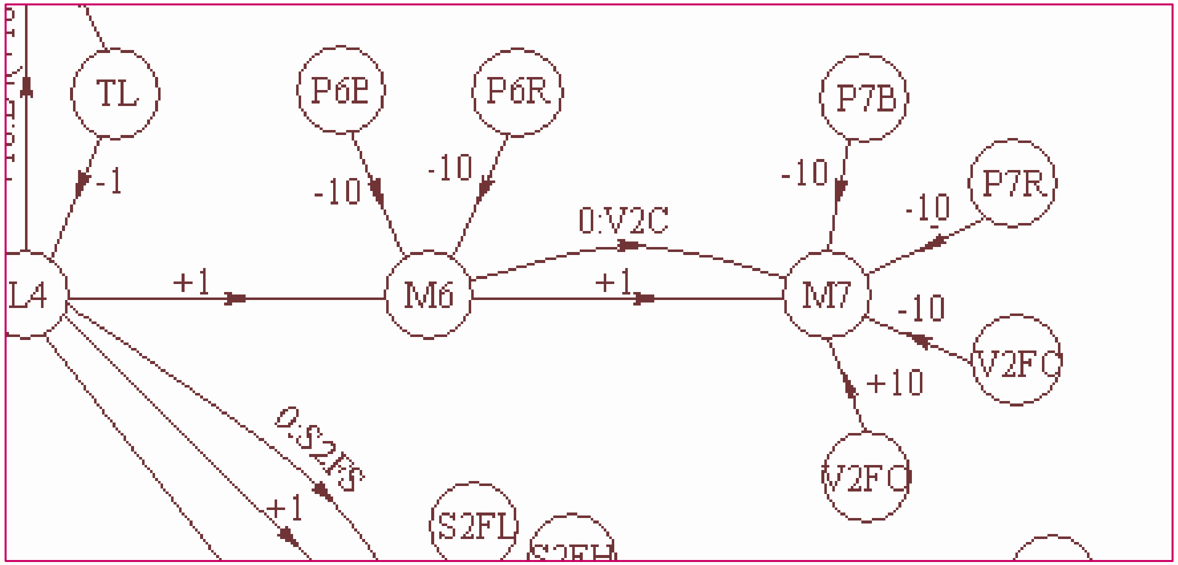


Fault Diagnostics of ‘FS16’

- Node M7 addressed – represents status of mass flow exiting V2.
- M7 is ‘marked’ on the system digraph.
- Determine the failure modes leading to large negative disturbance i.e. -10.
- -10 represents registered ‘no flow’ status.
- Back-tracing commences from M7(-10); reveals five component failure modes.

Fault Diagnostics of ‘FS16’

- M7(-10) → V2FC, P7B, P7R.
- M7(-10) → M6(-10) → P6B, P6R.
- M7(-10) → M6(-10) → L4(-10), back-tracing ceases.
- Five component failure mode results: Valve 2 failed closed, Pipe 7 blocked or ruptured, Pipe 6 blocked or ruptured.



Conclusions

- Component failure mode results are consistent with recorded sensor readings.
- Flagging of non-deviating sections removes conflicting results, also reduces number of determined fault combinations.
- Method 2 advised method since results displaying inconsistencies between sensor readings are removed.
- Digraph suitable method for steady state analysis.

Future Research

- Implications for dynamic behaviour – preliminary results are positive.
- Investigation into computational optimisation of back-tracing enabling real-time analysis.
- Scalability – it is necessary to apply method to larger, more complex, system to ensure industrial validity.

Summary

- Digraphs clearly illustrate the information flow in a cause-effect relationship.
- Closely reflect the physical structure of the system under investigation.
- Conduct diagnostics through back-tracing from a known deviation → introduce flagging of non-deviating sections.
- Valid diagnostic results determined for steady state.

Thank you for your attention.

Contact:

Emma Kelly: E.M.Kelly@lboro.ac.uk

Dr. L. Bartlett: L.M.Bartlett@lboro.ac.uk