Cause-and-Effect Matrix specifications for interlock based systems

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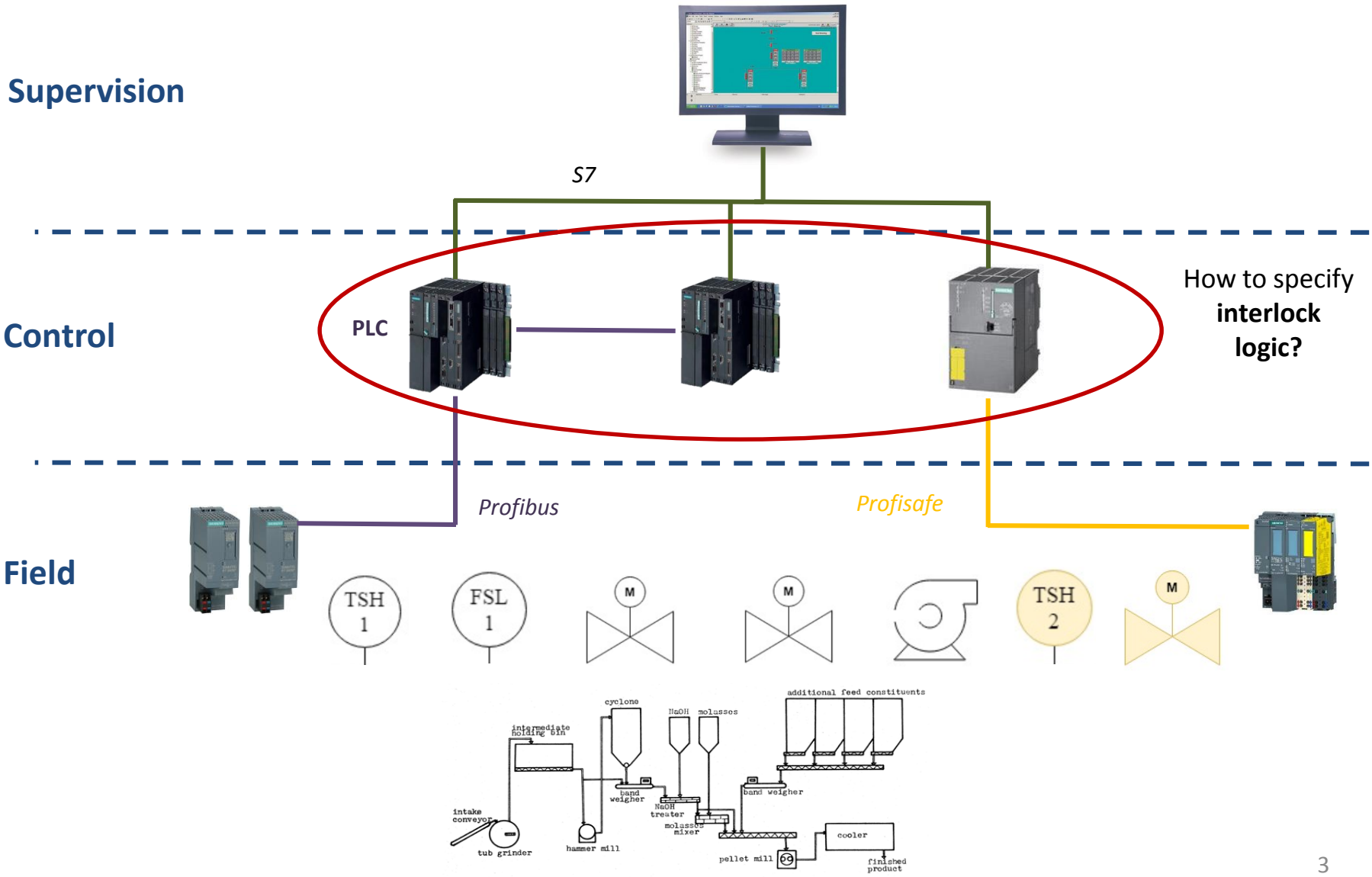
Context

Specifications for interlock logic in

Industrial controls and
Safety Systems

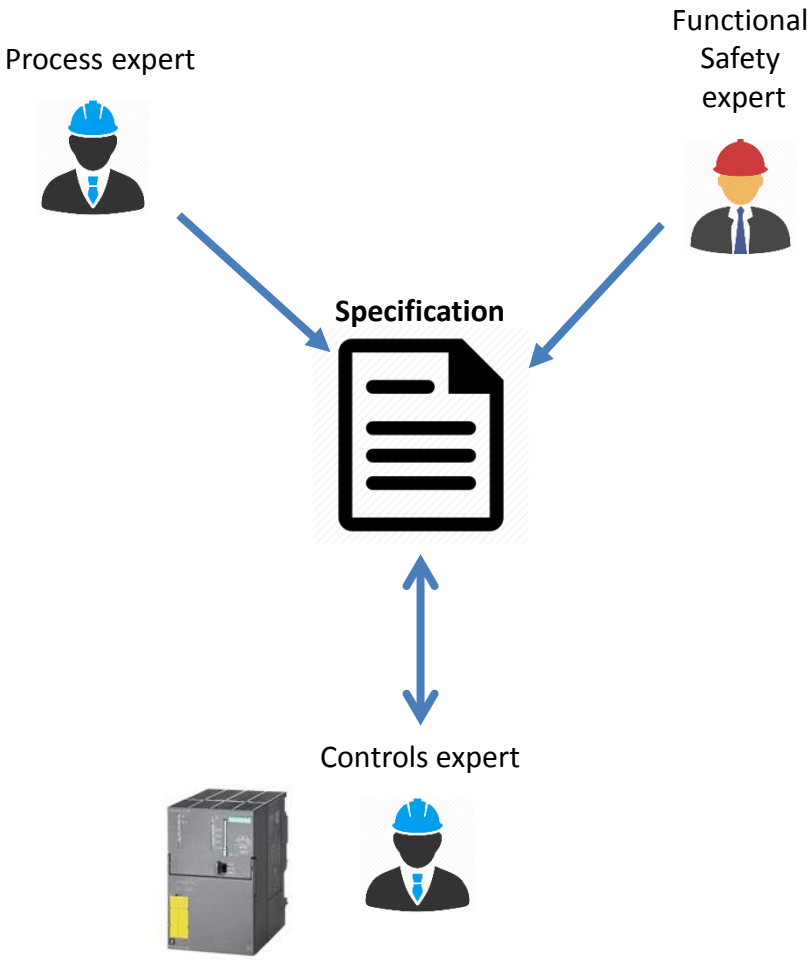
Industrial controls

Safety Systems



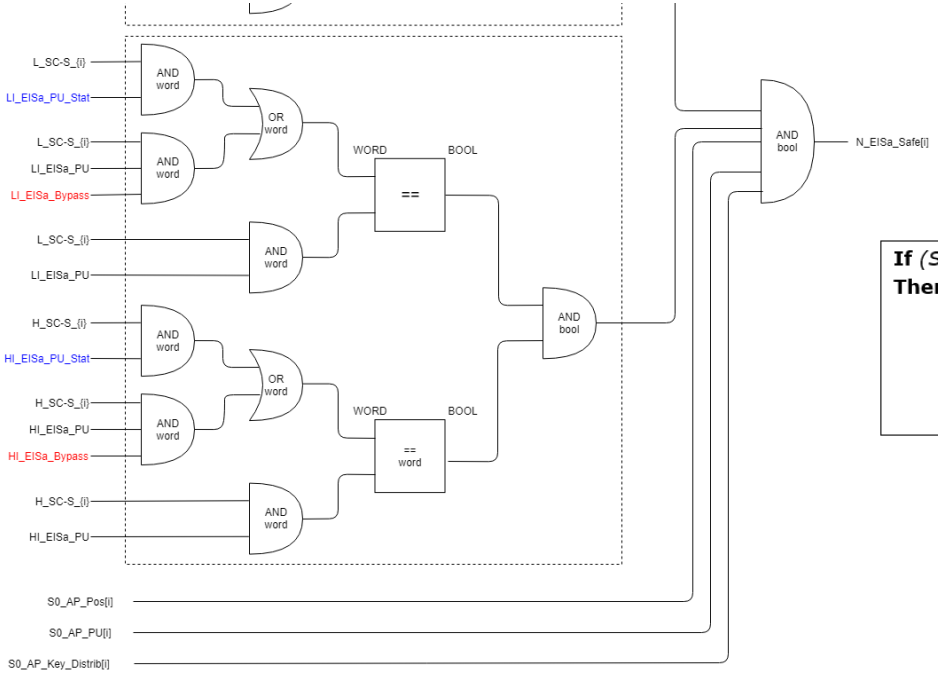
Main problems with specifications

1. **Ambiguous** specification
2. **Incomplete** specification
3. **Complex** specification



Specification options for stateless logic (some examples)

Logic diagram



Boolean expression

If *(SC-S_{i}[n]* **and** *I_EISa_Pos[n])*
Then*:*

N_EISa_Safe_{i}[n] **=** *(I_EISa_Bypass[n]* **or** *I_EISa_Pos_Stat[n])* **and** *(I_EISa_Bypass[n]* **or** *I_EISa_PU_Stat[n])* **and** *S0_AP_Pos[i]* **and** *S0_AP_PU[i]* **and** *S0_AP_Key_Distrib[i]*

Specification options for stateless logic (some examples)

Cause and Effect Matrix

StateOfElementsSC{1}		Description			
		Tag	N_EISa_Safe{1}[1]	N_EISa_Safe{1}[2]	N_EISa_Safe{1}[3]
Description	**Tag**		1	2	3
Assignment of element [n] to safety chain {i}	**SC-S{1}[1]**	1	N,A1,A2,A3,A4		
Installation of door contact [n]	**I_EISa_Pos[1]**	2	A3,A4		
Installation of emergency handle [n]	**I_EISa_PU[1]**	3	A2,A4		
Feedback of door contact [n]	**I_EISa_Pos_Stat[1]**	4	A1,A2		
Feedback of emergency handle [n]	**I_EISa_PU_Stat[1]**	5	A1,A3		
Bypass on element (both door contact and emergency handle) [n]	**I_EISa_Bypass[1]**	6	A2,A3,A4		
Assignment of element [n] to safety chain {i}	**SC-S{1}[2]**	7		N,A1,A2,A3,A4	
Installation of door contact [n]	**I_EISa_Pos[2]**	8		A3,A4	
Installation of emergency handle [n]	**I_EISa_PU[2]**	9		A2,A4	
Feedback of door contact [n]	**I_EISa_Pos_Stat[2]**	10		A1,A2	
Feedback of emergency handle [n]	**I_EISa_PU_Stat[2]**	11		A1,A3	
Bypass on element (both door contact and emergency handle) [n]	**I_EISa_Bypass[2]**	12		A2,A3,A4	
Assignment of element [n] to safety chain {i}	**SC-S{1}[3]**	13			N,A1,A2,A3,A4
Installation of door contact [n]	**I_EISa_Pos[3]**	14			A3,A4
Installation of emergency handle [n]	**I_EISa_PU[3]**	15			A2,A4
Feedback of door contact [n]	**I_EISa_Pos_Stat[3]**	16			A1,A2
Feedback of emergency handle [n]	**I_EISa_PU_Stat[3]**	17			A3,A1
Bypass on element (both door contact and emergency handle) [n]	**I_EISa_Bypass[3]**	18			A2,A3,A4

Outline

- Case Study
- Applicability of CEM
- Conclusions

Case Study – CERN test bench facility

- Test benches for superconducting magnets (**SM18**, FAIR, B311)

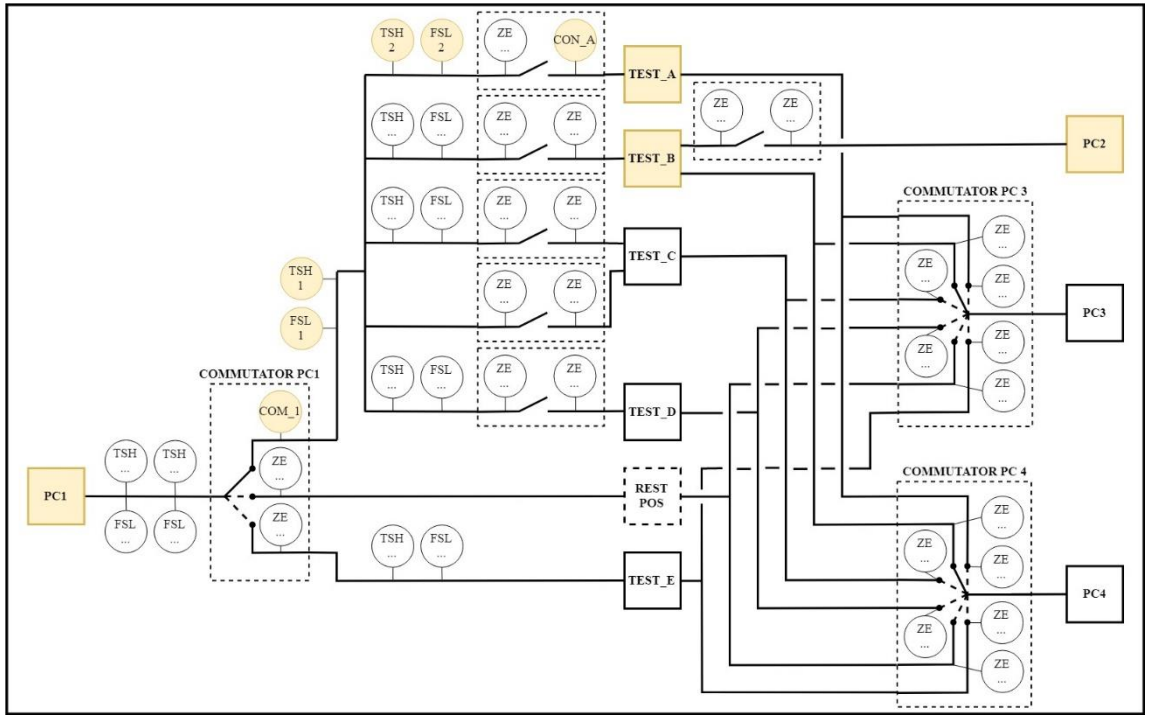
- **Risks** to personnel and equipment
  - Cryogenics
  - Vacuum
  - Power converters
  - Cooling & ventilation

- Need for **Safety Instrumented Systems (IEC 61511 standard)**

- Specification was divided in **Operational requirements** and **Safety requirements**

Case Study – CERN test bench facility

- **5 test benches** and **4 different power converters**
- **42 analogue input signals** (e.g. temperature and voltage sensors)
- **130 digital input signals** (e.g. flow switches, commutators feedbacks)
- **56 output signals** (e.g. digital relays to operate the power converters)



Case Study – Operational specification

Test Types

SCADA Commands

Process Inputs

Process Outputs

TYPE OF TEST TO SELECT

		Signal name	LONGUE	HFM
TEST CONFIG.	Par.	MTBG_Q_TO_CRYO_MIN_CUR_PC20	xxx A	xxx A
		MTBG_Q_TO_CRYO_MIN_CUR_PC10		
		PC selection (PC20, PC10, PC600_1, PC600_2)		
		QH_selection (QH 1- 8)		
		PC10_INV_POL_selection (POLA or POLB)		
		TEST_selection_on _DIODE_STATION (DIODE / LEAD)		
		LEAD3_INSTALLED_on_LONGUE		
		MTBG_QH_MIN_VOLT	xxx V	xxx V
		MTBG_MAGNET_PHASE		
	31	MTBG_TROLLEY_REST_DIODES	if PC = PC20, 1	if PC = PC20, 1
	32	MTBG_TROLLEY_CONN_AUX	if PC = PC20, 0	if PC = PC20, 0
	33	MTBG_TROLLEY_REST_AUX	if PC = PC20, 1	if PC = PC20, 1
	34	MTBG_COM20_CC	if PC = PC20, 0	if PC = PC20, 0
	35	MTBG_COM20_BUSBAR	if PC = PC20, 1	if PC = PC20, 1

TYPE OF TEST TO SELECT

		Signal name	LONGUE	HFM
TEST CONFIG.	Par.	MTBG_Q_TO_CRYO_MIN_CUR_PC20	xxx A	xxx A
		MTBG_Q_TO_CRYO_MIN_CUR_PC10		
		PC selection (PC20, PC10, PC600_1, PC600_2)		
		QH_selection (QH 1- 8)		
		PC10_INV_POL_selection (POLA or POLB)		
		TEST_selection_on _DIODE_STATION (DIODE / LEAD)		
		LEAD3_INSTALLED_on_LONGUE		
		MTBG_QH_MIN_VOLT	xxx V	xxx V
		MTBG_MAGNET_PHASE		
OUTPUT SIGNALS	DIGITAL OUTPUTS 26	MTBG_Q_TO_CRYO_DIODES		
	27	MTBG_Q_T_CRYO_AUX		
	28	MTBG_PC20_CUR_TO_CRYO	MTBG_PC20_CUR	MTBG_PC20_CUR
	29	MTBG_PC10_CUR_TO_CRYO	MTBG_PC10_CUR	MTBG_PC10_CUR
	31	MTBG_PC600_2_CUR_TO_CRYO	MTBG_PC600_2_CUR	MTBG_PC600_2_CUR
	32	MTBG_QH_CONN_CHECK	ACTION TAKEN BY OPERATOR	ACTION TAKEN BY OPERATOR
	33	MTBG_QH_CONN_CHECK_2		
	34	MTBG_CMD_QH_SWITCH_LONGUE	ACTION TAKEN BY OPERATOR executed only if MTBG_V_QH1-16 = 0)	0
	35	MTBG_CMD_QH_SWITCH_HFM	0	ACTION TAKEN BY OPERATOR executed only if MTBG_V_QH1-16 = 0)
	36	MTBG_CMD_QH_SWITCH_DIODES	0	0
	37	MTBG_CMD_QH_SWITCH_AUX	0	0
	38	MTBG_CMD_INV_POLA		if PC = PC10, 1 when POLA selected
	39	MTBG_CMD_INV_POLB		if PC = PC10, 1 when POLB selected
	40	MTBG_PC600_1_PERMIT	if PC = PC600_1, 1 when all input conditions fullfilled	if PC = PC600_1, 1 when all input conditions fullfilled
	41	~~MTBG_PC600_1_DIRECT_PA?~~		
	42	MTBG_PC600_2_PERMIT	if PC = PC600_2, 1 when all input conditions fullfilled	if PC = PC600_2, 1 when all input conditions fullfilled
	43	~~MTBG_PC600_2_DIRECT_PA?~~		
	44	MTBG_PC10_PERMIT		if PC = PC10, 1 when all input conditions fullfilled
	45	MTBG_PC10_DIRECT_PA		
	46	MTBG_PC10_MCB_CMD		if PC =PC10, [pulse of 1s to 0, 100ms after MTBG_NO_Q_DETECT_HFM = 0 ; 1 if MTBG_NO_Q_DETECT_HFM = 1]
	47	MTBG_PLC_EE10_OPEN_RQ		if PC = PC10, [1 if MTBG_PC10_EE_OPEN_RQ = 1]
	48	MTBG_CLOSE_EE10 (500ms positive pulse)		if PC = PC10, ACTION taken by OPERATOR - See graphcet

Case Study – Operational specification

	Condition	Test_A	Test_B
SCADA	SEL_PC	PC1 / PC3 / PC4	PC1 / PC2 / PC3 / PC4
	...	...	...
Process Sensors	CRYO_A	1	
	CRYO_B		1
	DAQ_A	1	
	DAQ_B		1
	...	...	...
Process Actuators	PC1_OPER	if PC1, 1 when all conditions fulfilled	if PC1, 1 when all conditions fulfilled
	PC2_OPER		if PC2, 1 when all conditions fulfilled
	...	...	...

- **Simple** and **convenient** formalism for the process engineer
- but **ambiguous** specification

Case Study – Safety specification

FMEA risk analysis

Repère	Principal équipement en rapport avec le PLC (Inputs / Outputs)	Principaux composants Associés à la fonction	Fonction	Modes de défaillance potentielle	Effets de la défaillance	Causes potentielles	Événements redoutés pour la sécurité des opérateurs	Paramètre Sécurité des personnes				Niveau SIL cible (Sécurité)
								C	F	P	W	
1	WCC	Contrôleur de débit TOR PLC	Détecter un débit d'eau	Indication erronée	Plus de débit d'eau	Contrôleur de débit hors service	Dommages aux équipements : Brûlure des câbles, explosion des flexibles. Eau sur les équipements électriques. Brûlure par contact. Brûlure par projection d'eau chaude. Effet domino : Incendie	1	/	/	3	Pas d'exigence de sécurité particulière
2		Sondes de température PLC	Mesurer la Température de l'eau	Lecture erronée	Pas de refroidissement des câbles Cuivre.	Sondes de température défectueuse		1	/	/	3	SIF1 (SIL1)

Safety Function Specification

Reference	**SIF1_PC10**
Related risk	Risk analysis references 1 and 2
Functionality	Shutdown the PC (10KA) if the corresponding temperature of the cable is high (thermoswitch signal = 0) or the water flow is low (switch signal = 0)
Formalized functionality	**If** (**NOT** MTBG_WCCF_HFM_BIS_P **OR** **NOT** MTBG_WCCF_HFM_BIS_M **OR** **NOT** MTBG_WCCT_PC10_EE10 **OR** **NOT** MTBG_WCCT_EE10_INV **OR** **NOT** MTBG_WCCT_INV_HFM) **Then** (MTBG_PC10_PERMIT_Q = FALSE)
Safety level	SIL1
Safety mode	Low demand

- **Unambiguous** specification
- But **no tool support:**
  - **Test cases** generation
  - **Verification cases** generation
  - **Code** generation

Cause and Effect Matrix (CEM)

- A compact and intuitive **graphical** representation of **Boolean expressions**
- Adequate to **represent stateless logic**, where a given output depends only on a combination of the current input signals
- There are **many variants of CEMs** and the companies adopt the **semantics that best adapt to their processes and engineering practices**
  - SIMATIC Safety Matrix (Siemens Product)
  - IEC 62881:2018. Cause and effect matrix

Cause and Effect Matrix (CEM)

$$\begin{bmatrix} Q01 \\ Q02 \end{bmatrix} = \begin{bmatrix} I01 \vee TON(I02, 20s) \vee (\neg I03 \wedge I04) \\ I02 \wedge (I03 \vee \neg I04) \end{bmatrix}$$

Cause \ Effect	Q01	Q02
I01	X	
I02	TON20	A1,A2
I03	NA1	A1
I04	A1	NA2

Cause and Effect Matrix (CEM)

	Condition	Test_A	Test_B
SCADA	SEL_PC	PC1 / PC3 / PC4	PC1 / PC2 / PC3 / PC4
	...	...	...
Process Sensor	CRYO_A	1	
	CRYO_B		1
	DAQ_A	1	
	DAQ_B		1
	...	...	...
Process	PC1_OPER	if PC1, 1 when all conditions fulfilled	if PC1, 1 when all conditions fulfilled
	PC2_OPER		if PC2, 1 when all conditions fulfilled
	...	...	...

Reference	**SIF1**
Related risk	Risk analysis reference 1
Functionality	Shutdown the power converter if the corresponding temperature of the water-cooled cable is high (*FALSE*) or the water flow is low (*FALSE*)
Formalized functionality	*If* $(COM\_1 \wedge CON\_A \wedge (\neg TSH1 \vee \neg TSH2 \vee \neg FSL1 \vee \neg FSL2))$ *Then* $PC1\_PP = 0$
Safety Level	SIL2
Operation mode	Low demand

Variable discretization

(a) Top Operational CEM

Cause \ Effect	PC1_OPER	PC2_OPER
SEL_PC1	A1,A2,A3,A4,A5	
SEL_PC2		A1
TEST_A	A1	
TEST_B	A2	A1
TEST_C	A3	
TEST_D	A4	
TEST_E	A5	

(b) Top Safety CEM

Cause \ Effect	PC1_PP	PC2_PP
SIF1	NA1	
SIF2	NA1	
SIF3		NA1
SIF4	NA1	NA1
PC1_OPER	A1	
PC2_OPER		A1

(c) Bottom Operational CEM

Cause \ Effect	TEST_A	TEST_B
SEL_TEST_A	A1	
SEL_TEST_B		A1
CRYO_A	A1	
CRYO_B		A1
DAQ_A	A1	
DAQ_B		A1

(d) Bottom Safety CEM

Cause \ Effect	SIF1	SIF2
COM_1	A1,A2,A3,A4	
CON_A	A1,A2,A3,A4	
TSH1	NA1	
TSH2	NA2	
FSL1	NA3	
FSL2	NA4	
...		...

Cause and Effect Matrix (CEM)

(a) Top Operational CEM

Cause \ Effect	PC1_OPER	PC2_OPER
SEL_PC1	A1,A2,A3,A4,A5	
SEL_PC2		A1
TEST_A	A1	
TEST_B	A2	A1
TEST_C	A3	
TEST_D	A4	
TEST_E	A5	

(b) Top Safety CEM

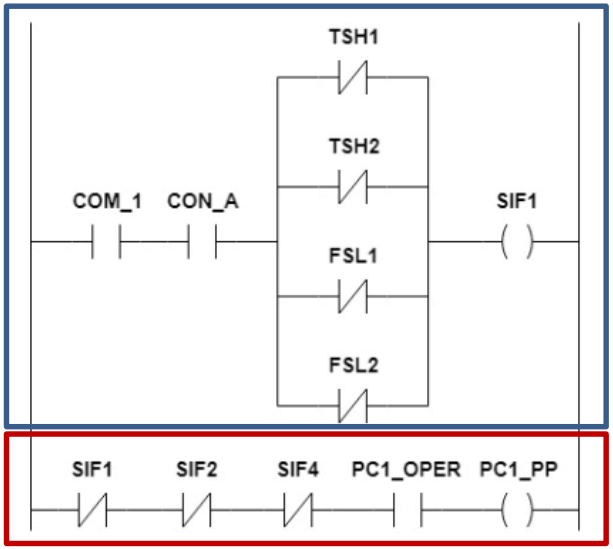
Cause \ Effect	PC1_PP	PC2_PP
SIF1	NA1	
SIF2	NA1	
SIF3		NA1
SIF4	NA1	NA1
PC1_OPER	A1	
PC2_OPER		A1

(c) Bottom Operational CEM

Cause \ Effect	TEST_A	TEST_B
SEL_TEST_A	A1	
SEL_TEST_B		A1
CRYO_A	A1	
CRYO_B		A1
DAQ_A	A1	
DAQ_B		A1

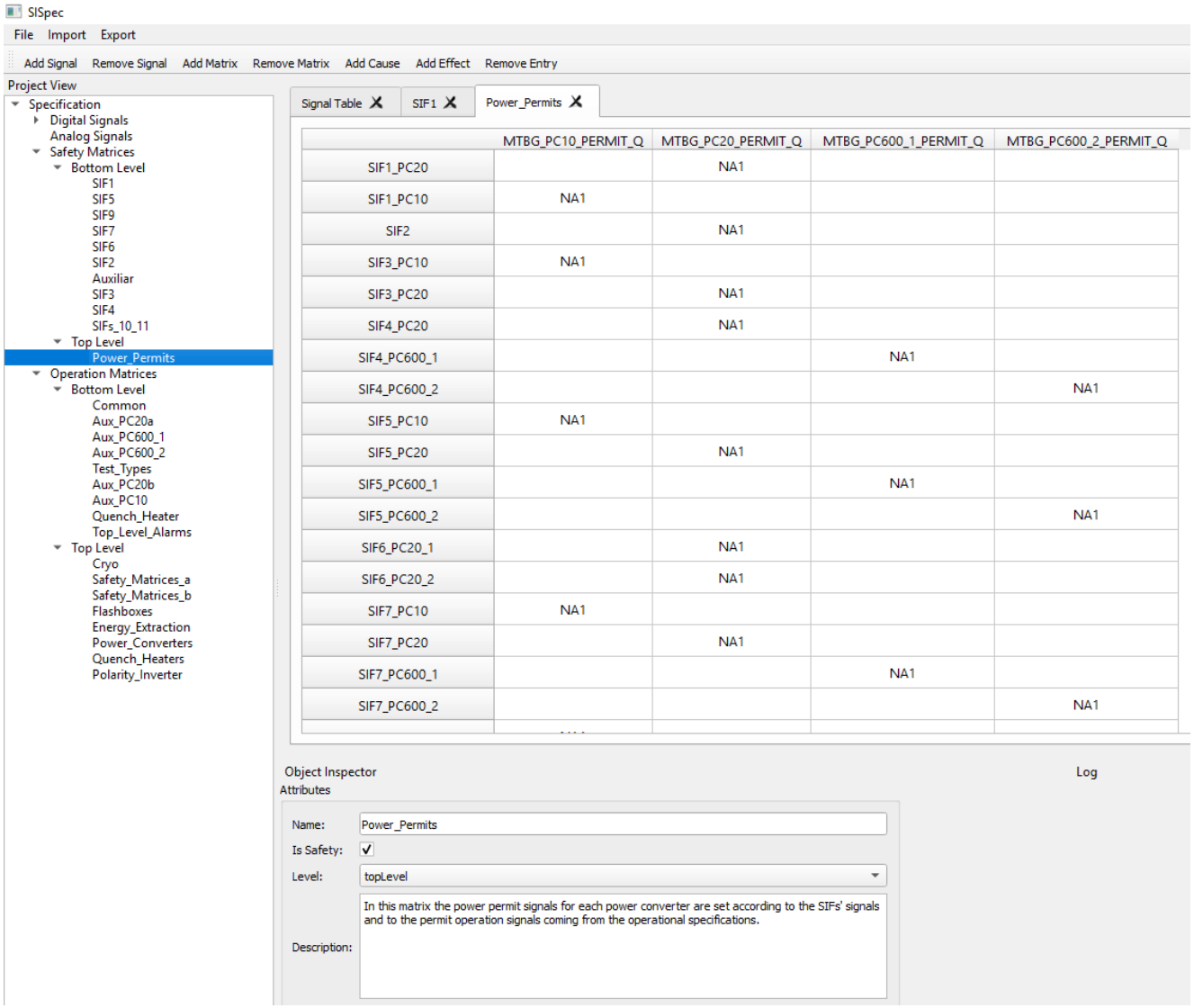
(d) Bottom Safety CEM

Cause \ Effect	SIF1	SIF2
COM_1	A1,A2,A3,A4	
CON_A	A1,A2,A3,A4	
TSH1	NA1	
TSH2	NA2	
FSL1	NA3	
FSL2	NA4	
...		...



- **Code** generation (when possible)
- **Test** case generation
- **Verification** cases generation

SISpec: CEM Editor



Conclusions

CEM pros	CEM cons	Future directions
• **Simple** and **graphical** mechanism • Allows a **better communication** between control, process and safety experts • **Trivial** generation of the **PLC code** • Allows **automatic generation of test and verification** cases • Improved **maintainability** of the PLC code and **traceability** of the whole project	• **Not appropriate** for **all types of processes.** Mainly convenient for stateless interlock logic • Certain Boolean logic may be difficult to express in one single CEM (auxiliary CEMs may have to be Included)	• Extension of the **CEM semantics** to different activation logics (rising edges, pulses, etc.) • **PLC code generation and integration** in the development cycle of SISs and interlock-based control systems