

Supplementary S1.1: Relevant elements of strategic environmental sustainability for zero impact transformations

Strategy element	Relevant aspect	Description	Source	Relevant management activities in automotive manufacturing
Strategic context	Absolute sustainability	Human activities respect the carrying capacities of ecosystems	[1]	Identification of requirements to establish an environmentally effective factory system
	Sustainable Development Goals (UN SDGs)	Global sustainable development agenda	[2] [3]	Implementation of the manufacturing requirements in UN SDGs number 8, 9, 12
	Legislation and regulation (European Union)	EU Climate and Energy Framework EU Circular Economy Action Plan EU Zero Pollution Action Plan EU Taxonomy	[4] [5] [5],[6] [7]	Strategic and technical adaptation of existing factories for environmental compliance
	Finance and reporting	Requirements of sustainability reporting schemes and finance markets (credit lending)	[8], [9]	Development of a holistic environmental data management
	Stakeholder demands	Demands of e.g. employees, local community, governmental and non-governmental organizations and suppliers	[10], [11]	Alignment of organizational processes with societal demands
	Upstream and downstream-processes	Availability of energy, water and resources as well as waste water and waste infrastructure	[12]	Provision of technical and economic resources to develop sustainable factory systems
Strategic process	Absolute goal setting – PB “climate change” (increasing to high risk)	Climate change mitigation in accordance with the Paris Agreement	[13], [14]	Definition of goals which include effective transition to carbon-free factories
	Absolute goal setting – PB “fresh water” (blue + green water = increasing risk)	Avoidance of further interference with the water cycle	[15]	Definition of goals which impact avoidance of factories in water-scarce regions
	Absolute goal-setting – PB “novel entities” (increasing to high risk)	Zero Pollution Action Plan of the European Union	[6], [16]	Definition of goals which include avoidance of anthropogenic substance emissions of factories
	Absolute goal setting - PB land system change (increasing risk)	Circular material flows and zero waste	[17], [18]	Definition of goals which aim to minimize use of natural resources through factories

	Transformative process – progress measurement	Measurability based on defined environmental aspects and accepted assessment methods	[19]	Implementation of impact-based methods to evaluate the factory transformation
	Transformative process – reporting	Environmental reporting to communicate the organizational progress	[20]	Implementation of internal and external reporting processes for management, legislative, rating and ranking reports.
	Transformative process – innovation and learning	Innovation and learning processes for sustainability (based on system innovation, cooperation and stakeholder integration)	[21]	Implementation of innovation and learning processes within the factory to develop zero impact solutions
Strategic content	Factory system - energy subsystem	Use of renewable energy	[22]	Realization of a carbon-free factory
	Factory system - material subsystem	Circular use of technical materials, use of biogenic materials, waste avoidance	[12]	Utilization of secondary materials and process organization for recycling
	Factory system - water subsystem	Circular use of water and use of rainwater	[23]	Minimal fresh water usage and maximum water recycling
	Factory system - production subsystem	Avoidance of emissions	[24]	Implementation of low-to-zero emission technologies in production
	Environmental compliance	Effective environmental compliance management	[25]	Identification of future legal requirements for factories
	Environmental management	Systems-based environmental management	[26]	Operationalization of strategic goals, processes, reporting, innovation and learning
	Factory architecture	Eco-positive design and building appearance	[22], [27], [28], [29]	Conceptualization of ecological factory
	Biodiversity management	Biodiversity-integrated industrial project management	[30] [31]	Integration of biodiversity management in environmental management processes
	Factory planning	Life-cycle oriented factory planning	[32]	Integration of life-cycle based evaluations in factory planning
	Digitalization of resource flows	Cyber-physical production management	[33]	Optimization of energy and resource flows within the factory
	Emission management	Zero emissions in water, soil, air and factory ambience	[6], [34]	Implementation of low-to-zero technologies in production

	Environmental engineering	Effective prevention and contamination rehabilitation	[35]	Implementation of technical standards for prevention and rehabilitation
	Transport and mobility management	Sustainable transport and mobility	[36]	Implementation of sustainable logistics and transport choices for employees

Supplementary S1.2: Selected technical benchmark values from the Site Checklist for a zero impact factory

Aspect of a zero impact factory	Technical aspect	Benchmark value
Architecture and perception	Roof / façade greening	≥ 50% of the building envelope (roof surfaces and external facades) is green
	Natural lighting	Natural lighting in ≥ 80% of the office space and in production areas where ecologically sensible
Digitalization	Energy and data management	Measurement data of all (100%) energy- and environmentally-relevant facilities are analyzed and evaluated in a central IT landscape (e.g. cloud system or similar)
Water	Fresh water	KPI fresh water ≤ 1.0 m ³ /vehicle for vehicle production sites or reduction of 50% per production unit compared to the base year for component sites
	Waste water (direct discharge)	Pollutant concentrations are adhered to: Cl ⁻ : 500 mg/l, SO ₄ ²⁻ : 500 mg/l, Ni: 0.05 mg/l, Zn: 0.05 mg/l, Mn: 0.05 mg/l, COD: 50 mg/l, conductivity: 1500 µS/cm
Energy	Heat	Efficient heat supply: annual efficiency ≥ 90 %
	Cooling	TEPF > 6.5 for compression chillers, TEPF > 0.7 for absorption chillers (TEPF=Total Energy Performance Factor)
	Compressed air	Efficient compressed air supply: generation efficiency ≤ 0.12 kWhel/Nm ³
	LED lamps	The proportion of lighting provided by LED lamps is ≥ 90% of the usable area of the site
	Paint shop	Energy-efficient paint shop (total energy) ≤ 5 kWh / m ² painted surface
	Vehicle production	Energy-efficient vehicle production (electrical energy) ≤ 0.4 MWhel / vehicle
	Renewable energy	100% renewable energies in external electricity supply
	Own generation	The site covers ≥ 10% of its heating needs and ≥ 10% of its electricity needs from renewable sources
	CO2 neutrality	The factory is operated in a CO2e-neutral manner (including neutralization of CO2e emissions)
Material	Plastic waste	≥ 60% by weight of the plastic waste is sorted separately according to composition and material
	Incineration	≤ 10% by weight of all production-specific recycling waste is thermally recovered
	Disposal	≤ 1% by weight of all production-related waste is for disposal
	Recycling	≥ 99% by weight of all production-specific waste is recycled (ultimate goal)
Biodiversity	Biodiversity-tool	The result (KPI) from the application of the biodiversity site assessment tool is ≥ 50%
Pollutants	Exhaust air (paint shop)	Regenerative / thermal afterburners - limit values: C _{tot} 10 mg/Nm ³ , CO 100 mg/Nm ³ , NOx 100 mg/Nm ³
	Dust emissions	Captured dust emissions (total dust) from the paint shop are ≤ 1 mg/Nm ³
	VOC emissions	VOC emissions from the paint shops are ≤ 8 g/m ² body surface
Mobility	Employees	≥ 90% of employees come to work CO2-neutral
	Freight transport	Logistics operations are 100% CO2-neutral

Supplementary S1.3.: Summary of strategic challenges and opportunities plus identified solutions by the strategic management

Strategy element	Identified Challenge	Opportunity	Solution through the strategic management
Overall strategy (including vision and goals)	Build up knowledge among decision-makers in top-management	Liability of the strategy	Informational meetings and workshops with decision-makers
	General strategic commitment by the company for the “zero impact”-transformation	Positive customer awareness, resource security and science-based strategic communication	Information on sustainability opportunities, stakeholder-based knowledge management
	Coordination of brands and generation of a long-term strategic commitment	Definition of the goals and the linear long-term target path until 2050	Facilitation of a top-down strategy implementation process supported with a top management decision
Strategy development	Interface management on Group-, brand- and factory-level	Structured information flow within the company	Implementation of management councils and working groups
	Knowledge management	Strategy alignment with current scientific findings	Facilitation of sub-projects and definition of project managers for structured content development.
	Quality management	Acceptance of external reviewers and stakeholders	Installation of review processes with internal revision, scientific review council and auditing company
	Adaptation management	Integration of novel topics into the strategy	Provision of capacities for new strategic projects
Prototype of a zero impact factory	Implementability of the vision	Visual and real-life representation of the strategic vision	Collection of best practice measures within the Group to show Implementability of the vision
	Acquiring and allocating financial resources for the transformation	Acceptance of the top management through highlighting the effectiveness of implemented measures	Priorization of transformative topics with regard to the impact reduction
Method development	Translation of PBs into business	Impact-based approach for strategic steering	Definition of “zero impact”-thresholds in accordance with scientific partners
	Benchmark values due to missing scientific evidence	Detailed factory analysis for technical and procedural optimization and progress documentation in auditing processes	Facilitation of a significant amount of expert knowledge in working groups and in iterative improvement processes

	Strategic and method-based steering	A successful operationalization of the “zero impact”-transformation process	Data and information management supported by tools and internal databases
	Internal and external acceptance	Internal acceptance contributes to successful strategy implementation, external acceptance contributes to positive company image	Knowledge transfer workshops (internal) and publication in official company reporting (external)
Strategic management	Strategy process management and strategy steering including stakeholder management, reporting and communication	Successful strategy implementation through a clear organizational structure and a high level of acceptance among all internal stakeholders	Regular management council meetings with structured agendas, clear strategy organizations on Group-, brand and factory-level and

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