Industrial Embedded Systems
- Design for Harsh Environment -

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Part III

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From Reliability to Safety

- Reliability has been defined as the probability of system function survival.
  “deliver a specified functionality under specified condition for a specified period of time”
- Requirements analysis gave us a list of functions, their failure modes and an RPN so we could identify the most risky functions in terms of failure (FMEA)
- Once critical failure modes had been identified an FTA could be used to look into root causes and/or combination of causes
- We looked into architectures which can make functions more reliable. We also introduced metrics (MTBF, failure rate) a proposed architecture can meet

From Reliability to Safety II

- However, we need to seperate functions which are critical because their failure means reduced availability from those that mean loss of lives or severe danger at the super system level. The latter is of public interest, the former more of a performance gain.
- Safety is about
  - Assessing the risk of those failures (similar to reliability)
  - Proposing risk reduction based on computer architecture and processes (different to reliability since not every architecture might be allowed, we also consider systematic failures to a great extent) – setting a target risk
  - Realizing a proposed system based on the proposed architecture – proving that the design risk meets the target risk
- Either those critical functions are made extremely reliable (architectural choices) or a safety function is added which introduces an independent way of achieving safety (IEC61508 for industrial systems)

Motivation

- Therac 25 (1985-87, N. America) radiation therapy machine: severe radiation overdose caused by software failure
- Ariane 5 (1996) software exception causes self-destruct
- Links
  - http://en.wikipedia.org/wiki/List_of_software_bugs
  - http://catless.ncl.ac.uk/Risks
  - http://www.csl.sri.com/users/neumann/illustrative.html
  - http://wwwzenger.informatik.tu-muenchen.de/persons/huckle/bugse.html
  - http://page.mi.fu-berlin.de/prechelt/swt2/node36.html

Hazards and Harm

Hazard

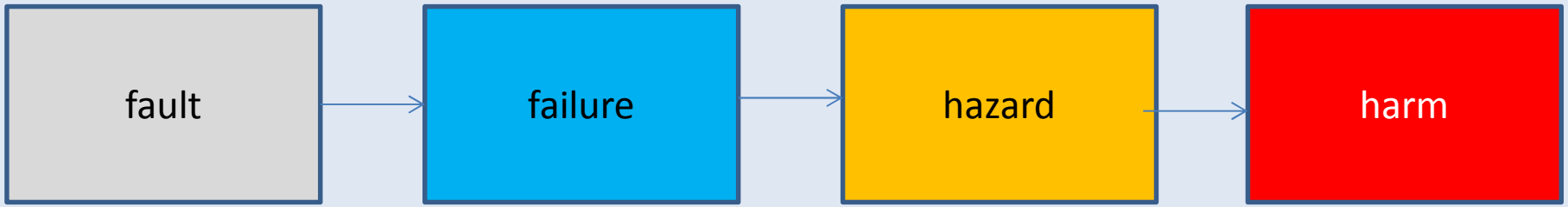
potential source of harm. Hazard is a system state resulting from a failure.

[Guide 51 ISO/IEC:1990]

Harm

physical injury or damage to the health of people either directly or indirectly as a result of damage to property or to the environment

[ISO/IEC Guide 51:1990 (modified)]



Risk

Risk
a measure of the probability and consequence of a specified hazardous event

Tolerable Risk
determined on a societal basis and involves consideration of societal and political factors (the tolerable risk for running nuclear power plant changed recently – but not the probability of failure!)

Residual Risk
risk remaining after protective measures have been taken

Risk assessment is necessary to phrase the missing safety requirements for the requirements specification.

Safety and Functional Safety

Safety
is the freedom from unacceptable risk of physical injury or of damage to the health of people, either directly as a result of damage to property or to the environment

Functional safety
is part of the overall safety that depends on a system or equipment operating correctly in response to its inputs

According to IEC61508: Part of the overall safety relating to the equipment and its associated control system which depends on the correct functioning of electrical, electronic and programmable electronic safety-related systems……".

Overall Safety = Non-functional Safety + Functional Safety

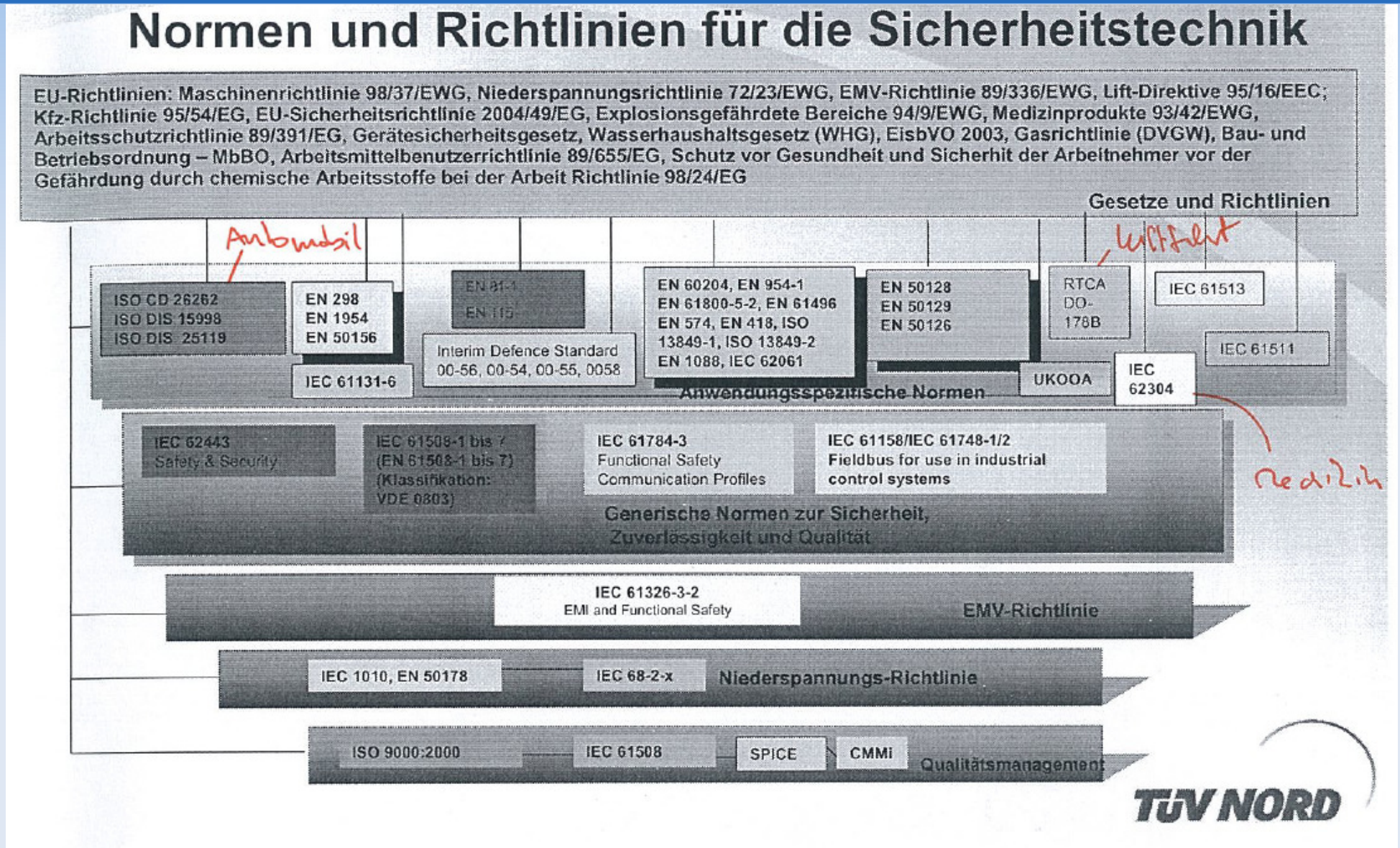
Safety-critical and Safety-related Systems

- The term ‘safety-related’ applies to any hardwired or programmable system where a failure, singly or in combination with other failures/errors, could lead to death, injury or environmental damage.
- ‘Safety-critical’ has tended to be used where failure alone, of the equipment in question, leads to a fatality or increase in risk to exposed people.
- ‘Safety-related’ has a wider context in that it includes equipment in which a single failure is not necessarily critical whereas coincident failure of some other item leads to the hazardous consequences.
  -> we will use the term safety-related here

Safety Standards

- Today more and more the devices and products dedicated to the safety of machinery incorporate complex and programmable electronic systems.
- Due to the complexity of the programmable electronic systems it is in practice difficult to determine the behavior of such safety device in the case of a fault.
- Therefore the standard IEC/EN 61508 with the title “Functional safety of electrical/electronic/ programmable electronic safety-related systems” provides a new approach by considering the reliability of safety functions.
- It is a basic safety standard for the industry and in the process sectors.

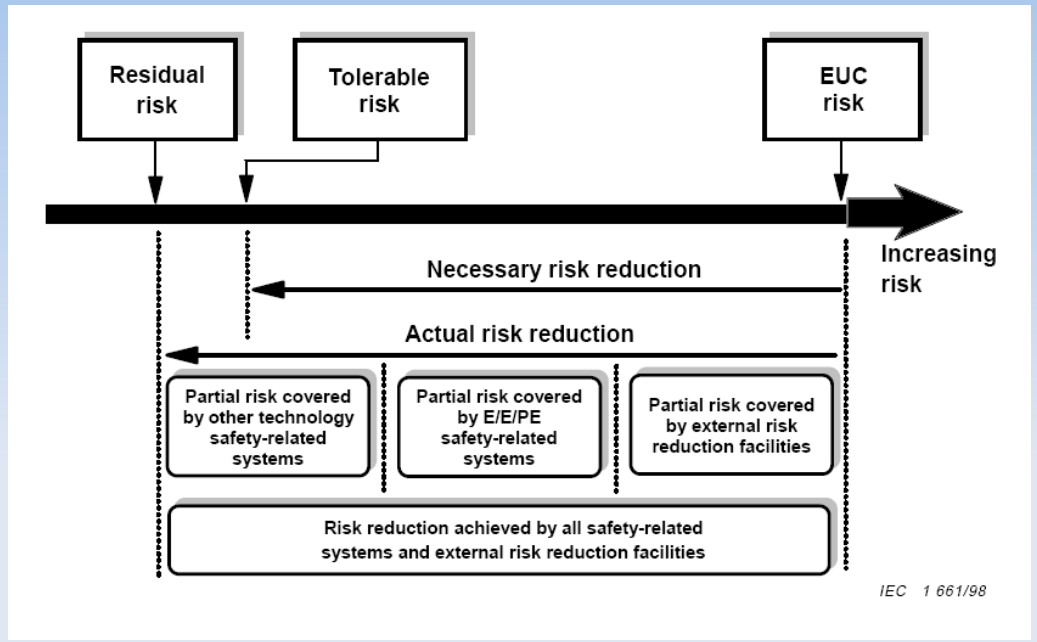
Safety Standards II

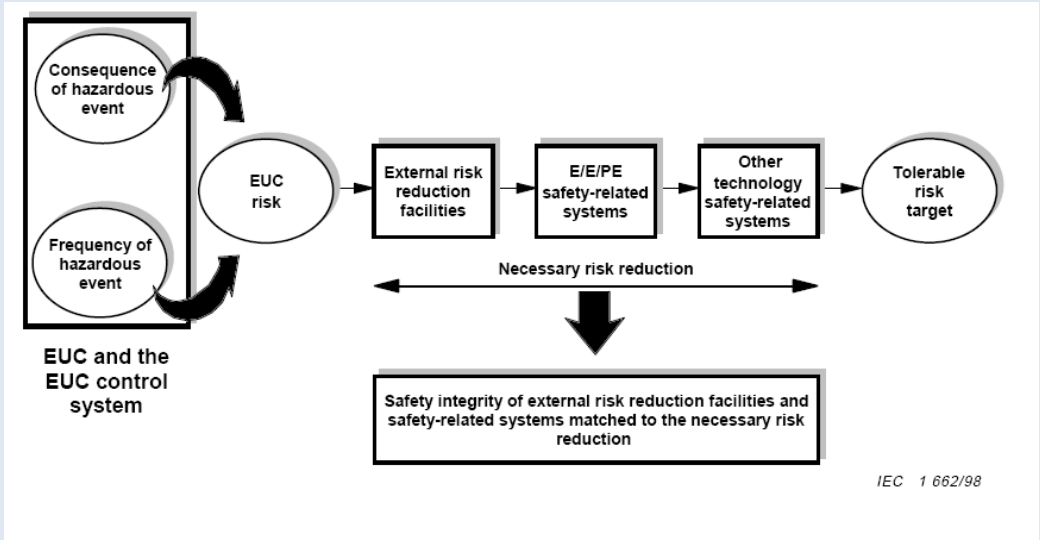


Safety Assessment

- Establish a risk target (the actual system as designed will be compared to the risk target at a later design step):
  - Formal hazard identification (FMEA, FTA) of not-protected system (np)
  - Set a maximum tolerable risk (society, etc.)
  - Carry out a quantified risk assessment on np system
  - Compare np system risk to maximum tolerable risk
  - What risk reduction is needed?
- Identify the safety function (the function will cause the hazard on failure) and its quality
  - Identification function (safety function) from FTA and FMEA
  - Identification of safety function integrity (failure probability) from risk reduction
  - Identification of safety function response time requirement

Risk and Risk Reduction (IEC61508)





EUC (from IEC61508):
System under control
E/E/PE (from IEC61508):
Electrical/electronic/programmable electronic system

Source:
IEC61508

Published Tolerated Risk

- Probability for nuclear meltdown: $< 10^{-5}$ pa (IAEA)
- Probability of larger amounts of radiation in case of an accident: $<< 10^{-6}$ pa (IAEA)
- Civil aviation:
  - Catastrophic event: $< 10^{-9}$ ph
  - Dangerous event: $< 10^{-7}$ ph
  - Other important flight operations: $< 10^{-5}$ ph
- Railway interlocking systems (Deutsche Bahn): $< 10^{-9}$ per setting

Safety Function and Safety Integrity Level (SIL)

Safety Function

function to be implemented by an electrical/electronic/programmable electronic safety-related system, other technology safety-related system or external risk reduction facilities, which is intended to achieve or maintain a safe state for the equipment under control (EUC), in respect of a specific hazardous event (from IEC61508)

Safety Integrity

probability of a safety-related system satisfactorily performing the required safety functions under all the stated conditions within a stated period of time (from IEC61508)

- The higher the level of safety integrity of the safety-related systems, the lower the probability that the safety-related systems will fail to carry out the required safety functions.
- There are four levels of safety integrity in IEC61508.

Safety Integrity Level (SIL)

IEC 61508 considers two modes of safety function operation:

high demand mode
the frequency of demands (safety function requests) is greater than one per year or greater than twice the proof check frequency (test interval)

Think of a safety function that calculates a specific result on a microprocessor (on failure of the safety function a wrong result is communicated immediately which will lead to the hazard)

low demand mode
the frequency of demands no greater than one per year and no greater than twice the proof test frequency

Think of a safety function requested on super-system failure only (e.g. an actuator). On failure of the safety function the actuator is not used immediately

Safety Integrity Level (SIL) II

- Probability of failure per hour – PFH (rate since hazardous state is entered immediately after failure)
- Probability of failure on demand – PFD (dimension less since hazardous state is measured agains number of demands)

SIL	High demand	Low demand
4	$10^{-9} \leq \text{PFH} \leq 10^{-8}$	$10^{-5} \leq \text{PFD} \leq 10^{-4}$
3	$10^{-8} \leq \text{PFH} \leq 10^{-7}$	$10^{-4} \leq \text{PFD} \leq 10^{-3}$
2	$10^{-7} \leq \text{PFH} \leq 10^{-6}$	$10^{-3} \leq \text{PFD} \leq 10^{-2}$
1	$10^{-6} \leq \text{PFH} \leq 10^{-5}$	$10^{-2} \leq \text{PFD} \leq 10^{-1}$

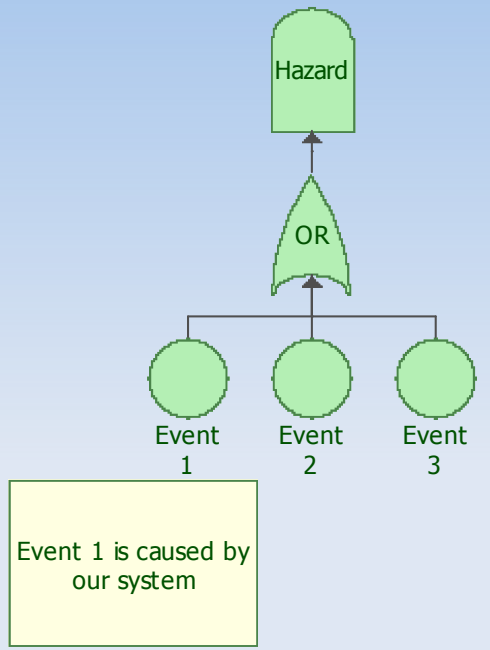
Source: IEC61508

Safety Assessment in Requirements Analysis

- Identify failure modes as in reliability analysis to get safety function
  - FTA – do on super-system level to discover root causes (on system level) of hazardous failures
  - Link those root causes (events) to failure modes and their effects
  - The safety function is a system function which will cause a hazardous failure (safety function depends on the super-system)
- Safety Integrity
  - Qualitative Methods
  - Quantitative Methods (Risk assessment, Reliability Block Diagrams)
  - Marketing (competitor analysis)

Safety Function Example

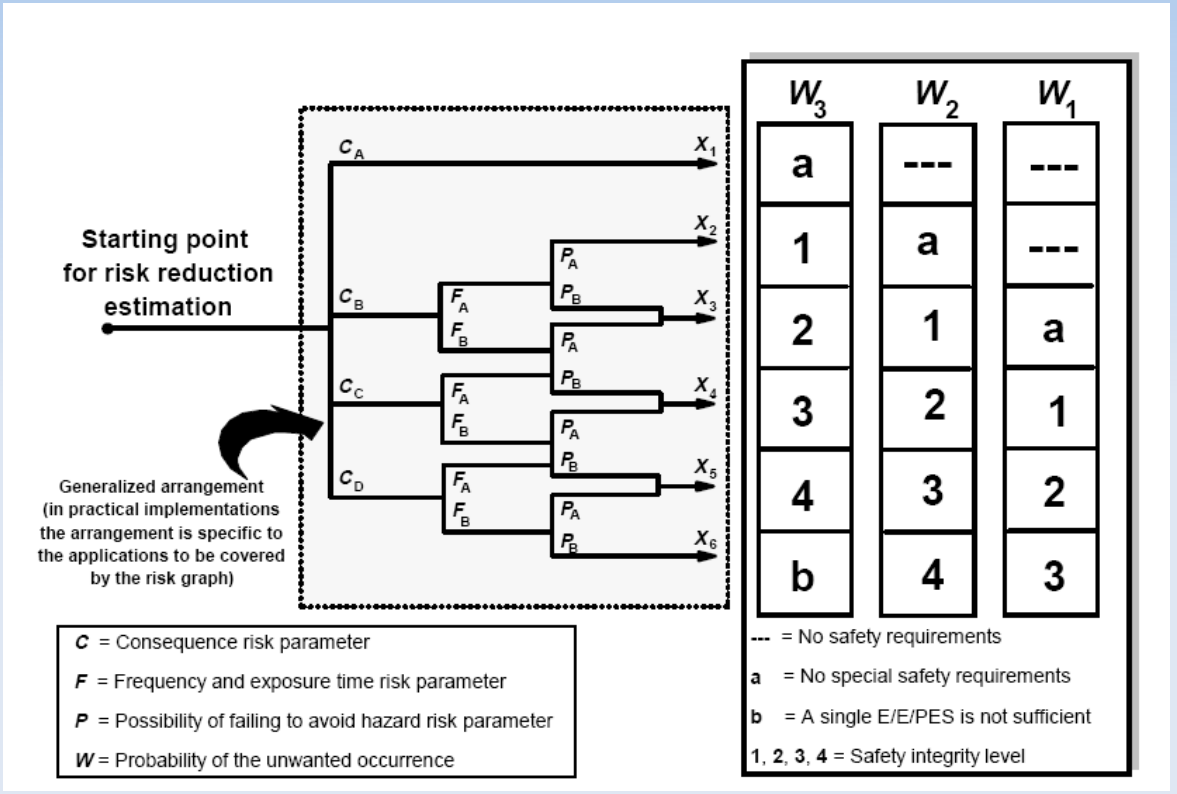
- FTA helps do discover events that could cause hazards in final applications
- Event is linked to failure mode(s) of our system
- Isolate failure modes and identify the safety function



Function	Failure	Effect	Si	Classification	Cause	Oi	Control (Prevention)	Control (Detection)	Di	RPNi
Function 1	Failure mode 1	Event 1	10		Cause 1	4		Detection 1	6	240
	Failure mode 2	Effect 2	8		Cause 2	2		Detection 2	6	96
	Failure mode 3	Effect 3	1		Cause 3	3		Detection 3	6	18
Function2	Failure mode 1	Event 1	10		Cause 1	5		Detection 1	6	300
	Failure mode 2	Effect 2	1		Cause 2	2		Detection 2	6	12

Qualtitative Risk Assessment
- risk graph -

Risk parameter		Classification	Comments
Consequence (*C*)	C_1	Minor injury	1 The classification system has been developed to deal with injury and death to people. Other classification schemes would need to be developed for environmental or material damage.
	C_2	Serious permanent injury to one or more persons; death to one person	
	C_3	Death to several people	2 For the interpretation of C_1, C_2, C_3 and C_4, the consequences of the accident and normal healing shall be taken into account.
	C_4	Very many people killed	
Frequency of, and exposure time in, the hazardous zone (*F*)	F_1	Rare to more often exposure in the hazardous zone	3 See comment 1 above.
	F_2	Frequent to permanent exposure in the hazardous zone	
Possibility of avoiding the hazardous event (*P*)	P_1	Possible under certain conditions	4 This parameter takes into account – operation of a process (supervised (i.e. operated by skilled or unskilled persons) or unsupervised); – rate of development of the hazardous event (for example suddenly, quickly or slowly); – ease of recognition of danger (for example seen immediately, detected by technical measures or detected without technical measures); – avoidance of hazardous event (for example escape routes possible, not possible or possible under certain conditions); – actual safety experience (such experience may exist with an identical EUC or a similar EUC or may not exist).
	P_2	Almost impossible	
Probability of the unwanted occurrence (*W*)	W_1	A very slight probability that the unwanted occurrences will come to pass and only a few unwanted occurrences are likely	5 The purpose of the *W* factor is to estimate the frequency of the unwanted occurrence taking place without the addition of any safety-related systems (E/E/PE or other technology) but including any external risk reduction facilities.
	W_2	A slight probability that the unwanted occurrences will come to pass and few unwanted occurrences are likely	6 If little or no experience exists of the EUC, or the EUC control system, or of a similar EUC and EUC control system, the estimation of the *W* factor may be made by calculation. In such an event a worst case prediction shall be made.
	W_3	A relatively high probability that the unwanted occurrences will come to pass and frequent unwanted occurrences are likely	



Source:
IEC61508

Quantitative Risk Assessment

Risk = Probability x Consequence

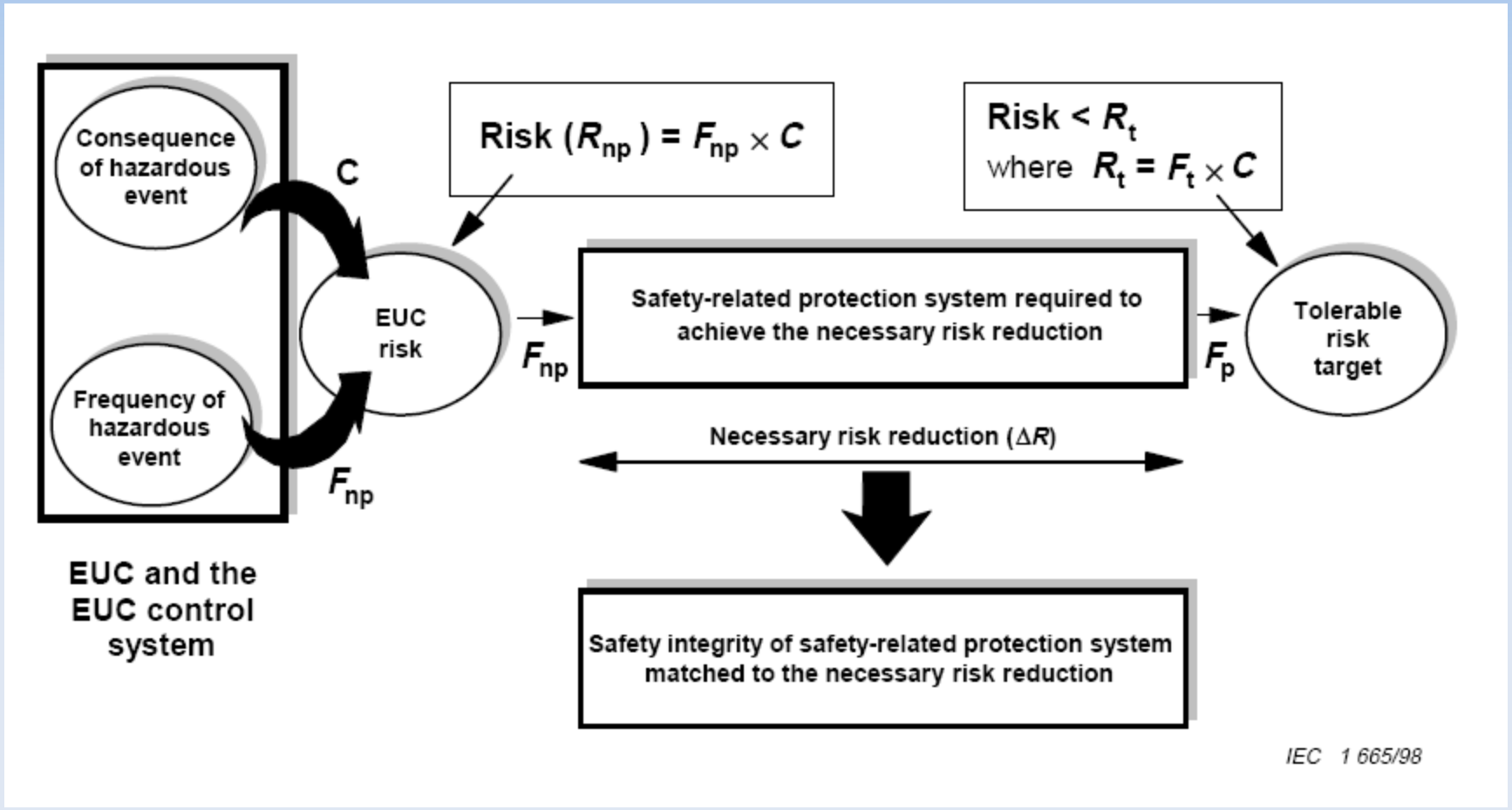
Maximum tolerable risk of fatality	*Individual risk (per annum)*
Employee	10^{-4}
Public	10^{-5}
Broadly acceptable risk (previously referred to as 'Negligible' (Employee and public))	10^{-6}

Catastrophic
Critical
Marginal
Negligible

Source:
Smith, Functional Safety

What are the hazards (state of the super-system)?, What is the frequency of occurrence (rate, probability)?, What are the consequences (harm)?

Quantitative Risk Assessment II



Source:
IEC61508

Quantitative Risk Assessment Example

The maximum tolerated fatality (harm) rate (one person dies) of a super-system has been decided to be 10^{-5} pa (society, discussions). 10^{-2} of the hazards under investigation lead to harm. From an independent assessment we know that the system as built today (no additional risk reduction) fails at 2×10^{-1} pa (failure rate of the safety function).

(a) Do we need an additional safety system?

(b) What quality (failure rate, etc.) must an additional safety system have if mandatory?

Quantitative Risk Assessment Example

Tolerated risk:
Risk = C x F; C = consequence, F = failure rate

Tolerated failure rate:
F = Risk/C = 10^{-5} pa/10^{-2} = 10^{-3} pa (tolerated failure rate)

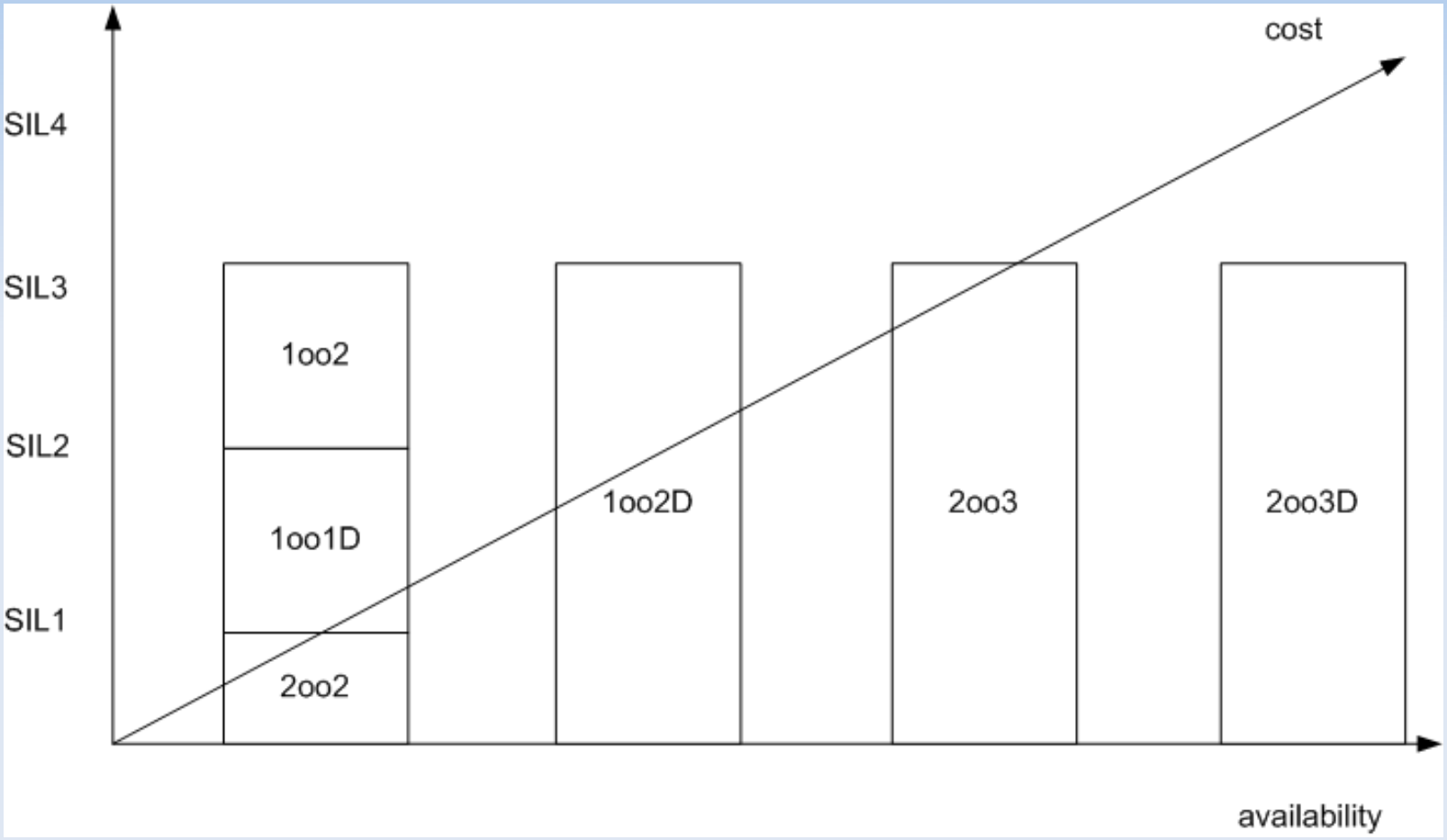
(a) yes, we need an additional risk reduction for the safety function since the failure rate of 10^{-3} pa is less than what we can achieve currently (2 x 10^{-1} pa)

(b) To minimize the risk the failure rate of an improved super-system must be addressed. Failure rate of the super-system is some function of the failure rate of the safety function in our system (RBD, FTA)

Where are we?

- We know that there are critical functions in our system that influence the proposed super-system (hazardous failure):
  - What can we do about that?
    Are there any architecturural or technology decisions we should make early on?
  - What metrics do we have?
    At this point we have only used categories (SIL) – but how are those categories related to future computer designs (architectures)?

Architectures



Architectures II

Safe failure fraction	Hardware fault tolerance (see note 2)		
	0	1	2
< 60 %	Not allowed	SIL1	SIL2
60 % – < 90 %	SIL1	SIL2	SIL3
90 % – < 99 %	SIL2	SIL3	SIL4
≥ 99 %	SIL3	SIL4	SIL4

NOTE 1 See 7.4.3.1.1 to 7.4.3.1.4 for details on interpreting this table.

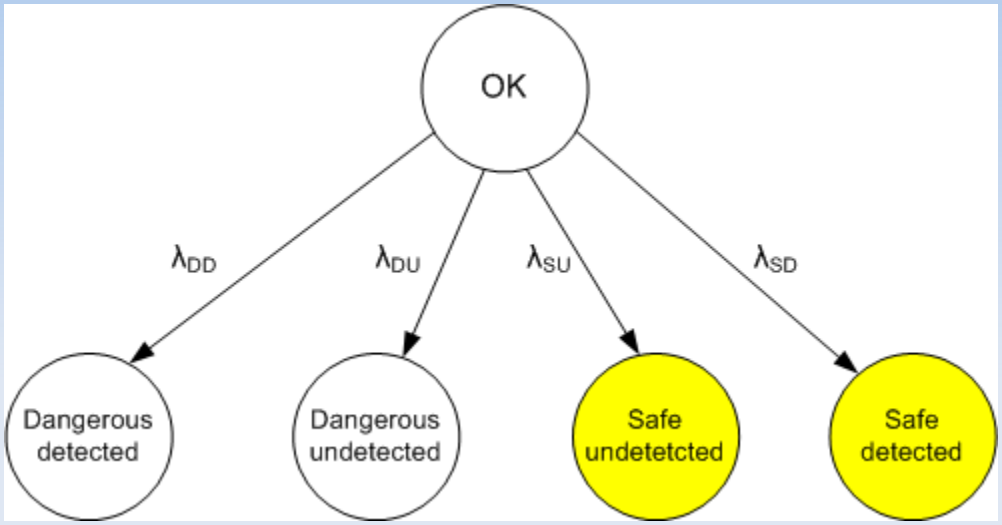
NOTE 2 A hardware fault tolerance of N means that N + 1 faults could cause a loss of the safety function.

NOTE 3 See annex C for details of how to calculate safe failure fraction.

Source: IEC61508

- Besides providing a specific quality (failure rate) a safety function must be hosted by a specific architecture in context of IEC 61508
- Besides architecture constraints also specific fault detection mechanisms must be realized by the final design. This is expressed by the safe failure fraction (SFF)

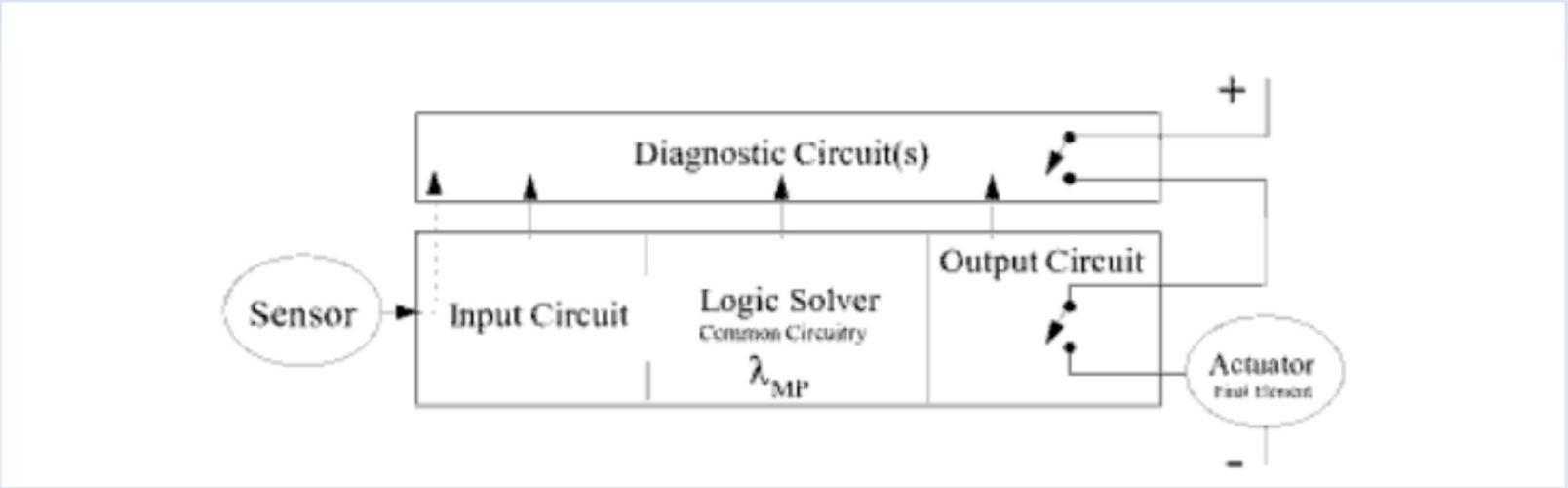
Safe Failure Fraction (SFF)



- Failure (this is the same failure rate as in the last lecture) can happen in a safe or dangerous way. Detection mechanisms are software enabled in the context of complex systems (involving microcomputers).
- SFF=1-$\lambda_{du}/\lambda_{total}$; $\lambda_{total} = \lambda_{du} + \lambda_{dd} + \lambda_{su} + \lambda_{sd}$

Architectures III
- 1oo1D -

- Single channel system with additional diagnostics capability
- If a failure is detected by the diagnostics part the safety function will provide its specified output.



Source:
Goble, Control Systems
Safety and Reliability

Where are we?

- We know that there are computer architectures that can improve the quality of the safety function
  - We need to know this early on since those architectures could add cost and additional effort in HW and SW design
  - If safety needs to be certified we need to go by some recommended functions
  - Safety function integrity can be imroved by the means of detection mechanisms (software)

Systematic Failures

- Depending on the SIL level under consideration the design process might be more rigorous
- A safety function always comes with a real-time requirement – the fault detection response time – which is the hard deadline until a fault which might lead to a dangerous failure must be detected

Functional Requirements

Functional Requirement

Core system function used to fulfill the system purpose – we ask what must the system do?

- Inputs and associated outputs (valid inputs, invalid inputs, warnings, errors)
- Formats for I/O
- User Interfaces and different roles (technician, customer, …)
- States of the system (operational, error)
- Failure modes

Functional Requirements Capture

Look at system as black-box

- Look at what it interacts with
  Other systems, devices, users (identified as user-roles)
  UML: use case diagram
- Look at how it interacts
  Data flow, control
  UML: sequence diagram
- Traditional, basic form: textual, according to some template or standard form (text document, unique ID)
- Model-based form: use case and sequence diagrams (UML) + textual description

Functional Requirements
- Textual Examples -

“The system shall connect to a pressure sensor with 4 – 20 mA interface.”

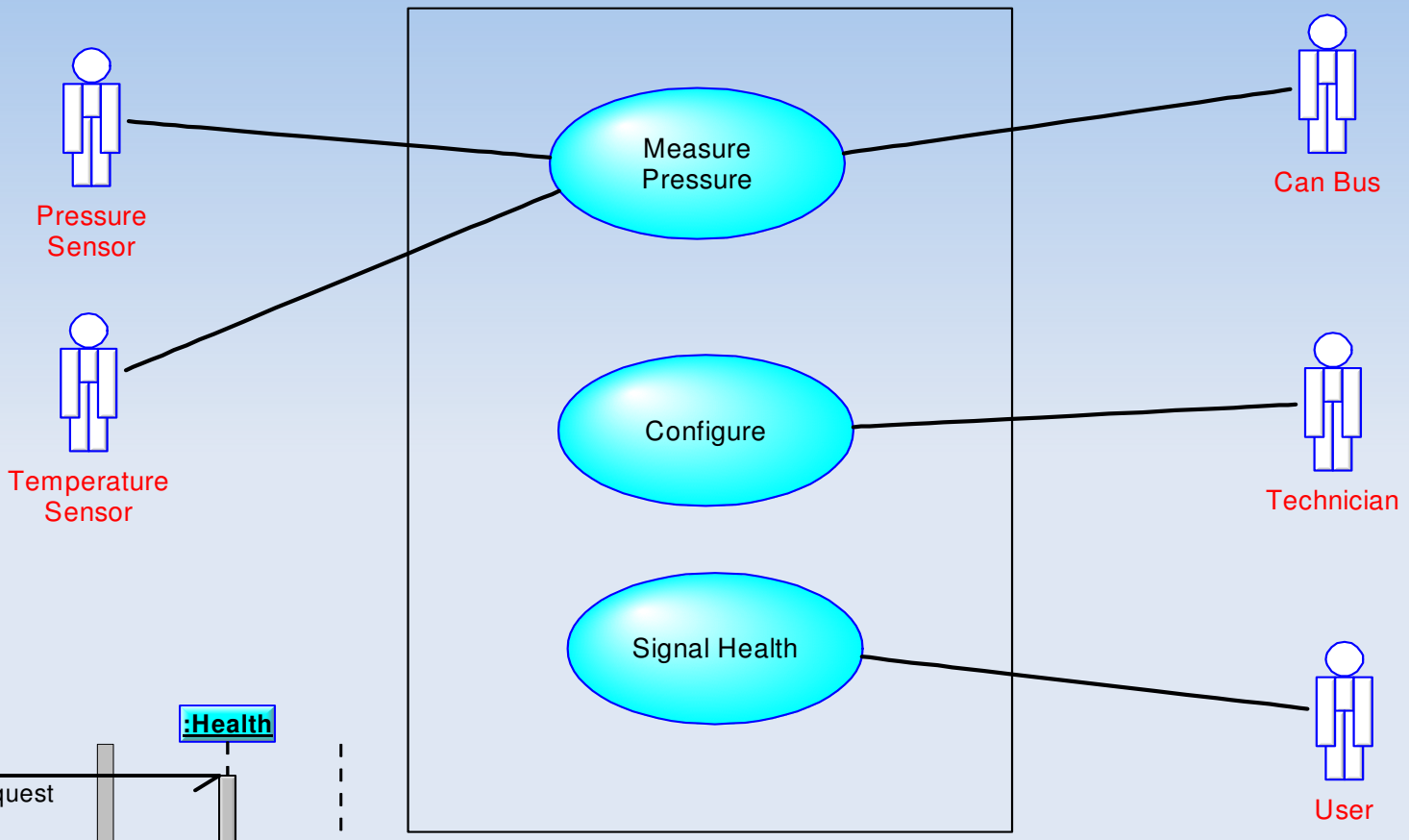
“The system shall not supply power to the pressure sensor.”

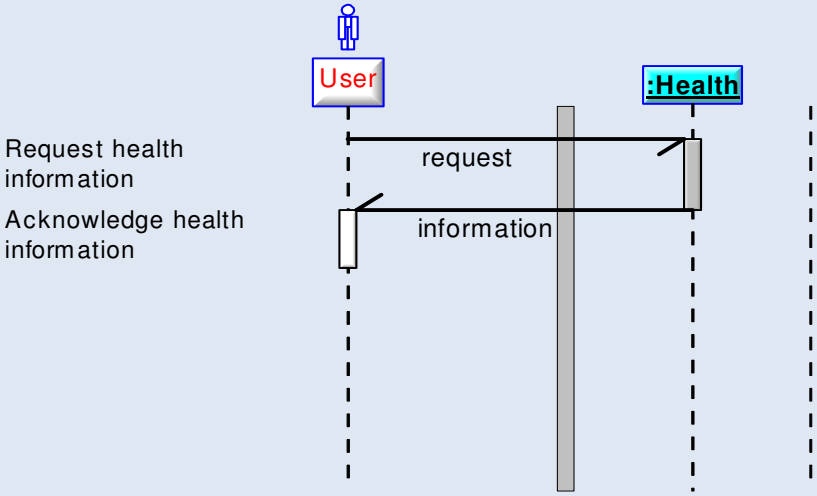
“The system shall indicate a violation of input range by an “out of range” error message according to [*std. xyz.*] if the current input is less than 5 mA or more than 19 mA.*”*

*“*All pressure readings shall be communicated via the CAN bus.”

“All pressure readings shall be communicated according to [*std. xyz*]”

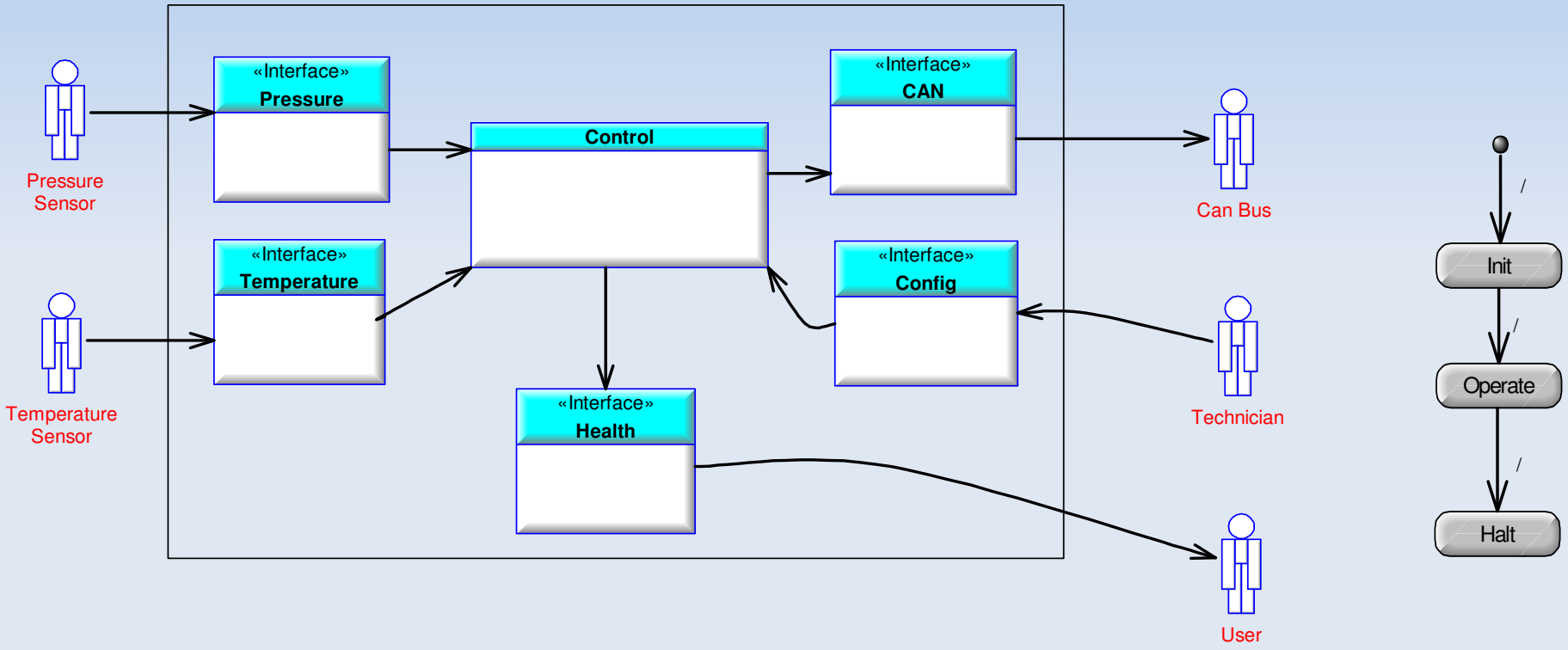
Functional Requirements
- Model Driven Development (MDD) Example -





- Functional View
- Actors = external users or devices
- Use cases = functions

MDD Example II



Non-Functional Requirements

Non-Functional Requirement

Constraints on implementation – How should the system be?

Includes

- Global constraints that influence system as a whole (shock, vibration, temperature,…)
- Function performance (response time, repeatability, utilization, accuracy)
- The “-ilities” (reliability, availability, safety, security, maintainability, testability, …)
- Other quality (ease of configuration and installation, …)

Non-Functional Requirements Capture

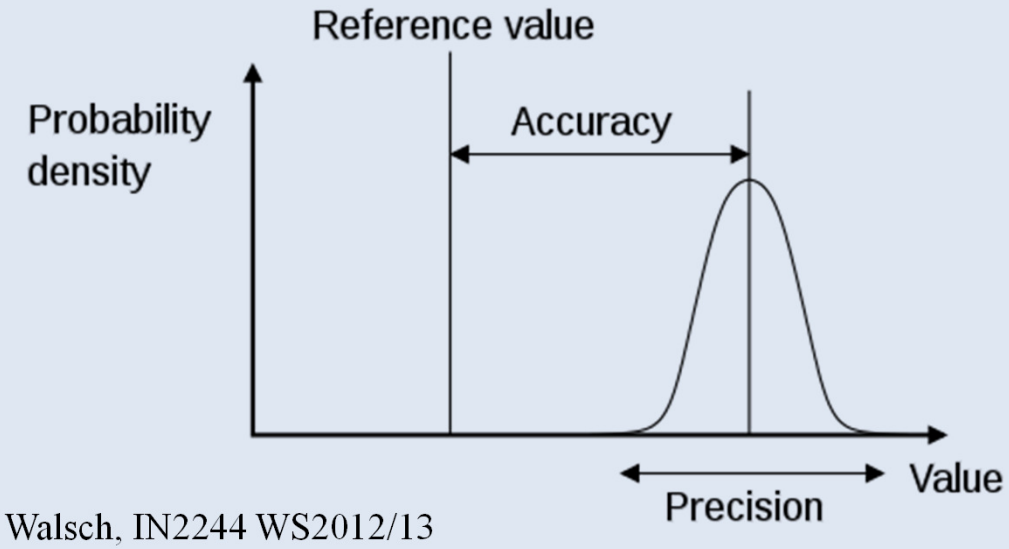
Look at system as black-box

- Look at real-time aspects
  e.g. response time
- Data quality
  accuracy, precision, sampling rate
- Refine functional requirements – make more specific and testable
- Look at comparable systems (prior art, competitors)
- Look at new laws or regulations (e.g. disasters – Fukushima, Deepwater Horizon)
- Safety and reliability

Non-Functional Requirements
- Textual Examples -

“Pressure samples shall be taken every 1s.”
“The response time for pressure measurement shall be less than 10ms.”
“Reliability: 1000 FIT”
“The measurement shall have an accuracy of 2%.”
“The measurement shall be repeatable with a precision not less than 0.5%.”
“The system shall meet the safety criteria according to [std.].”

Source: wikipedia



A final Look at Requirements

- Validity
  Does the system provide the functions which the customer expects?
- Consistency
  Are there any requirements conflicts?
- Completeness
  Are all functions required by the customer included? Are more functions included?
- Realism
  Can the requirements be implemented given available budget and technology -> feasibility?
- Verifiability
  Can the requirements be tested?

Traceability

Traceability

Traceability is concerned with the relationships between requirements, their sources and their design implications. Traceability can be a requirement itself.

- Source traceability
  - Links from requirements to stakeholders who proposed these requirements
- Requirements traceability
  - Links between dependent requirements
- Design traceability
  - Links from the requirements to the design

Requirements Specification Structure

Typical document layout:

Requirement Specification

1. Objective
2. System Description (boundary, interfaces, major components)
3. Functional Requirements
4. Non-functional Requirements
5. Mechanical Constraints
6. Environmental Constraints
7. RAMS (safety in a sperate document)

All requirements get numbers which allow forward and backwards tracing.

Questions?