Supplementary Material

Title: Practical incorporation of lifecycle flexibility into products at their early development stage

Authors: Oliver Moerth-Teo, Richard de Neufville, Eun Suk Suh, Christian Ramsauer

Workshop data: Criticality assessment of uncertainty effects

Group A (Department focus: Design engineering)

Uncertainty effects	Severity	Occurrence	Responsiveness	Effect criticality
Change of product requirements	8	10	9	**720**
Change of production requirements	7	10	5	**350**
Change of cell type or technology: Impacting entire pack	10	4	8	**320**
Failure of supplier of cells / modules: Requiring substitution	10	3	9	**270**
Failure of supplier of electronics: Requiring substitution	8	4	7	**224**
Fluctuation of required production volume of battery packs	8	7	4	**224**
Change in technical solutions	4	10	5	**200**

Group B (Department focus: Product quality and lifecycle management)

Uncertainty effects	Severity	Occurrence	Responsiveness	Effect criticality
Change of product requirements	8	7	7	**392**
Failure of supplier of cells / modules: Requiring substitution	8	6	8	**384**
Change of geometry of battery packs	8	6	8	**384**

Group C (Department focus: Production and supply chain)

Uncertainty effects	Severity	Occurrence	Responsiveness	Effect criticality
Increase of usage of solid-state cells	8	6	8	**384**
Change of product requirements	8	6	7	**336**
Change of production requirements	8	6	7	**336**
Change of requirements for subsystems or components	8	6	7	**336**
Change of cell type or technology: Impacting entire pack	8	6	7	**336**
Introduction of new battery pack models: New production system	8	6	7	**336**
Failure of supplier of cells / modules: Requiring substitution	6	5	8	**240**
Change of cell type or technology	9	3	8	**216**

Group D (Department focus: Systems engineering)

Uncertainty effects	Severity	Occurrence	Responsiveness	Effect criticality
Change of cell type or technologies: Impacting entire pack	7	8	6	**336**
Failure of supplier of cells / modules: Requiring substitution	10	2	10	**200**
Failure of supplier of electronic components: Requiring substitution	8	3	7	**168**
Failure of supplier of sheet metal bending or welding constructions: Requiring substitution	8	3	7	**168**
Failure of battery pack production	8	3	7	**168**
Change of geometry of other battery pack elements	8	3	7	**168**
Change of geometry of cells / modules – production phase	10	2	8	**160**
Increase of energy density of cells, modules and packs	10	2	8	**160**
Change of cell type or technology: Impacting entire pack	10	3	5	**150**

Workshop data: Relevance assessment of flexibility measures

Group A (Department focus: Design engineering)

Flexibility measures	Cost (20%)	Time (50%)	Quality (30%)	Flex-relevance
Continuous coordination of the supply chain	9	10	8	9.2
Increased accuracy of sales forecasts for improved production planning	8	10	7	8.7
Early definition of scope of the development project (requirements, resources, time frame, quality gates)	7	10	7	8.5
Standard cell geometries for interchangeability	6	10	6	8.0
Derivation of subsystem designs from high-level specifications (top-down approach)	5	10	6	7.8
Standard components for interchangeability	8	8	7	7.7
Storage of critical components for demand peaks	3	10	7	7.7
Combined development of the electric vehicle and battery pack (purpose design)	3	10	4	6.8
Extended period of sales forecasts for improved production planning	8	5	8	6.5
Standard module geometries for interchangeability + Universal modules for integration of different cell types	3	8	4	5.8
Multiple design solutions that are successively narrowed down (set-based design)	4	7	3	5.2
Multi-sourcing of cells and modules	4	4	7	4.9

Group B (Department focus: Product quality and lifecycle management)

Flexibility measures	Cost (20%)	Time (50%)	Quality (30%)	Flex-relevance
Early and complete definition of product requirements	8	8	8	**8.0**
Standard cells and modules for interchangeability	8	8	8	**8.0**
Requirements and change management	8	8	7	**7.7**
Feasibility evaluation of the fulfillment of demanded requirements from stakeholders before the actual commitment through a virtual concept study	7	7	8	**7.3**
Alignment of supplier lot sizes to actual demand	6	6	5	**5.7**
Production system for different battery pack geometries	4	7	5	**5.3**
Definition of alternative suppliers in advance (backup)	4	7	4	**5.0**

Group C (Department focus: Production and supply chain)

Flexibility measures	Cost (33%)	Time (33%)	Quality (33%)	Flex-relevance
Universal modules for the integration of different cell types	8	8	10	**8.7**
Standardization of all components and subsystems	8	8	10	**8.7**
Adaptable designs of battery packs and modules for the integration of solid-state cells	8	8	10	**8.7**
Adaptable designs of battery packs and modules for the integration of different cell types	8	8	10	**8.7**
Decision support based on reasonable, reliable, and quantitative information	4	8	10	**7.3**
Simultaneous engineering (closed loop between development and production)	6	7	8	**7.0**
Multi-sourcing of cells and modules	8	8	4	**6.7**
Early definition of production system requirements	4	6	8	**6.0**
Consideration of alternative manufacturing technologies (at the early product development stage)	4	4	8	**5.3**
Preparation of options for supplier failures	4	7	4	**5.0**
Integration of innovative features into the battery pack	4	6	5	**5.0**

Group D (Department focus: Systems engineering)

Flexibility measures	Cost (33%)	Time (33%)	Quality (33%)	Flex-relevance
Reduction of different components within the battery pack design (usage of standard components)	8	9	8	**8.3**
A-sample design (early development phase) of battery pack or modules based on complete B-sample of cells (subsystems need higher maturity)	8	8	8	**8.0**
A-sample design (early development phase) of battery pack or modules based on cell performance evaluation	8	8	8	**8.0**
Universal battery packs design for different vehicles	8	8	8	**8.0**
Overdesign of measurements system in production based on performance forecasts	7	8	8	**7.7**
Standard module geometries for interchangeability + Universal modules for the integration of cells with different performances	7	8	8	**7.7**
Gripper in production for different cell geometries	7	8	6	**7.0**
Consistent supplier management (continuous evaluation of suppliers)	4	6	9	**6.3**
Continuous risk assessment of the entire production system	4	6	8	**6.0**
Multiple production lines for related battery pack models	3	7	5	**5.0**
Multi-sourcing of standardized modules	4	6	5	**5.0**

Workshop data: Prioritization order of design objectives

Group A (Department focus: Design engineering)

Design objectives	Impact score [%]	Prioritization order
Product standardization	71	1
Product platform	71	1
Cost saving	71	1
Product simplification	59	4
Product quality	56	5
Manufacturing enhancement	52	6
Assembly enhancement	52	6
Maintenance enhancement	52	6
Reusability / Remanufacturability	52	6
Cooperation and integrability	48	10
Interchangeability	43	11
Product durability	43	12
Product safety	43	12
Product modularization	40	14
Supply availability	35	15
Lifecycle consideration	34	16
Development enhancement	30	17
Product robustness	30	18
Product upgradability	25	19
Product differentiability	23	20
Transport enhancement	22	21
Product overdesign	20	22
Environmental impact reduction	17	23
Recyclability	17	23

Group B (Department focus: Product quality and lifecycle management)

Design objectives	Impact score [%]	Prioritization order
Product standardization	100	1
Product modularization	100	1
Cost saving	83	3
Product quality	75	4
Cooperation and integrability	74	5
Product simplification	72	6
Product platform	60	7
Development enhancement	53	8
Interchangeability	50	9
Supply availability	42	10
Lifecycle consideration	37	11
Product differentiability	36	12
Product durability	33	13
Product safety	33	13
Product overdesign	26	15
Assembly enhancement	22	16
Transport enhancement	22	16
Product upgradability	18	18
Manufacturing enhancement	14	19
Product robustness	8	20
Maintenance enhancement	0	21
Environmental impact reduction	0	21
Recyclability	0	21
Reusability / Remanufacturability	0	21

Group C (Department focus: Production and supply chain)

Design objectives	Impact score [%]	Prioritization order
Cost saving	90	1
Manufacturing enhancement	90	1
Assembly enhancement	90	1
Product standardization	83	4
Product simplification	71	5
Product robustness	57	6
Product modularization	54	7
Lifecycle consideration	54	7
Transport enhancement	51	9
Interchangeability	50	10
Product quality	45	11
Environmental impact reduction	45	11
Recyclability	45	11
Supply availability	44	14
Cooperation and integrability	37	15
Product safety	36	16
Product platform	33	17
Product upgradability	31	18
Maintenance enhancement	31	18
Product durability	30	20
Product overdesign	12	21
Development enhancement	7	22
Reusability / Remanufacturability	5	23
Product differentiability	0	24

Group D (Department focus: Systems engineering)

Design objectives	Impact score [%]	Prioritization order
Product standardization	59	1
Cost saving	52	2
Product simplification	44	3
Supply availability	44	4
Product quality	39	5
Product differentiability	33	6
Product robustness	30	7
Manufacturing enhancement	23	8
Assembly enhancement	23	8
Product modularization	22	10
Product overdesign	22	10
Product upgradability	22	10
Cooperation and integrability	18	13
Product safety	17	14
Interchangeability	17	14
Transport enhancement	15	16
Product platform	10	17
Product durability	10	17
Maintenance enhancement	10	17
Recyclability	10	17
Development enhancement	0	21
Environmental impact reduction	0	21
Reusability / Remanufacturability	0	21
Lifecycle consideration	0	21

Questionnaire data: Support evaluation

Definition of critical uncertainties and effects (Step 1 & 2 of the DFLF guideline)

No.	Questions	Assessment of individual participants													Average
		a	b	c	d	e	f	g	h	i	j	k	l	m	
1.1	The identified uncertainty effects comprehensively consider the lifecycle of battery packs.	4	5	3	4	4	4	4	5	4	5	3	5	5	**4.23**
1.2	The definition of critical uncertainty effects through the presented evaluation (based on FMEA) is practically applicable.	5	5	4	4	5	2	4	5	5	5	4	5	5	**4.46**
1.3	The definition of critical uncertainty effects through the presented evaluation (based on FMEA) is applicable at the early development stage.	5	4	4	4	4	4	4	4	3	5	4	5	4	**4.15**
1.4	The applied evaluation criteria (severity, occurrence, responsiveness) are complete to define critical uncertainty effects.	5	5	5	3	5	5	4	5	5	4	4	5	4	**4.54**
1.5	The criteria “severity” is clearly described and the rating scale (1-10) is understandable and distinguishable.	5	4	5	5	5	4	3	4	5	4	4	5	4	**4.38**
1.6	The criteria “occurrence” is clearly described and the rating scale (1-10) is understandable and distinguishable.	5	4	5	5	5	4	4	4	5	4	4	5	4	**4.46**
1.7	The criteria “responsiveness” is clearly described and the rating scale (1-10) is understandable and distinguishable.	5	4	3	3	4	3	4	4	5	4	4	4	4	**3.92**
1.8	Selecting the criticality level allows focusing on the most critical uncertainty effects.	4	4	4	4	4	5	4	5	5	5	3	5	4	**4.31**

Definition of relevant flexibility measures (Step 3 & 4 of the DFLF guideline)

No.	Questions	Assessment of individual participants													Average
		a	b	c	d	e	f	g	h	i	j	k	l	m	
2.1	The identified flexibility measures are sufficient to cope with the critical changes.	4	4	3	3	4	3	4	4	4	4	4	5	5	**3.92**
2.2	The identified flexibility measures consider two coping strategies: prevention & reaction.	4	4	3	4	4	4	3	5	5	4	4	4	5	**4.08**
2.3	The identified flexibility measures consider two aspects: product & process.	4	4	3	3	5	4	4	5	3	4	4	4	4	**3.92**
2.4	The applied assessment criteria (cost, time, quality, additional factors) are complete to define relevant flexibility measures.	4	4	4	4	3	2	4	5	4	5	3	5	5	**4.00**
2.5	The criteria “cost” is clearly described and the rating scale (0-10) is understandable and distinguishable.	4	3	4	4	4	2	4	5	5	4	3	5	4	**3.92**
2.6	The criteria “time” is clearly described and the rating scale (0-10) is understandable and distinguishable.	4	4	4	4	4	4	4	5	5	4	3	5	4	**4.15**
2.7	The criteria “quality” is clearly described and the rating scale (0-10) is understandable and distinguishable.	4	4	3	4	4	4	4	5	5	4	3	5	3	**4.00**
2.8	Weighting the evaluation criteria allows focusing on the most relevant needs.	5	5	3	5	4	5	4	4	5	4	4	4	4	**4.31**
2.9	The definition of relevant flexibility measures through a value-benefit analysis is practically applicable.	4	5	3	4	4	3	4	5	5	4	3	4	5	**4.08**
2.10	The definition of relevant flexibility measures through a value-benefit analysis is applicable at the early development stage.	4	5	3	4	4	5	4	4	4	5	3	4	4	**4.08**
2.11	The relevant flexibility measures were systematically and objectively defined.	5	5	3	4	4	5	4	5	5	5	3	4	4	**4.31**

Recommendation of enhancing design objectives (Step 5 & 6 of the DFLF guideline)

No.	Questions	Assessment of individual participants													Average
		a	b	c	d	e	f	g	h	i	j	k	l	m	
3.1	Integrating the flex-relevance of flexibility measures enables focusing on the important preferences.	4	4	5	4	5	4	4	5	5	5	4	4	5	**4.46**
3.2	The design objectives are complete to enhance the fulfillment of relevant flexibility measures.	4	4	5	4	3	3	3	5	4	4	4	5	5	**4.08**
3.3	All design objectives are clearly described and understandable.	5	5	5	5	4	4	4	5	5	4	3	4	5	**4.46**
3.4	The design objectives consider the entire product lifecycle.	4	4	5	4	5	4	4	5	5	4	4	5	5	**4.46**
3.5	The design objectives are applicable at the early development stage.	3	4	4	5	4	4	4	5	5	4	3	4	5	**4.15**
3.6	The design objectives support the early development stage through summarizing design rules from relevant DFX guidelines.	4	4	5	5	4	4	4	5	4	4	3	5	5	**4.31**
3.7	Deriving the prioritization order of design objectives through the presented methods is practically applicable.	4	3	4	4	4	3	3	4	5	5	4	5	4	**4.00**
3.8	Deriving the prioritization order of design objectives through the presented methods is applicable at the early development stage.	4	4	5	4	4	4	4	4	5	5	4	4	4	**4.23**
3.9	The prioritization order of design objectives was systematically and objectively derived.	5	5	5	5	3	4	4	5	4	4	4	5	5	**4.46**
3.10	The prioritization order of design objectives supports the early development stage through recommending the design focus.	4	4	5	5	5	4	4	5	5	5	4	4	4	**4.46**

Questionnaire data: Applicability evaluation

Applicability of the DFLF guideline

No.	Questions	Assessment of individual participants													Average
		a	b	c	d	e	f	g	h	i	j	k	l	m	
4.1	The steps of the DFLF guideline are structured and straightforward.	5	5	4	5	5	5	4	4	5	4	4	5	5	**4.62**
4.2	The steps of the DFLF guideline are practically applicable.	5	5	4	3	4	4	4	4	5	4	3	5	4	**4.15**
4.3	The steps of the DFLF guideline are applicable at the early development stage.	5	5	5	5	5	3	3	5	5	5	4	5	4	**4.54**
4.4	The design objectives of the DFLF guideline are applicable at the early development stage	5	5	5	5	4	4	4	5	5	5	4	5	4	**4.62**
4.5	The steps of the DFLF guideline are applicable on other powertrain elements (e.g. combustion engine).	5	5	4	4	5	5	4	5	5	3	4	5	4	**4.46**
4.6	The steps of the DFLF guideline are applicable in different industry sectors.	5	5	5	5	3	4	4	5	4	4	3	4	4	**4.23**
4.7	The design objectives of the DFLF guideline are applicable in different industry sectors.	5	5	5	5	3	4	4	5	4	4	4	4	4	**4.31**