

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 |
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| 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 |

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| | 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 |

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| | 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 |
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| 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 , NO _x 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 |
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| 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 |

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| | 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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