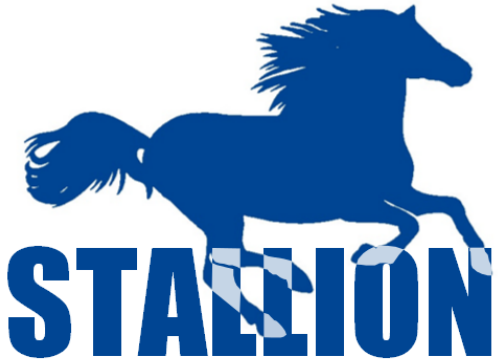


Supporting the deployment of safe Li-ion stationary batteries for large-scale grid applications

Risk assessment of the battery system

F. J. Soares, INESC Porto Jos van der Burgt, DNV GL

Düsseldorf, 10 March 2015

INESC Technology and Science (former INESC Porto)

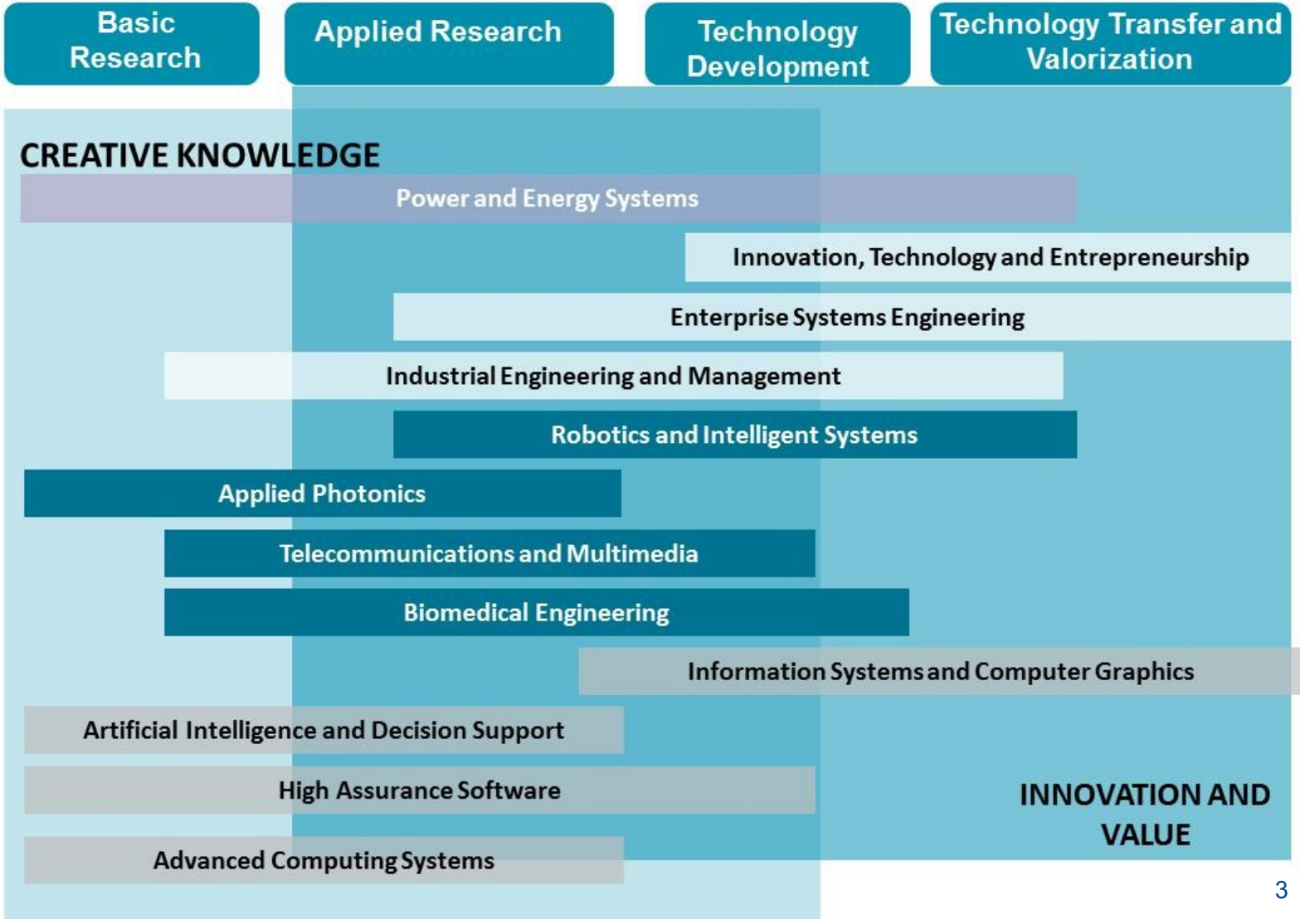
INESC TEC is an Associate Laboratory with 30 years of experience in R&D and technology transfer. It incorporates 12 R&D Centres and one Associate Unit with complementary competences.

INESC TEC mission is to advance science and deploy high technology in the service and industrial sectors by creating and spawning research teams who perform science based innovation.

INESC TEC brings together more than 800 collaborators, of which around 300 have PhDs, forming a robust cluster with complementary skills and with notable international presence.

INESC Technology and Science

R&D Centers position along the value chain



Risk Analysis – Methodology

1. **Risk Identification**
   → Risks that may appear in each stage of the battery life cycle;

2. **Risk Evaluation** → Qualitative evaluation of the risks;

3. **Recommended Mitigation Measures**
   → Safety measures to mitigate the risks;

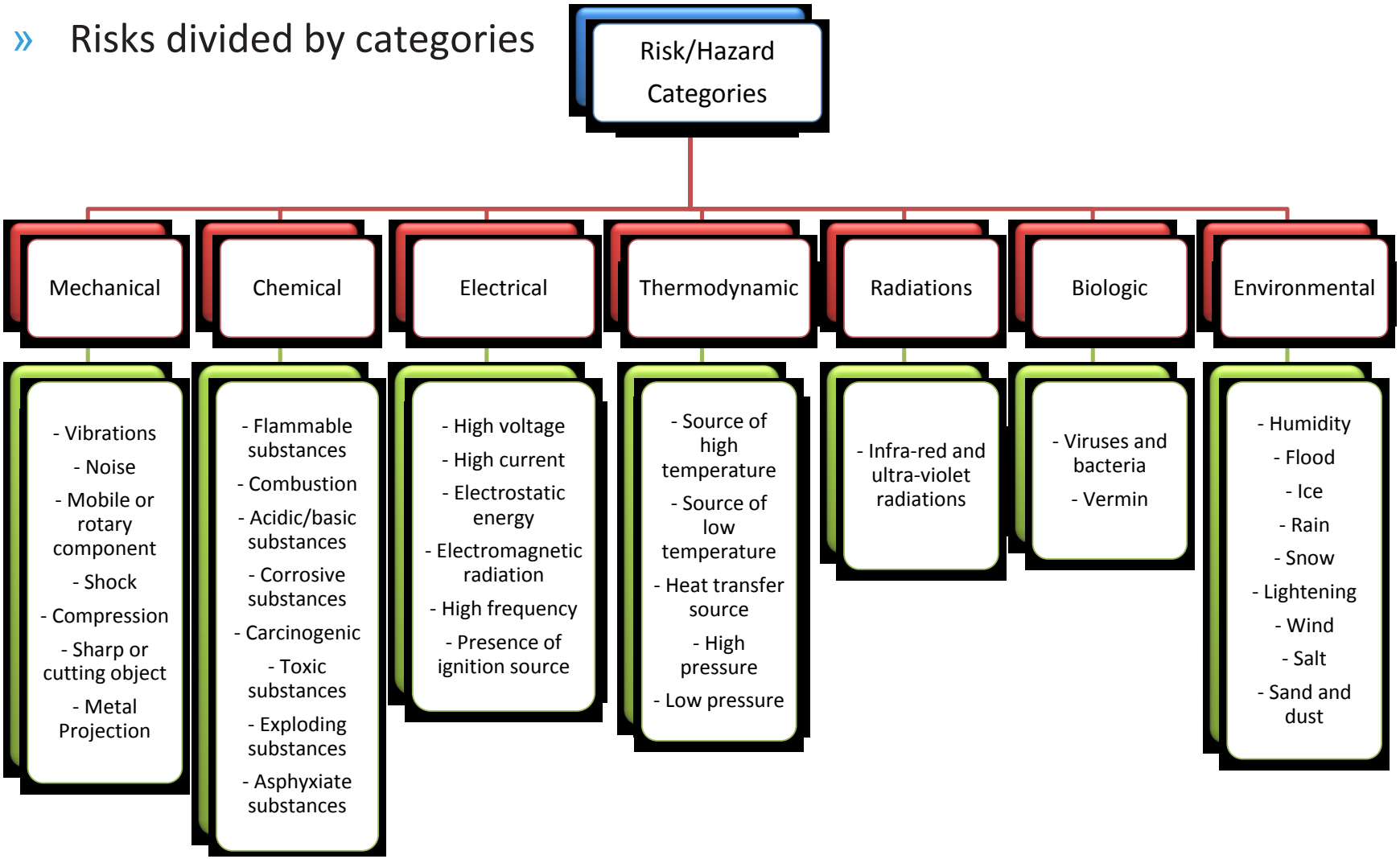
4. **Risk Re-evaluation** → Qualitative evaluation of the risks assuming that the recommended mitigation measures were implemented.

1. Risk Identification

- Results obtained from surveys made to the STABALID partners
- Literature review
- Expertise of specialized staff of SAFT, INERIS, TÜV and EDPD

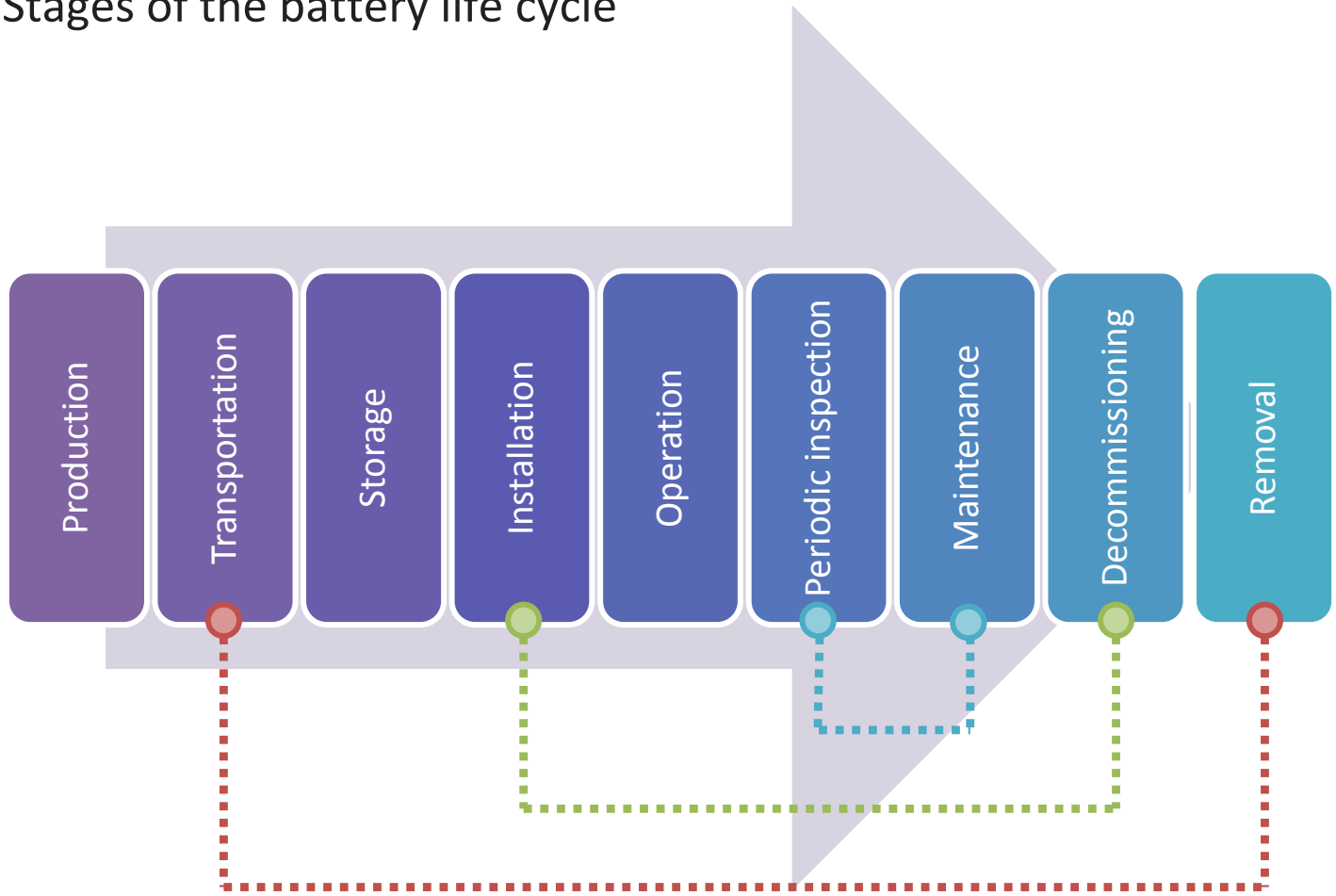
1. Risk Identification

» Risks divided by categories



1. Risk Identification

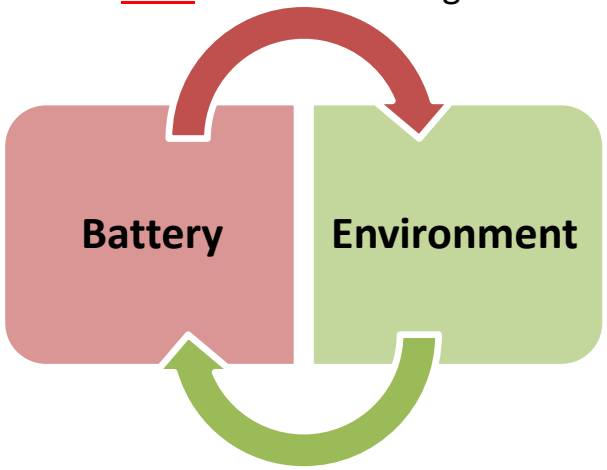
» Stages of the battery life cycle



1. Risk Identification

- Two analyses were made for each stage of the battery life cycle:
  - Internal problem analysis
  - External peril analysis

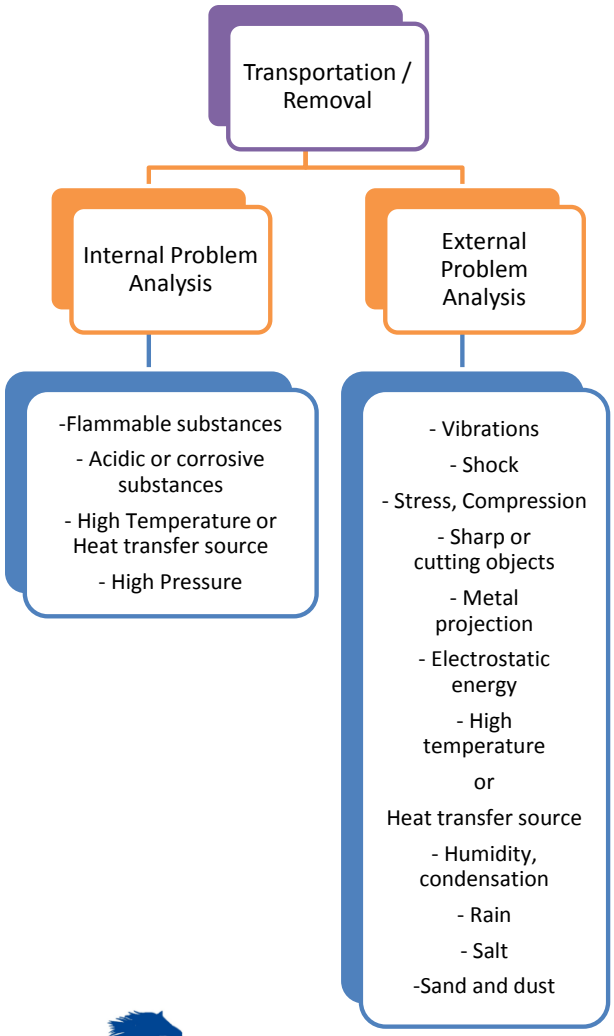
Internal problem **analysis**
(aggression **over** the surrounding environment)

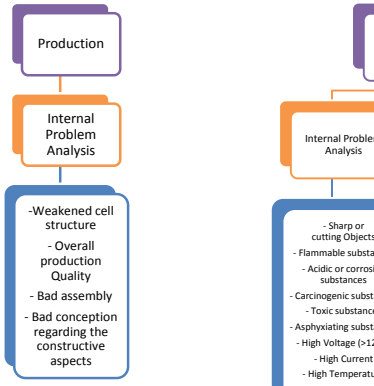


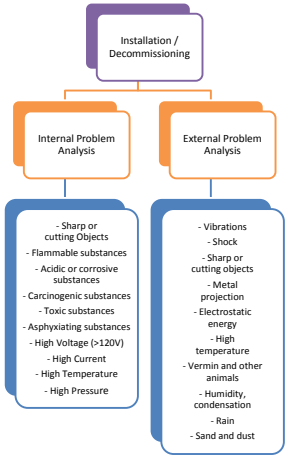
External peril **analysis**
(aggression **from** the surrounding environment)

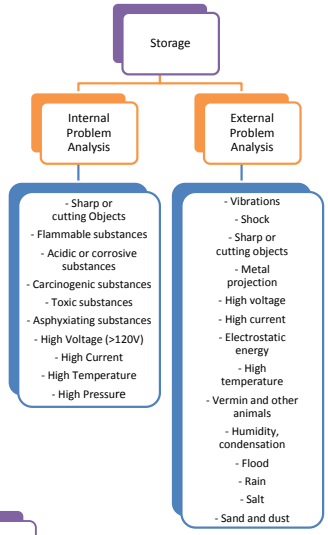
1. Risk Identification

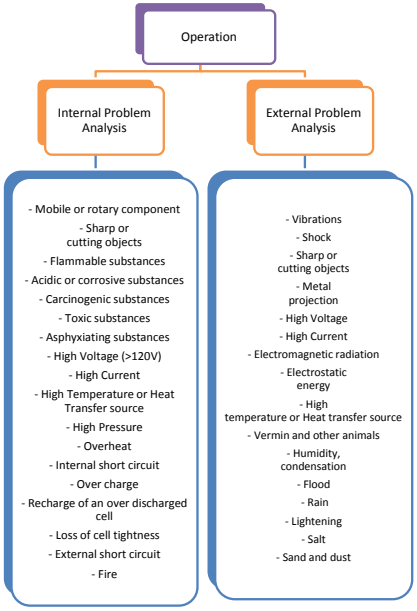
» Risks were mapped in the battery life cycle stages

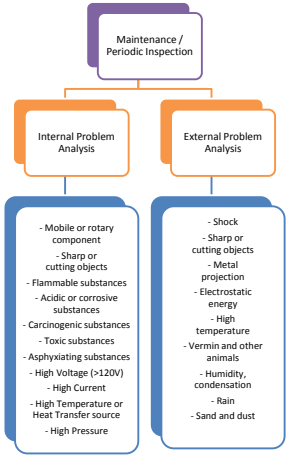












2. Risk Evaluation

» Risks probability of occurrence (P) and severity (S) were defined upon agreement with project partners

Level	Probability
1	$P \leq 10^{-9}/h \rightarrow$ Improbable Event
2	$10^{-9} < P \leq 10^{-7}/h \rightarrow$ Remote Event
3	$10^{-7} < P \leq 10^{-5}/h \rightarrow$ Occasional Event
4	$P > 10^{-5}/h \rightarrow$ Probable Event

Level	Severity	Description
1	Minor	• Slight degradation of battery performance → the owner can still use the battery • Maintenance operation is advisable, but not mandatory → limited cost impact • Low risk for user or operator → small reduction in safety conditions
2	Major	• Considerable degradation of battery performance → the owner can still use the battery but a quick maintenance is requested • Low risk for user or operator → important reduction in safety conditions
3	Hazardous	• The battery is out-of-service → possibility of significant damage on the battery • Immediate maintenance is mandatory → significant intervention cost • Low risk for user or operator (possible injury) → large reduction in safety conditions
4	Catastrophic	• The battery is out-of-service → major damage on the battery • Significant risk for user or operator (significant or fatal injury) or important environmental degradation

RA		S			
		1	2	3	4
P	1	Acceptable	Acceptable	Acceptable	Tolerable
	2	Acceptable	Acceptable	Tolerable	Intolerable
	3	Acceptable	Tolerable	Intolerable	Intolerable
	4	Tolerable	Intolerable	Intolerable	Intolerable

2. Risk Evaluation

» Example of the Transportation/Removal stages
→ Internal Problem Analysis

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA
Vibrations	Container	During transportation the battery container is subjected to vibrations	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable
Shock or drop	Container	During transportation the battery container is subjected to shock or drop	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable
	Module or Cell	Shock against a heavy object or drop	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable
			Asphyxiating gas, carcinogenic substance or Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	4	Intolerable
			Module fire	Equipment in proximity	Fire propagation	3	4	Intolerable
Stress, Compression	Container	During transportation the battery container can be subjected to compression	Deformation of the battery container	Pilling up of other containers upon it	Crush of the battery container	4	4	Intolerable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable
	Module or Cell	Impact against a heavy object	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Intolerable
			Asphyxiating gas, carcinogenic substance or Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	4	Intolerable
			Module fire	Equipment in proximity	Fire propagation	3	4	Intolerable
Metal projection	Container	Projection of a metallic object against the battery container	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable

3. Recommended Mitigation Measures

» A set of 43 risk mitigation measures were proposed

	Description	Classification	Risk/Undesirable Event
RMM01	Determine the nature, volume and toxicity of the gas generated inside the battery container in case of gases being liberated from cells	Analysis and test	Intoxication and asphyxia
RMM02	Carry out analyses to show that in case of cell overpressure, the cells venting is correctly functioning	Analysis and test	Cell venting
RMM03	Carry out analyses to identify the risk of electrical hazards due to carbon powder release (safety distance to avoid the creation of electrical arcs)	Analysis	Pollution of surrounding equipment
RMM04	Implement a thermal barrier against thermal runaway propagation between cells inside the module in case of fire on one cell	Thermal protection	Fire propagation
RMM05	Implement a thermal barrier to avoid fire contamination outside the module in case of fire on one cell	Thermal protection	Fire propagation
RMM06	Define a procedure for checking the defects during cell assembling	Quality check	Cell internal short circuit
RMM07	Carry out experiments to determine the conditions which lead to fire in case of cell internal short circuit	Analysis	Cell internal short circuit
RMM08	Carry out analyses to determine the level of leaking current corresponding to an internal short circuit on a cell	Test	Cell internal short circuit
RMM09	Use an electronic board design which avoids fire contamination on cell in case of short circuit on the board	Electronic protection	Fire propagation
RMM10	Carry out a DFMEA[1] analysis on battery container internal short circuit in order to determine the type of short circuit from which the container should be protected	Analysis	Battery internal short circuit
RMM11	Conceive a design that minimises the risk of insulation failure	Design	Insulation failure
RMM12	Use electronic boards specifically designed to avoid corrosion	Design	Corrosion
RMM13	Disable the fire detection system before entering inside the container	Rule	Asphyxia

3. Recommended Mitigation Measures

» A set of 43 risk mitigation measures were proposed

	Description	Classification	Risk/Undesirable Event
RMM14	Establish a visual verification of the battery container during the production phase	Quality check	Cuts and other injuries (due to sharp or cutting objects)
RMM15	Find out, according to the empty space existing in the battery container, the air leak and the result of RMM01, the acceptability of the substances released in case or thermal runway, venting or leaking cell; Calculate the maximum number of cells below which the concentration of asphyxiating, toxic, carcinogenic and flammable substances is not hazardous	Calculation	Burnt and fire propagation (due to flammable substances)
RMM16	Depending of the result of the RMM15, the battery container size should be enough to create a sufficient air renewal and stay below the hazardous concentration of flammable substances threshold	Calculation	Burnt and fire propagation (due to flammable substances)
RMM17	The maintenance and installation operators have to be qualified, strictly follow the maintenance and installation protocols and wear IPE[1]	Rule	Intoxication, electrical shock and burnt (due to carcinogenic, toxic or asphyxiating substances release or high voltage or current)
RMM18	The battery container installation on customer site has to be done by qualified operators only	Rule	Electrical shock and burnt (due to high voltage or current)
RMM19	The battery container has to be equipped with a safety valve in order to avoid overpressure	Mechanical protection	High pressure
RMM20	Establish a visual inspection of the container once arrived on customer site	Quality check	Shock, metal projection and sharp or cutting object
RMM21	Install a shock sensor inside the battery container in order to see if the container has been submitted to any significant shock during transportation	Mechanical protection	Shock, metal projection and sharp or cutting object

3. Recommended Mitigation Measures

» A set of 43 risk mitigation measures were proposed

	Description	Classification	Risk/Undesirable Event
RMM22	The storage site should be a safe place with restricted access to reduce the probability of shock occurrence	Storage instruction	Shock, metal projection and sharp or cutting object
RMM23	The place where the battery will be installed should have a restricted access	Rule	Shock, metal projection and sharp or cutting object
RMM24	The module transportation has to be done in a solid closed box with no direct or easy access	Transportation Instruction	Shock, metal projection and sharp or cutting object
RMM25	The temperature on the environment external to the battery system and modules must be lower than the maximum allowable	Storage instruction	High temperature
RMM26	During preventive maintenance the battery container gaskets have to be checked	Storage instruction	Vermin and other animals
RMM27	The modules should not be directly installed on the ground without adequate protection	Rule	Vermin and other animals
RMM28	Use a system inside the battery container to control the humidity level during transportation	Transportation Instruction	Humidity
RMM29	Perform field studies before the container installation, to avoid install it on areas subjected to flood	Field study	Flood
RMM30	Protect the metallic structure of the container against corrosion, e.g. using corrosion-proof paint	Design	Corrosion
RMM31	Follow the preventive maintenance plan for modules as spare part (do not recharge them after an over discharge)	Rule	Charge after an over discharge (modules in storage)
RMM32	Preventive maintenance actions to verify the battery container paint (scheduled according to the external environment characteristics)	Rule	External aggressions
RMM33	Protect each battery module and battery system metallic part against corrosion	Design	Corrosion
RMM34	During assembling phases (cells and modules) verify if each connection is correct	Verification	Short circuit

3. Recommended Mitigation Measures

» A set of 43 risk mitigation measures were proposed

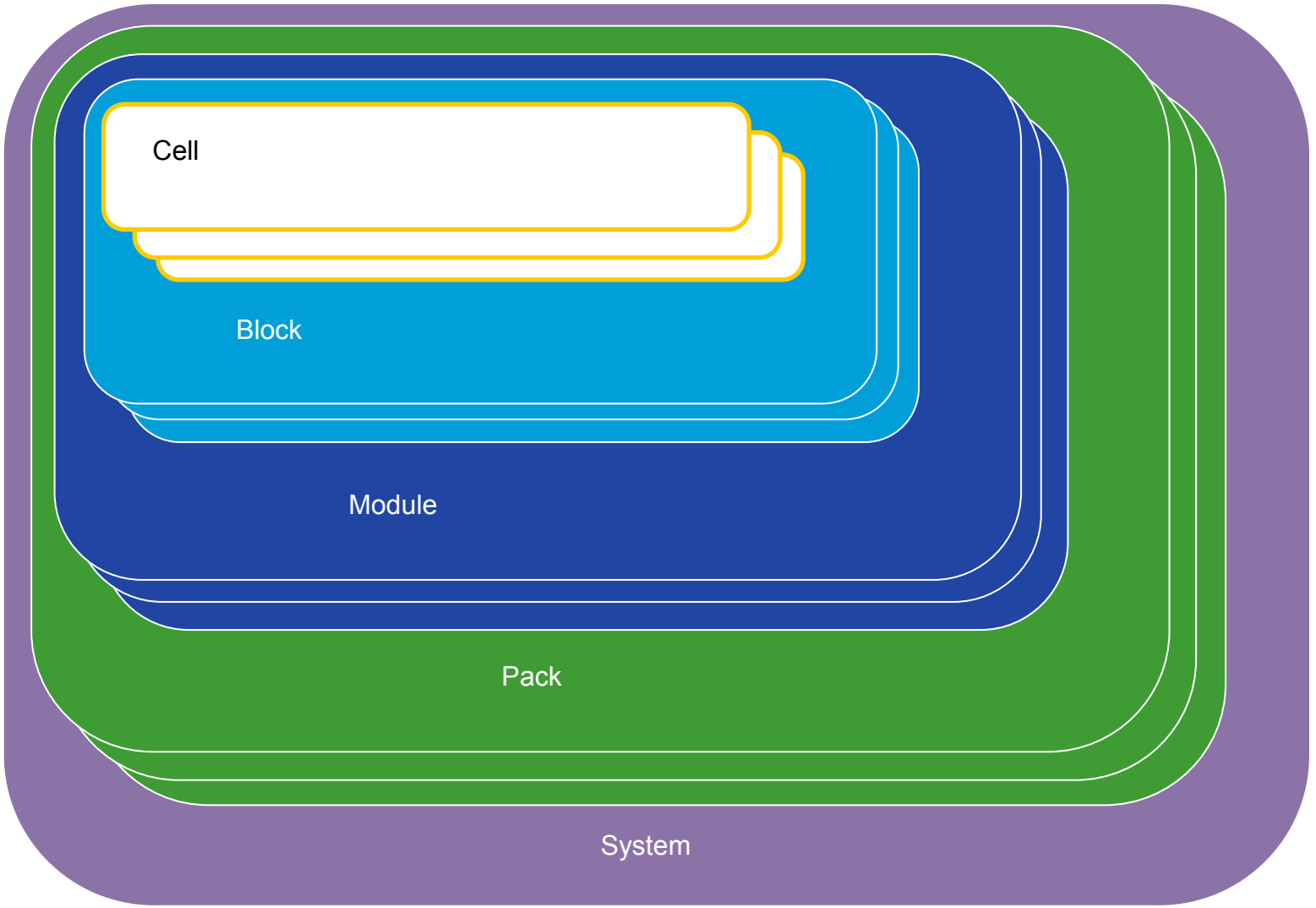
	Description	Classification	Risk/Undesirable Event
RMM35	Strictly follow the maintenance and user manuals	Maintenance and usage instructions	High voltage or current
RMM36	Use ESD[1] protection equipment during electronic board handling	Maintenance and installation instructions	Electrostatic energy
RMM37	Implement an electronic protection against cell overheat	Electronic protection	Cell overheat
RMM38	Implement an electronic protection against overcharge on cell (to stop charge/discharge if a cell reach the maximum voltage value)	Electronic protection	Cell overcharge
RMM39	Implement an electronic protection against cell charge after an over discharge	Electronic protection	Charge after an over discharge
RMM40	Implement on the battery an electronic protection against overheating on battery	Electronic protection	Overheat on battery
RMM41	Implement on the battery an electronic and electrical protection against short circuit and overload to avoid fires	Electronic/Electrical protection	Battery internal short circuit/overload
RMM42	Perform electromagnetic studies during assembling to minimize the damage from electromagnetic radiation	Analysis	Electromagnetic radiation
RMM43	Provide test results during cell voltage inversion at nominal discharge current (200A/module) in order to verify there is no dangerous phenomenon	Test	Cell inversion

4. Risk Re-evaluation

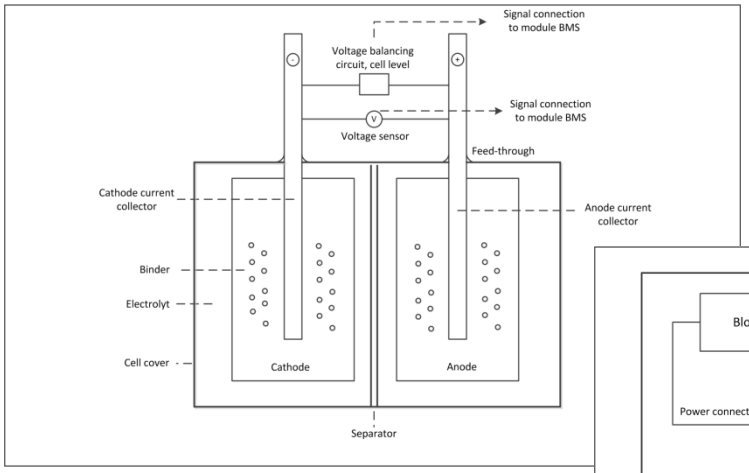
» Example of the Transportation/Removal stages
→ Internal Problem Analysis

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Vibrations	Container	During transportation the battery container is subjected to vibrations	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM26 RMM32	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable
Shock or drop	Container	During transportation the battery container is subjected to shock or drop	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM21 RMM26 RMM32	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable
	Module or Cell	Shock against a heavy object or drop	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable
			Asphyxiating gas, carcinogenic substance or Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	4	Intolerable	RMM02 RMM03 RMM24	1	3	Acceptable
			Module fire	Equipment in proximity	Fire propagation	3	4	Intolerable	RMM04 RMM05 RMM24	1	3	Acceptable
Stress, Compression	Container	During transportation the battery container can be subjected to compression	Deformation of the battery container	Pilling up of other containers upon it	Crush of the battery container	4	4	Intolerable	RMM20 RMM26	1	4	Tolerable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM21	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable
	Module or Cell	Impact against a heavy object	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Intolerable	RMM12 RMM24 RMM33	2	2	Acceptable
			Asphyxiating gas, carcinogenic substance or Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	4	Intolerable	RMM02 RMM03 RMM24	1	3	Acceptable
			Module fire	Equipment in proximity	Fire propagation	3	4	Intolerable	RMM04 RMM05 RMM24	1	3	Acceptable
Metal projection	Container	Projection of a metallic object against the battery container	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM21	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable

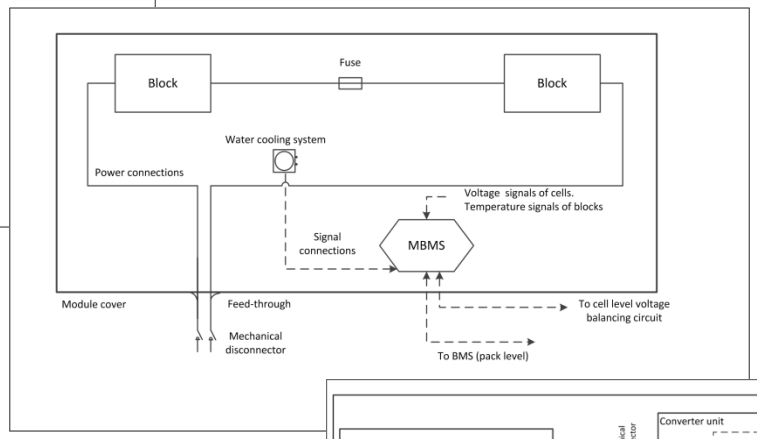
STALLION FMECA – Sub-system level approach



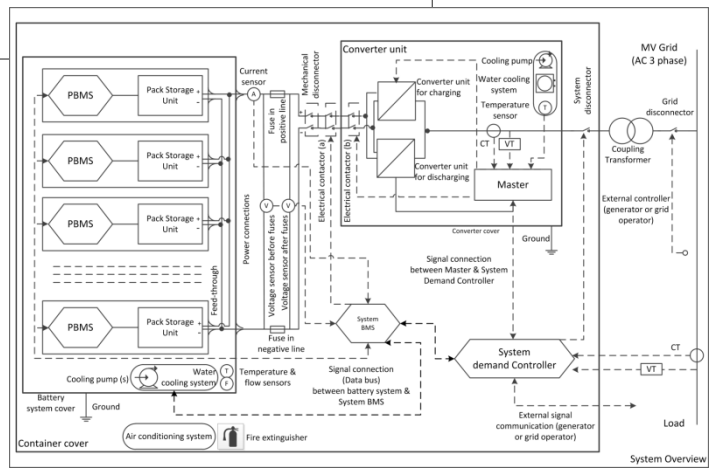
System hierarchy



Cell



Module



System

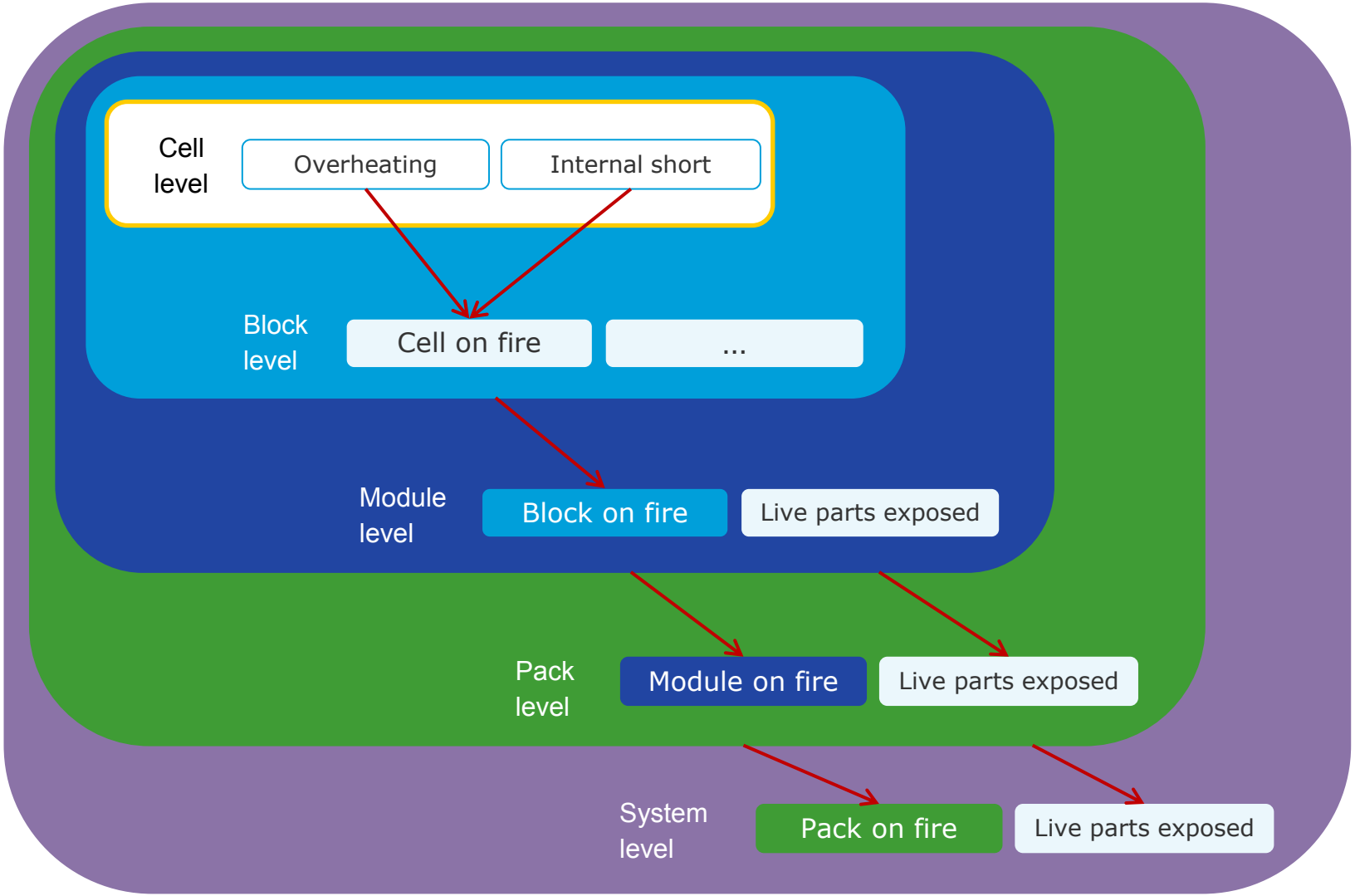
Probability

» Probability = *function* (initial failure rate, failure of present measures, number of components)

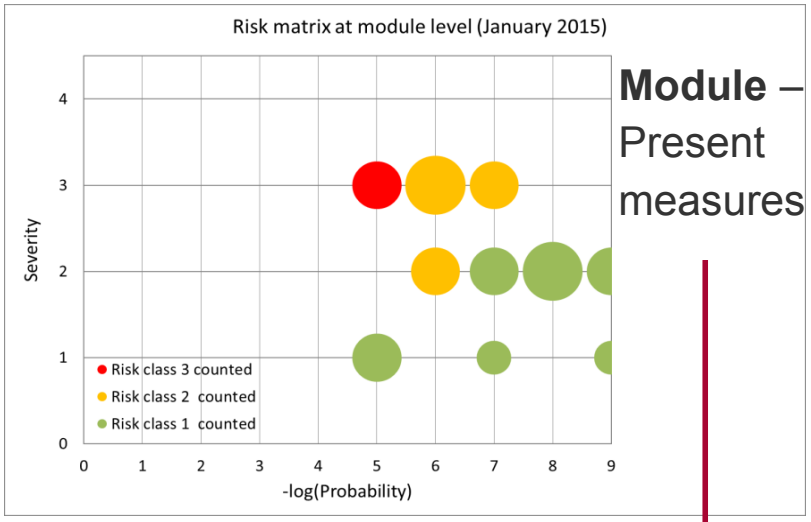
	# cells per level	# blocks per level	# modules per level	#packs per level
cell				
block	7			
module	14	2		
pack	224	32	16	
system	28000	4000	2000	125

RA		S			
		1	2	3	4
P	1	Acceptable	Acceptable	Acceptable	Tolerable
	2	Acceptable	Acceptable	Tolerable	Intolerable
	3	Acceptable	Tolerable	Intolerable	Intolerable
	4	Tolerable	Intolerable	Intolerable	Intolerable

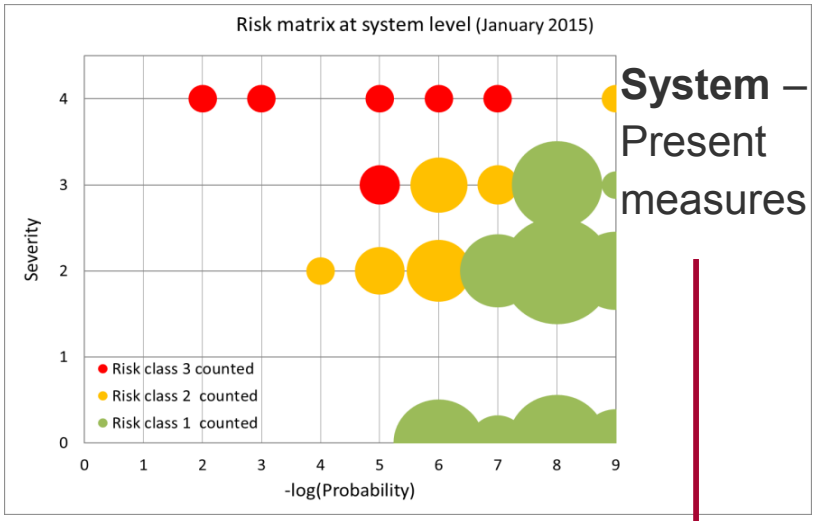
Failure propagation



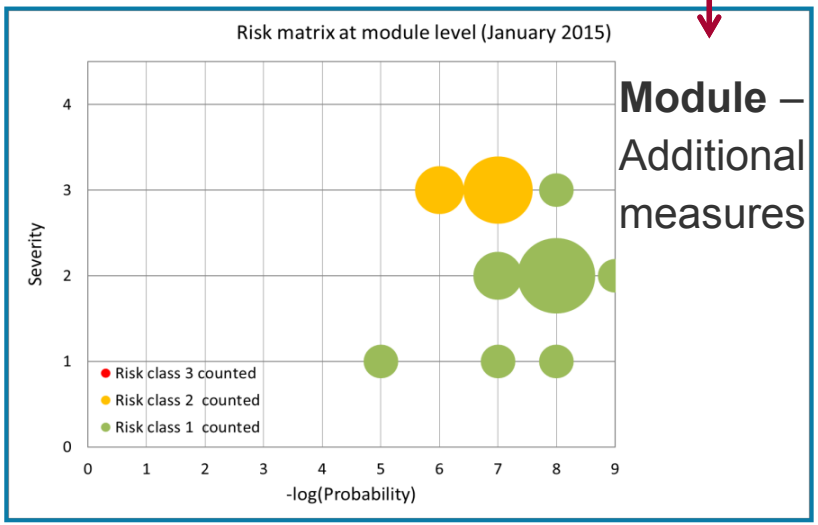
FMECA results



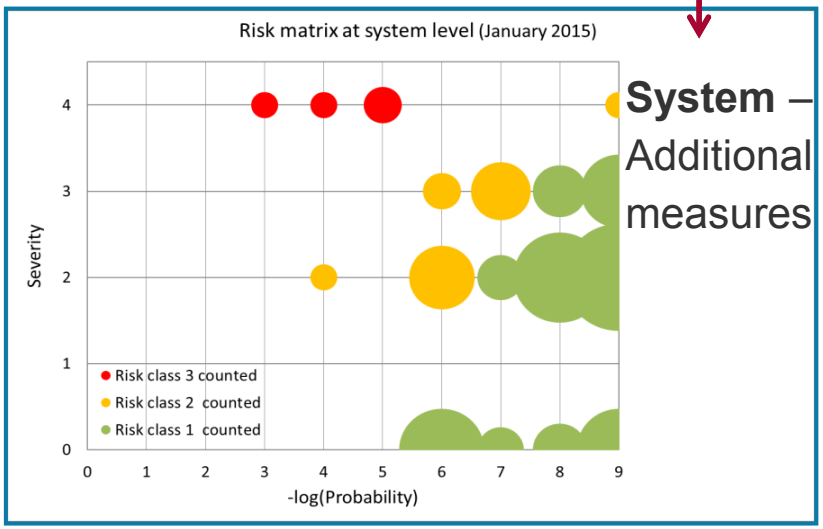
Module – Present measures



System – Present measures



Module – Additional measures



System – Additional measures

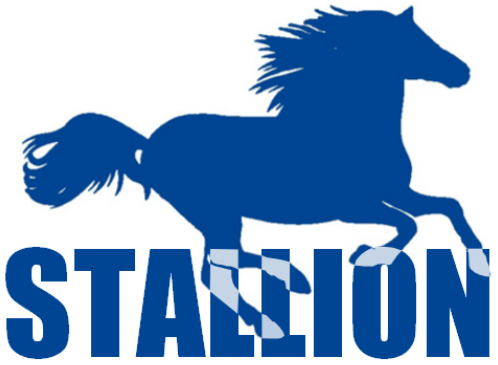
Conclusions review STALLION FMECA

Risk class 3 failures per level, 2015

System level	Pack level	Module level	Block level	Cell level
		(No risk class 3 failures)	(No risk class 3 failures)	(No risk class 3 failures)
Pack on fire	Module on fire	←	←	←
Release of poisonous gas from pack	←	←	←	←
Release of explosive gas from pack	←	←	←	←
Electrocution by live contact with pack	←	←	←	←
	No sufficient gas flow from cooling tubes			

Risk assessment – Conclusions

- **Risk of fire propagation:**
  - Start with safe materials/cells – fit for application → presentation
  - Apply thermal barrier between cells in module and between modules
  - More data from cell manufacturer is needed, e.g. runaway inception temp
  - Venting tests to quantify cell venting risk
- **Risk of release of explosive gas or poisonous gas:**
  - Apply detector for toxic and/or flammable gases
- **Risk of electrocution:**
  - Provide strict handling/maintenance procedures, PPE (the human factor)
- **General design rules for safe system**
  - BMS safety functions should be redundant
  - Apply UPS for BMS if battery is empty and off-grid
  - Fail-safe mode of all electronics
- **STABALID-STALLION test procedures:**
  - Extra tests for certain safety issues → presentation
  - Perform location study for risk of flooding



Supporting the deployment of safe Li-ion stationary batteries for large-scale grid applications

Thank you!

Risk assessment of the battery system

F. J. Soares, INESC Porto
fsoares@inescporto.pt

Jos van der Burgt, DNV GL
Jos.vanderburgt@dnvgl.com

Düsseldorf, 10 March 2015