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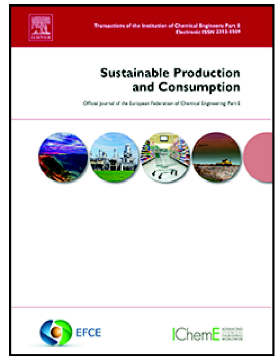

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Designing Sustainable Innovations in Manufacturing: A Systems Engineering Approach

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ABSTRACT

Innovating manufacturing systems can substantially support a sustainable transformation of value creation across the industry toward higher sustainability maturity levels. The research presents a novel systems engineering approach for innovating manufacturing systems with a focus on sustainability. The systems engineering approach aims at supporting manufacturing companies in realizing sustainable innovations. It allows companies to cope with current and future global challenges while maintaining and improving their competitiveness. The concepts of integrated values and global innovation pathways set the research's scope and practical relevance. A narrative literature review of the earlier and later phase of the sustainable-oriented innovation process is presented. The systems engineering approach for creating sustainable manufacturing innovations with a defined macro and micro cycle is introduced. The macro cycle determines the important design phases for the life cycle of the innovation while the micro cycle provides a process for finding sustainable solutions. A case study grounded on a start-up that developed an innovative wind turbine tower system is introduced for verifying, validating, and evaluating the proposed systems engineering approach within the application field of manufacturing large-scale products.

Keywords: Sustainable Development, System Design, Manufacturing Systems, Renewable Energy

1 INTRODUCTION

1.1 Motivation and rationale

Based on the reactions of the global community to recent shocks, such as the Corona pandemic, droughts in Europe, or the war in Ukraine, demonstrate that the global community is insufficiently prepared both individually and collectively for disasters on a global scale. Among the most crucial short-term risks are, according to the World Economic Forum, crises in employment and livelihood, widespread youth disillusionment, digital inequality, economic stagnation, human-made environmental degradation, erosion of societal cohesion, and acts of violence [1]. These risks translate into long-term global challenges for the global community.

Against this backdrop of intensifying global challenges, manufacturing companies continue to apply individual business models within globalized value creation networks, i.e., the formation of inter-organizational cooperation to create value, often through technological advancements. Competitiveness in global markets is a major tenet of these networks with a focus on economic objectives, often without considering missed or detrimental environmental or social values. The concept of value must radically change for business activities in early and newly industrialized countries with the potential for establishing more sustainable practices that incorporated profit with social well-being and environmental stewardship [2, 3]. Value creation of companies needs to shift towards a modern paradigm with an emphasis on sustainable development and community resilience [4, 5].

However, companies tend to struggle with designing sustainable manufacturing systems due to the complexity of the underlying subsystems which requires a holistic and systems thinking perspective from decision-makers [6, 7]. Decision-makers must be enabled to successfully navigate the action field of radical and incremental innovations and local and global value creation. They must be capable of effectively combining different manufacturing domains while integrating advanced manufacturing technologies and materials into the manufacturing system [8].

Value creation oriented toward sustainable development and community resilience enables companies to cope with the global challenges by combating and dismantling their underlying causes and by gaining the capabilities to react and grow from unforeseen shocks. Sustainable innovation can create new opportunities for value creation that allows companies to grow long-term competitive advantages while fulfilling their societal and environmental responsibilities [9]. Sustainable innovation in manufacturing systems can be achieved by designing and implementing novel integrated systems of business models, products, and services [10, 11]. Systems thinking approaches support decision-makers to efficaciously address the complexity and interconnectedness of economic, technological, human, social, and ecological systems during the design process of innovations [12].

In conclusion, there is a substantial need across the manufacturing industry for designing sustainable manufacturing systems to cope with future global challenges. The research presented in this paper is an attempt to propose a systems engineering approach for innovating manufacturing systems to improve the sustainability performance of the system through integrated values.

1.2 Competitive advantages of sustainable innovation

Sustainable innovation must go hand in hand with maintaining and increasing industrial competitiveness. Companies who compete with their business models in global value networks must be able to achieve competitive advantages through the implementation and deployment of sustainable value creation as a precondition in an economy following capitalist principles. Sustainable innovation of value creation in manufacturing can realize different competitive advantages: through short-term and long-term effects as well as by increasing positive and reducing negative effects (Figure 1). This proven potential for increasing industrial competitiveness through sustainable innovation serves as a key motivation and frame condition for the research laid out in the following. It specifically highlights the industrial relevance of sustainability for companies also from a competitiveness perspective.

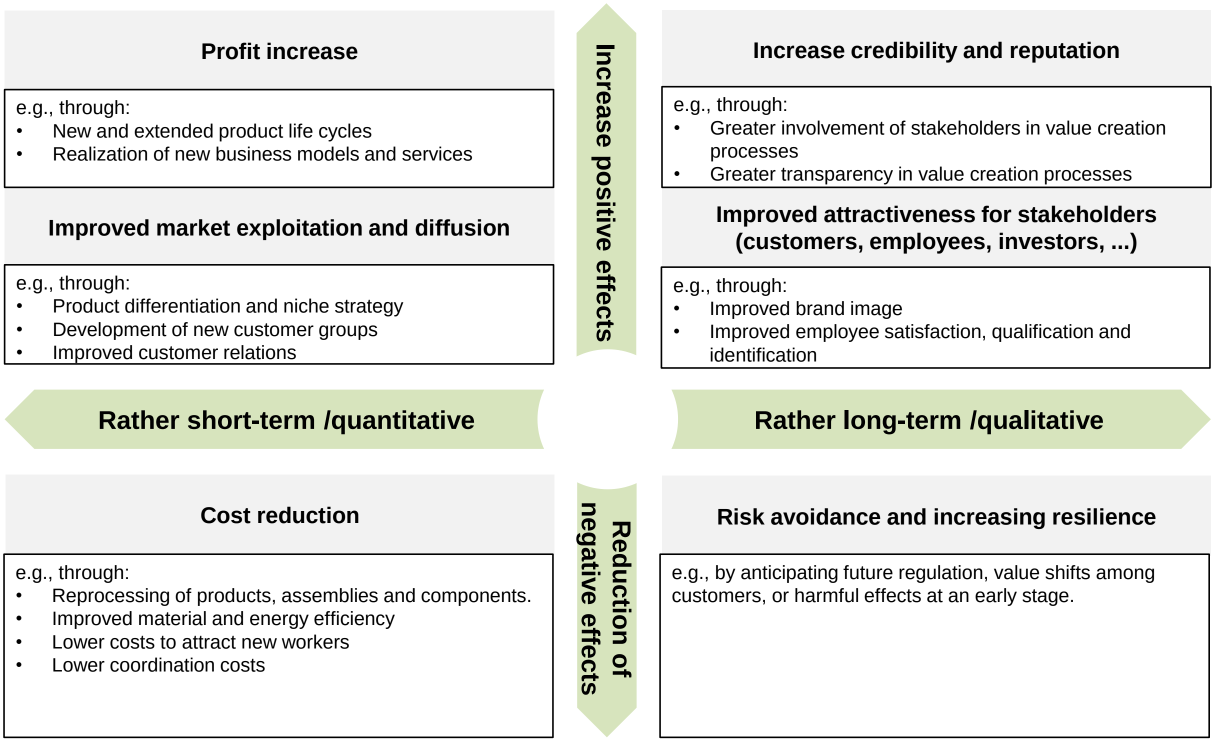


Figure 1. Competitive advantages of sustainable innovation (adapted from [13], and based on visualization ideas from [14], [15])

1.3 Research methodology and paper structure

The research intends to answer the following question: How can manufacturing companies efficaciously and systemically utilize sustainable innovations through the application of a systems engineering approach? This approach enables industrial companies to cope with the global sustainability challenges while maintaining and improving the competitiveness of their manufacturing system. The focus of the research is put on discrete manufacturing systems.

The research follows a qualitative methodology (Figure 2). A narrative literature review provides the basis for positioning the research within the state-of-the-art and for deriving the research gap, contribution, and novelty. Subsequently, phases of analyses and syntheses were utilized for conceptualizing the novel systems engineering approach derived from best practices in systems thinking and systems engineering. The concept was iteratively adjusted and improved until a consensus among the authors was reached and thus following the idea of the Delphi method to extract and process expert knowledge [16]. This consensus enables a harmonious interplay of the different elements of the approach. Verification, validation, and evaluation of the fundamental efficacy of the concept were conducted based on a case study in the field of manufacturing large-scale products. Learnings from the case study were constantly fed back for further improving the concept.

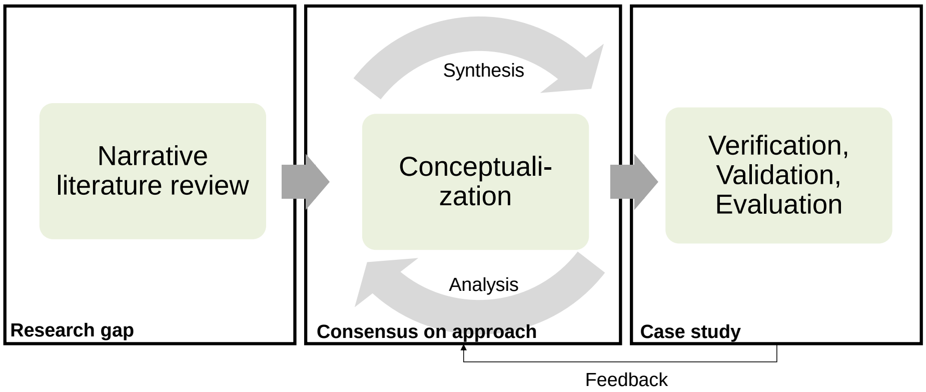


Figure 2. Research methodology

Following the research methodology, the paper is structured as follows:

- Section 2 elaborates on global pathways of innovation as a foundation for determining the scope and context of the research.
- Section 3 presents the state-of-the-art based on a narrative literature review of the earlier and later phase of designing sustainable innovations. Further, the section describes the research gap, as well as the contribution, and novelty of the research.
- Section 4 introduces a qualitatively novel systems engineering approach for the design of sustainable innovation in manufacturing systems based on a specific macro and micro cycle. The macro cycle determines the important design phases for the life cycle of the innovation while the micro cycle provides a process for finding sustainable solutions throughout these phases.
- Section 5 provides verification and validation of the proposed macro and micro cycles by the means of a manufacturing case study of a tower system for wind turbines. A critical reflection also covering an evaluation of the efficacy of the proposed systems engineering approach is derived.
- Section 6 includes a conclusion and summary of the research activities and results.

2 FOUNDATIONS AND RESEARCH SCOPE

2.1 Innovation in manufacturing systems

Systems thinking serves as the overarching principle for the design of innovation in complex systems such as manufacturing systems. Systems thinking enables the understanding of systems and of their relation of the interrelation of the system elements as well as the knowledge of how systems relate to the overall context [17].

A system is a function-providing object. and can be divided into different subsystems which in itself cannot provide the overall function that the system provides [18]. A system-of-systems (SoS) is a system with a set of at least two subsystems [18]. A technical system "encompasses the set of use-oriented, artificial, concrete objects (artifacts or object systems), the set of human actions and institutions in which object systems originate, [and] the set of human activities in which object systems are utilized” [19].

There seems to be no commonly used definition of innovation in complex systems. Systemic or systems innovation is defined by Mulgan and Leadbeater as “an interconnected set of innovations, where each influences the other, with innovation both in the parts of the system and in the ways in which they interconnect” [20]. In a manufacturing context, a systems innovation can be identified as a qualitative novelty introduced into the SoS, i.e., the overall manufacturing system, through an interconnected set of innovations within the subsystems: value creation, value delivery, and value proposition. The design process toward an innovation can be categorized into earlier and later phases. The earlier phase, sometimes also called the fuzzy front end of innovation, aims at finding ideas for addressing a societally relevant problem, while the later phase covers the design of the product and related business model based on the idea [13]. Figure 3 shows the earlier and later phases, respectively, comparing the relevant innovation approaches described by Thom's 3-phase model [21], Ropohl's phases of technical ontogenesis [22], and Cooper's stage-gate-model [23].

Earlier phase (Fuzzy Front End)		**Later phase**			
Approach from Thom, 1992					
Idea Generation	**Idea Acceptance**	**Idea Realization**			
Determination of the search field, Idea generation	Evaluation, Creation of a realization plan	Realization, Sale to an addressee, Checking the acceptance			
Approach from Ropohl, 2009					
Cognition	**Invention**	**Innovation**			**Diffusion**
Research	Technical conceptualization	Technical and economic realization			Societal utilization
Approach from Cooper, 2014					
Idea Generation	**Idea Scoping**	**Build Business Case**	**Development**	**Test and Validation**	**Launch**

Figure 3. Earlier and later phases of the innovation process (adopted from [13])

2.2 Global pathways of innovation

The concepts developed by Visser in [12, 24, 25] for coping with the paradox of sustainable development [26] serve as a foundation for deriving global pathways of innovation that can shape a long-term sustainable transformation of the global community. According to Visser [12], a systems thinking approach to the global challenges of sustainable development resulted in the Framework of Five Forces of Fragmentation and Integration (Figure 4). The Five Forces of Fragmentation describe the global systemic problems, or in other words, the most critical areas of a systemic breakdown in society: (1) discontent, (2) disruption, (3) disconnection, (4) disparity, and (5) destruction. These forces can be directly countered and reversed by Forces of Integration [12, 27], and global pathways of innovation are defined by designing solutions that systematically facilitate these Forces of Integration. Global pathways of innovation coin societally relevant systems that contribute to a transition towards higher sustainability maturity levels based on integrated values. Following Visser, integrated values are defined as the simultaneous building of multiple capitals through systemic innovation across the resilience, exponential, access, circular, and well-being economies that result in a world that is more secure, smart, shared, synergetic, and satisfying [24]. Global pathways of innovation can be understood as a holistic approach to facilitating a sustainable transformation by offering innovative solutions to the global challenges which are presented by the WEF in [1].

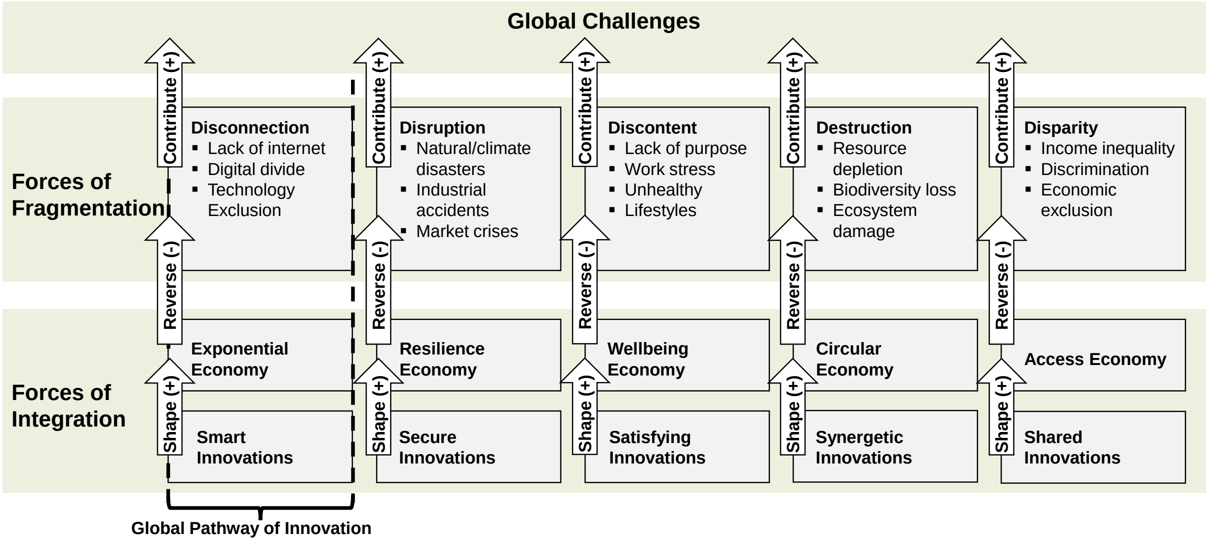


Figure 4. Global pathways of innovation (following the ideas from [12])

2.3 Research scope

The foundations discussed throughout this section set the scope and context for the subsequent literature review and the research methodology. In light of this paper,

- an innovation describes a qualitatively novel manufacturing SoS. This manufacturing SoS is also the System-of-Interest (SoI) and is essentially defined by its (sub-)systems: the value proposition, value network, and value distribution.
- the innovation process is divided into an earlier and a later phase and follows the ideas of technical ontogenesis. The cognition in the earlier phase contains the systematic search for a possible solution idea for a socially relevant task. In the later phase, the design of the (sub-)systems from the idea to a fully specified SoS takes place, based on the outcomes of the earlier phase.
- global pathways of innovation based on integrated values are essentially coining a sustainable value creation throughout manufacturing SoS.

In conclusion, the research examines the hypothesis that by innovating manufacturing SoS based on integrated values, a sustainable transformation of the manufacturing industry toward higher sustainability maturity levels can be achieved. Hereby, the research scope is constrained by discrete manufacturing systems as also reflected by the nature of the case study which is addressing a large-scale product.

3 LITERATURE REVIEW

3.1 Structure

The literature review covers the innovation process to support sustainable value creation in manufacturing. Approaches discussed among the scientific community in this search field can be clustered according to the classification scheme presented in Table 1.

Table 1. Classification of Approaches for the Development of Sustainable Innovations

Innovation Phase	Purpose	Underlying concept	Approach
The earlier phase of the innovation process	Generation of solution ideas	Theory of inventive problem solving (TRIZ)	▪ SUSTAINability Map [28], ▪ Blue Design Principles [29]

		Design Thinking	▪ Value Mapping [30] ▪ Model for the development of sustainable solution ideas [10]
	Evaluation of solution ideas	Life Cycle Assessment	▪ Life cycle sustainability Assessment [31] ▪ Three-tiered approach [32] ▪ Digital Life Cycle Twin [32] ▪ Sustainability Safeguard Star [33] ▪ Product sustainability assessment with closed-loop indicators [34]
The later phase of the innovation process	Product innovations	Target-driven	▪ Target-driven sustainable product development [35, 36] ▪ Framework for sustainable product development [37]
		Servitization	▪ Sustainable and smart product (SSP) ecosystem [38]
	Business Model Innovations	Based on archetypes, principles, or strategies	▪ Sustainable business model archetypes [39] ▪ Product-service systems (PSS) business models archetypes [40] ▪ Strategies and drivers of sustainable business model innovation [41] ▪ 20 Business model innovations for sustainability [42] ▪ The sustainable business model pattern taxonomy [43] ▪ Sustainability-oriented business model development [44] ▪ Sustainable product service system (S-PSS) business models [45]
		Value-oriented	▪ Value uncaptured for sustainable business model innovation [46] ▪ Value mapping tool for sustainable business modeling [47] ▪ Values-based network and business model innovation [48] ▪ A stakeholder theory perspective on business models [49]
		Triple-bottom-line	▪ The Triple Layered Business Model Canvas [50]

3.2 Research gap, contribution, and novelty

The classification scheme (Table 1) shows that there have been hardly any approaches discussed among the scientific community for developing manufacturing innovations that:

- cover the complete innovation process from the earlier to the later phase.
- apply systems thinking and engineering to innovate manufacturing systems or cover the integrated design of the relevant (sub-)systems, i.e., the value proposition, value network, and value distribution.
- focus on holistically coping with the sustainability challenges i.e., apply an integrated value approach.

The authors intend to contribute to closing these three beforementioned research gaps by proposing a systems engineering approach for innovating manufacturing systems with a focus on sustainability.

With the systems engineering approach, the authors essentially intend to scientifically contribute to the field of systems engineering theory within the application field of manufacturing and production. The systematic and integrated perspective on innovating domains in manufacturing, i.e., the value proposition, value network, and value distribution, seems to be a relevant contribution to the scientific field.

Additionally, the authors aim to contribute to industrial manufacturing practice with the novel systems engineering approach which can serve as a guideline for manufacturing companies to realize sustainable innovations while maintaining and improving competitiveness. The approach can be used to support companies in adopting new sustainability regulations as well as in future-proofing their business models for the global sustainability challenges.

The presented research is aiming for novelty in the field of systems innovation and design by demonstrating the integrated design of sustainable manufacturing systems. The integrated design in this sense interlinks the structured design of the business model with the design of the product and services as well as with the design of the manufacturing process chain. This novelty is specifically highlighted in the proposed systems engineering approach (Section 4) by the integrated design of the three system domains: value proposition, value network, and value distribution. An integrated perspective allows for holistically identifying and deploying relevant sustainability principles for the entire life cycle of a newly created manufacturing system innovation. The authors believe that the novelty in the field of systems innovation and design is further facilitated by the unique case study (Section 5). The case study aims to showcase to researchers and practitioners how relevant principles of sustainability can be applied in a simple manner during the earlier and later phase of the innovation process for a rather complex discrete manufacturing system.

Other novelty aspects of the research are essentially determined by the new combination of three existing and peer-reviewed scientific approaches (Figure 5) from different scientific disciplines. In their new integrated, cohesive combination, an innovation in the field of systems engineering research is created, following Schumpeter’s notion of new combinations as an essence for novelty and innovation [51]. The novelty of the research is further coined through the transdisciplinary collaboration of the authors to develop a coherent systems engineering approach based on these three individual approaches to create the scientific and industrial contributions as described.

4 SYSTEMS ENGINEERING APPROACH FOR SUSTAINABLE INNOVATION

4.1 Overview

The research results introduced within this section propose a systems engineering approach for creating sustainable innovations in manufacturing systems. The approach combines the Diamond model from van Erp [11, 13] with the SPADE model from Haskins [52] and the Integrated Value model from Visser [12] (Figure 5). In other words, it is compiled from different qualitative approaches in systems thinking and systems engineering [11, 13, 52] as well as in sustainability research [12].

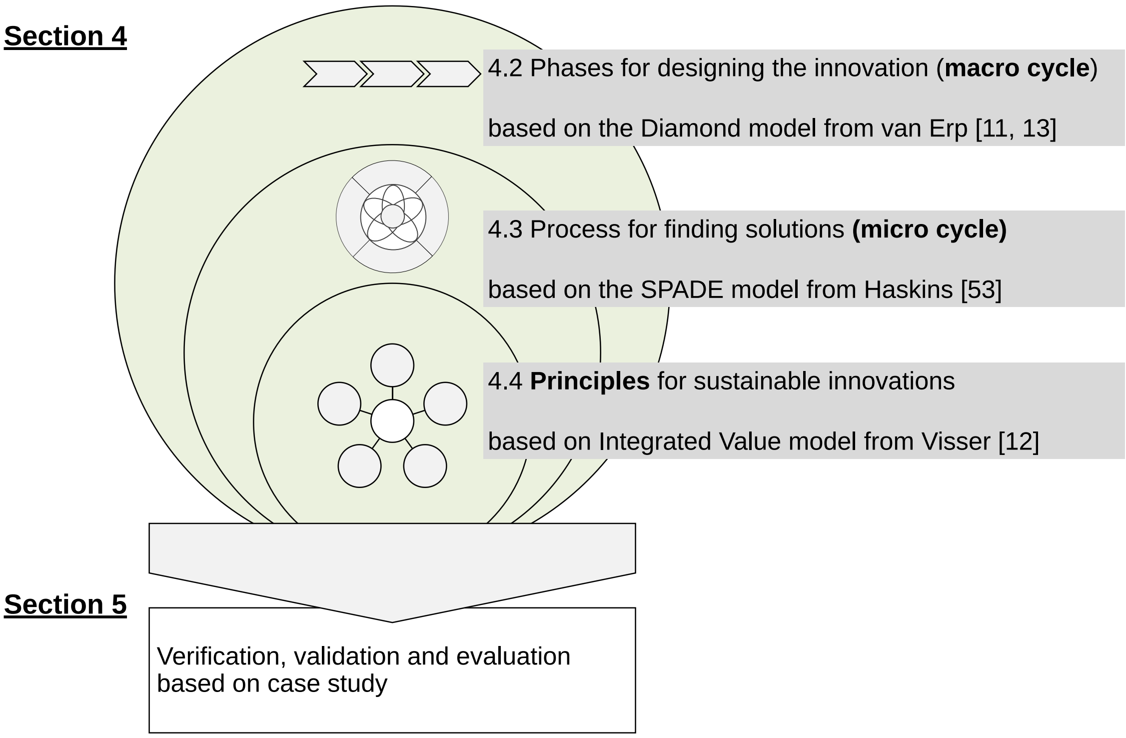


Figure 5. Structure of the systems engineering approach

Section 4 covers the description of the systems engineering approach. The approach combines a macro cycle for designing the life cycle of the innovation with a micro cycle for finding solutions for specific problems or tasks during the earlier and later phase of the innovation process. The deployment of integrated values into the solutions-finding cycle through defined principles ensures that the innovation is following the global pathways of innovation from Figure 4.

Section 5 includes a verification, validation, and evaluation of the proposed systems engineering approach based on a case study. The case study focuses on applying different, relevant elements of the approach for the application field of manufacturing large-scale products.

4.2 Macro cycle: Phases for designing the innovation

The macro cycle determines the important process phases for designing the innovation, i.e., the manufacturing SoS, (Figure 6). It adds the life cycle perceptive to van Erp's Diamond Model [11, 13], while also expanding the (sub-)systems of van Erp's model to a value-oriented view of the manufacturing SoS.

The innovation is composed of different (sub-)systems which are required for describing a manufacturing system: the value proposition, the value network, as well as the value distribution. These (sub-)systems in turn also consist of specific (sub-)systems, i.e., the domains. The value proposition comprises the tangible product with software, electrics/electronics, and mechanics, as well as intangible service throughout its life cycle. The value network comprises the different elements which are required to create the value proposition for the customer(s) i.e., the manufacturing technology, material flow, information flow/ICT, and the industrial digital twin in globally networked manufacturing systems. The value distribution contains the relevant elements for delivering and exchanging the value propositions i.e., the channels, the costs, the sales, as well as the targeted customer(s) segment(s).

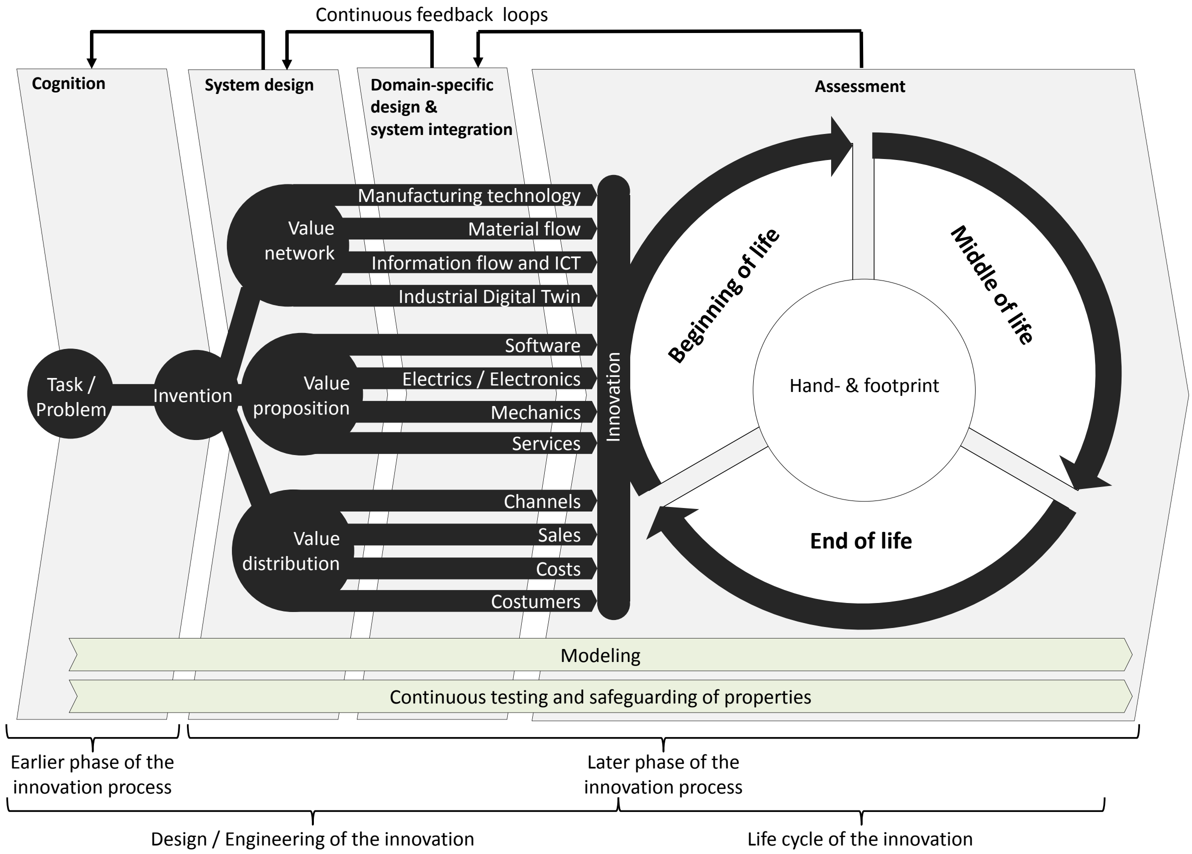


Figure 6. Process phases for designing the innovation (macro cycle)

The innovation can be characterized by its life cycle with a beginning, middle, and end of life [53]. The design determines the life cycle phases of the manufacturing system and thus has the highest impact on its hand- and footprint. The beginning of life addresses the design, raw material acquisition, and manufacturing phases. The middle of life comprises the value selling e.g., the use phase of the actual innovation whereas the end of life covers the reprocessing and disposal of the innovation i.e., it deals with transferring the innovation and its components into the next life. Four essential design phases are embedded in the macro cycle: cognition, system design, domain-specific design, and system integration. A run through the phases focuses on evolving the maturity level of the innovation system from finding the first ideas for a socially relevant problem or task to bringing the innovation onto the market.

Cognition is the starting point of the macro cycle and covers the Fuzzy Front End of innovating the manufacturing system. It is characterized by the search for a solution idea for a societal-relevant task or problem. Eventually, the solution idea determines an invention i.e., the first concept for a qualitatively novel manufacturing system.

The **system design** aims at developing a concept for the overall architecture of the innovation with its relevant (sub-)systems: value proposition, value network, and value distribution. The main task of the system design is to conceptualize basic solutions based on the system requirements for relevant functions of these three (sub)-systems.

The **domain-specific design** is oriented toward developing the domains of the manufacturing system, namely manufacturing technology, material flow, information flow/ICT, and the industrial digital twin for the (sub-)system value network. The electrical domain, electrics/ electronics, and mechanics, as well as services, determine relevant domains for the (sub-)system value proposition. The (sub-)system value distribution comprises the domains channels, sales, costs, and customer(s). These domains can be interpreted as systems that are fulfilling distinct functions of the innovation. The solution iterations of the domain-specific design process need to be constantly integrated across the three domains to ensure the functional fit between all (sub-)systems, domains, and their modules, components, parts, or other artifacts. Thus, continuous integration plays an essential role from an agile development perspective [54]. **System integration** focuses on creating experiments based on digital and/or physical prototypes to test the interfaces and the intended interplay between the solution iterations. This phase eventually aims to identify faults and challenges as well as to verify the properties of the overall innovation. The system integration continuously runs in parallel to the domain-specific design process until the innovation has reached a maturity level where it can be introduced to the market. The start of manufacturing concludes the system design phase. This means that the value network is sufficiently designed to produce the value proposition to realize the value distribution.

Assessing the hand- and footprint during the beginning, middle, and end of life phases follows the system design. The handprint determines the positive impacts of the innovation on society and the environment and represents its integrated value over the life cycle [55]. In contrast, the footprint specifies the negative impact of the innovation on the environment and society and represents the burden over its life cycle [56]. The findings and learning from the assessment are used for further improving the system design for subsequent iterations of the manufacturing system.

Modeling continuously supports the design of the innovation by applying modeling methods for the (sub-)system and domains under consideration. The models are used to elaborate designs for each level of concretization by creating virtual and/or physical surrogate models. These designs allow the identification, verification, validation, and evaluation of relevant parameters of the innovation and thus contribute towards the continuous concretization and improvement of the manufacturing SoS and its (sub-)systems and domains. In addition to modeling, **continuous testing and safeguarding of properties** is another essential action supplementing the design of the innovation. This requires continuous research, continuous testing of requirements, functions, solutions, and designs of the manufacturing SoS, (sub-)systems, and domains as well as the continuous exchange of data, information, and knowledge between the involved stakeholders.

Table 2 lists the design task /subject, design methods, and potentially relevant modeling tools for the process phases of the macro cycle.

Table 2. Examples of modeling tools for the design phases of the innovation

System-level	Design task /subject	Design methods	Modeling tools (examples)
	Cognition		
SoS / Invention	Idea for a potential system innovation	Ideation	TRIZ, Design Thinking, Problem-solving, and creativity tools
	System Design		
SoS / System Architecture	System and domain requirements	Conceptual design	List of requirements, House of Quality
	System and domain functions		Energy, material and

			signals modeling, Object Process Methodology, CAE
	Basic system- and domain-solutions		Morphological Analysis, Utility Analysis
	Domain-specific Design		
Domain 1: Value Proposition	Mechanics	Integrated Design Engineering, service design	M-CAD
	Software		CASE tools
	Electrics/electronics		E-CAD
	Services		Value Proposition Canvas, Business Modell Canvas
Domain 2: Value Network	Manufacturing technology	Factory planning and design, supply chain design	CAM
	Material flow		Discrete Event Simulation, Value stream mapping
	Information flow and ICT		Object Process Methodology
	Industrial Digital Twin / Asset Administration Shell		Asset Administration Shell Explorer
Domain 3: Value Delivery	Stakeholders including the customers	Innovation accounting, lean analytics	Value Proposition Canvas, Experiment Canvas, Lean Dashboard
	Channels		
	Cost structure		Life-Cycle Costing, Economic Scenarios
	Sales structure		
	System Integration		
Domain Solutions	Integrating different design solutions across the domains	Experi-mentation	Virtual and physical/tangible prototypes, e.g.,

			cardboard engineering
	Assessment		
The life cycle of the system	Hand- and footprint of the system innovation	Life cycle assessment (LCA)	Life Cycle Sustainability Assessment (LCSA)

4.3 Micro cycle: Process for finding solutions

The micro cycle is based on the SPADE framework which was first introduced by Haskins (2007) and further refined in 2008 [52]. It is a non-linear representation which means that SPADE can be entered at any point and can be traversed left, right, or across the center. During the design process of the macro cycle, SPADE provides specific phases for finding concrete design solutions for the manufacturing SoS, its (sub-)systems, and domains. The SPADE phases are: Stakeholders, problem, alternatives, decision-making, and evaluation (Figure 7).

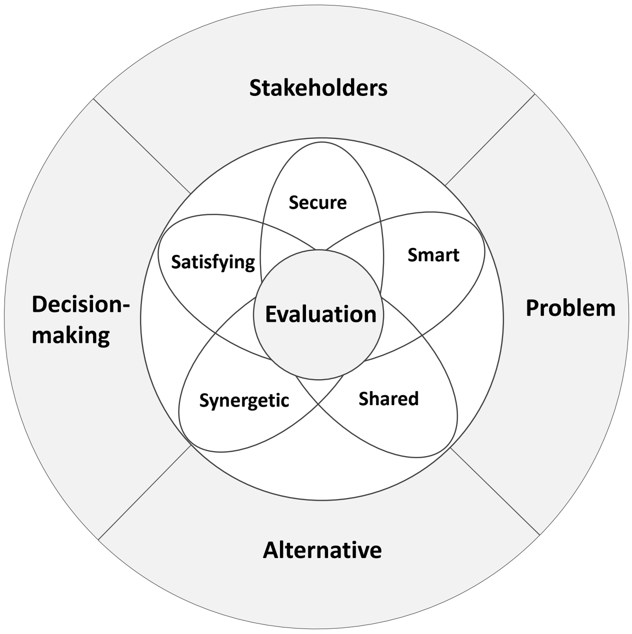


Figure 7. SPADE model for finding solutions during the design phases (micro cycle)

A **Stakeholder** can be defined as "[…] an individual, an organization, or a group of people that has an interest in or might be affected by a system" [57]. Examples of stakeholders might be customers, users, suppliers, beneficiaries, service providers, government, and citizenry, including individuals and groups which experience negative impacts of the system [52, 57]. The stakeholder phase includes the continuous search for and identification of stakeholders. It also means engaging with the stakeholders to reveal deeper insights into their beliefs and values as well as to immerse into the stakeholders' experiences related to the system (following the ideas of [58]. In the context of the macro cycle, this phase is specifically tailored to continuously analyzing and adapting the scope of the human factor of the innovation e.g., finding direct and indirect stakeholders impacted by the value creation. In addition, identifying and continuously updating the targeted customer(s) and customer segments is a crucial aspect of this phase.

Problem formulation deals with the continuous understanding of the stakeholders' motivations, needs, and conflicts while analyzing the current situation and deriving hypotheses of desirable futures, as well as defining and establishing performance and success metrics/criteria for the evaluation of developed solutions. The emphasis is to holistically identify and derive the different perspectives of stakeholders who are relevant to the identified problem and possible sub-problems. Further, problem formulation serves to transfer complex and thus difficult-to-handle problems into concrete and executable tasks. However, the human-centric background of SPADE implies that problem formulations shall be linked to specific motivations, needs, and conflicts of the stakeholders. In the context of the macro cycle, the phase aims during the earlier phases of the design process to analyze and understand the basic problem which shall be solved by the intended innovation. During later phases of the design process, the problem formulation becomes more and more related to understanding specific problems for developing the different (sub-)systems and domains of the manufacturing SoS as well as to integrating current solutions throughout the different (sub)-systems and domains.

The problem formulation with its different stakeholders' perspectives and concrete tasks is the starting point for finding **alternatives** aimed at resolving the problem. While the problem evolves with changing frame conditions, system boundaries, or updated stakeholders' perspectives, the alternative solutions must be updated and further refined continuously. In the context of the macro cycle, alternative solutions deliver concrete functional, principal, or design solutions for the overall innovation and its connected (sub-)systems and domains. These solutions also coin the system's maturity which develops from functional solutions to a detailed design solution. This development usually requires iterative jumps between the different levels of maturity i.e., between a functional, principal, and design solutions, to integrate new learnings gained while traversing through the SPADE framework.

Informed **decision-making** lays the foundation for implementing a solution based on learnings gained during all phases of the SPADE framework. It determines a concrete course of action and requires a commitment of resources and competencies. The decision made for a certain course of action is subject to continuous improvements and refinements according to new learnings. This allows the integration of new solutions or activities toward resolving the problem and satisfying the stakeholders. In the context of the macro cycle, decision-making lays out specific courses of action for exploring and implementing ideas during the earlier phase of the innovation process as well as functional, principal, or design solutions during the later phase.

Evaluation is arranged in the center of SPADE and thus connects all its phases. It aims to be open to new viewpoints and learnings as well as to integrate stakeholders' feedback. Designing alternative solutions based on an alternation between synthesis and analysis processes requires a constant evaluation of these solutions. Decisions are evaluated based on performance and success criteria before, during, and after their implementation. Evaluation also serves as the link to the global pathways of innovation based on integrated values. These values are the key building block on which the evaluation should build up for coining a sustainable transformation towards higher sustainability maturity levels. In the context of the macro cycle, continuous evaluation requires the conduction of experiments and is necessary to safeguard the overall manufacturing SoS, (sub-)system, and domain properties. Modeling the SoS, its (sub-)systems, and domains digitally and tangibly is an important aspect to validate and evaluate ideas, solutions, and artifacts in this regard. All ideas, solutions, and artifacts related to the innovation resulting from the earlier and later phase of the design process can be evaluated against the backdrop of the integrated values. By utilizing integrated values, the innovation's footprint can be minimized, and its handprint maximized for the life cycle phases.

4.4 Principles for sustainable innovations

The integration of the principles for sustainable innovations into the micro cycle is based on Visser's research on global pathways of innovation in different economic spheres (Figure 8). In this context, integrated values are characterized by creating capital across the economic spheres through innovation, leading to more secure, smart, shared, synergetic, and satisfying solutions.

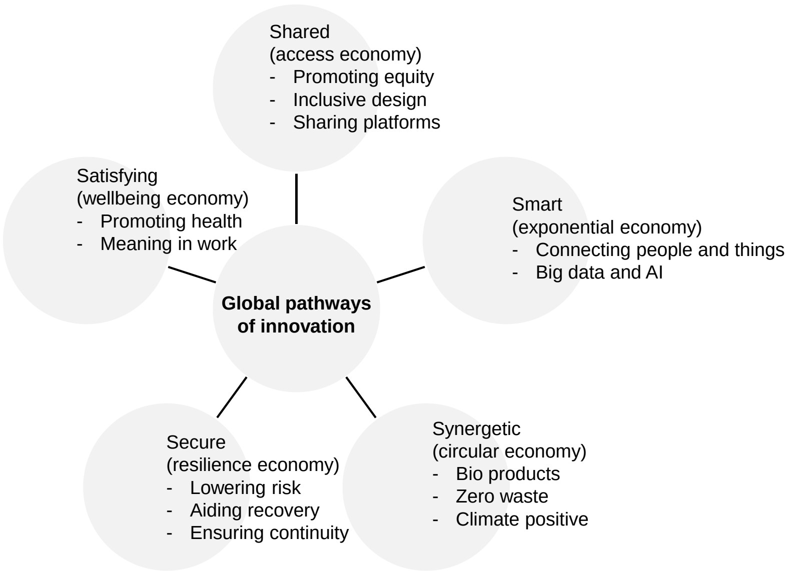


Figure 8. Global pathway of innovation (following the ideas of [12])

Realizing integrated values means that ideas, solutions, and artifacts which are being developed during the design of the innovation are constantly evaluated against their contribution to these economic spheres. For each of the economic spheres, different principles can be applied to evaluate and systematically improve the value generated by the innovation. Table 3 lists 29 principles for sustainable innovation in the different economic spheres. The 29 principles are qualitative per se and should be rather seen as broad principles guiding the innovation process. This allows the manufacturing company to define the specific implementation and evaluation metrics according to their individual needs.

Table 3. Principles for sustainable innovations (adapted from [12])

Economic spheres	Innovation pathways	Principles for sustainable innovation facilitate…
Resilience Economy	Secure	1) …readiness for preparing, responding, and recovering from emergencies and catastrophes 2) …awareness about risks and risk mitigation and adaption 3) …agility and adaptability to new system boundaries and frame conditions 4) …robustness of the system and its sub-systems 5) …redundancies in sub-systems 6) …human resilience through emotional, psychological, and physical support of employees 7) …realization of opportunities in crisis 8) …continuity throughout system processes
Exponential Economy	Smart	9) …democratic governance on macro and micro levels 10) …connection of people and things 11) …utilization of automated solutions 12) …application of artificial intelligence in systems and sub-systems 13) …implementation of digital twins for systems and sub-systems
Access Economy	Shared	14) …diversity for more inclusive workplaces and working environments

		15) …transparency about the distribution of value in systems 16) …inclusive workplaces, which value the diversity that fairly represents gender, ethnicity, age, and abilities 17) …inclusive organizational forms 18) …shared models of production and consumption, which offer functionality rather than ownership
Circular Economy	Synergetic	19) …bionics, biomimicry, and nature-inspired solutions throughout systems and sub-systems 20) …biobased solutions for fully biodegradable end-products 21) …usage of renewable energy and resources for creating value 22) …zero waste in the system process 23) …closed-loop life cycles for system artifacts: components, parts, products 24) …industrial symbiosis ecosystems with cross-company waste and resource streams
Wellbeing Economy	Satisfying	25) …human health 26) …meaning in work 27) …quality of life 28) …happiness and wellbeing 29) …high-quality services for satisfying human needs

5 CASE STUDY

5.1 Overview

The tower height is often the efficiency-limiting component of a wind turbine. The SmarTower innovation aims to tackle this challenge by providing a new tower system for wind turbines. The case study is based on a typical manufacturing engineering project which was conducted between 2012 to 2015 in research cooperation between Technical Universitaet Berlin (TU Berlin) and a berlin-based manufacturing SME and is an expansion and further development of the case initially presented in [13]. Multiple research engineers and more than 10 engineering students from TU Berlin as well as manufacturing engineers from the SME were involved in the tower design process. The sustainability perspective of the system was an important research aspect throughout the whole project. Firstly, the beneficial sustainability impact of the innovation was important for the funding agency. Secondly, realizing the competitive advantages linked to sustainable value creation (also highlighted in Figure 1) was substantially important for the SME; especially since a novel wind turbine tower system has a relatively high hand- and footprint, e.g., through the materials used, affects many stakeholders, e.g., local communities at the site of operation, and holds a great risk in case of potential failures.

5.2 Macro cycle

5.2.1 Cognition

The novel tower system aims at reducing the material, manufacturing, and transportation costs as well as at increasing the efficiency and service life of a wind turbine. The SmarTower system is characterized by a tower profile for reduced wind resistance, a modular lightweight structure, and a ground-based azimuth bearing for wind tracking (Figure 9) [13]. Shaping the idea for the tower system is linked to cognition during the earlier phase of the innovation process.

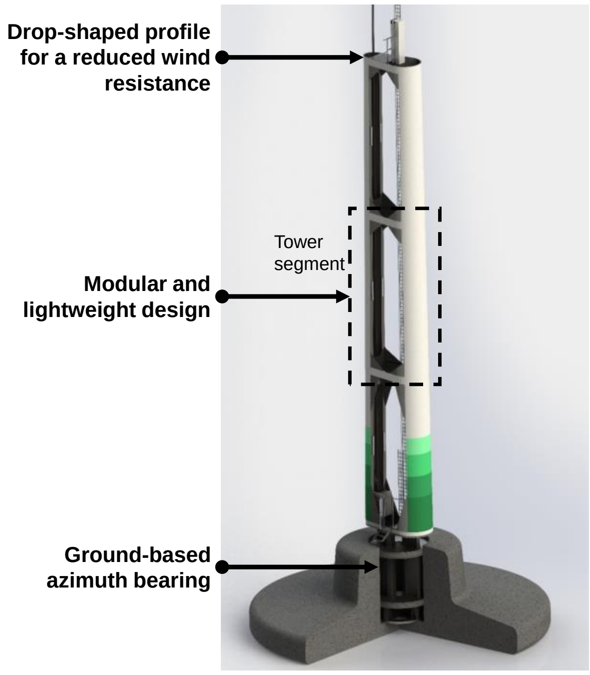


Figure 9. Concept of the novel SmarTower system

5.2.2 System design

The system design aims at developing a concept for the overall system architecture of the SoS, i.e., the SmarTower, with its (sub-)systems and domains. The starting point of the system design phase is to create a list of requirements for the overall system and its (sub-)systems i.e., for the value proposition, value network, and value distribution. This list of requirements is intended to be a living list or "flexible backlog" which evolves with the progress of the design process. Reviewing the state-of-the-art and expected future developments, i.e., technological, and economic trends in the field of wind turbines, as well as analyzing relevant standards, guidelines, and certificates for wind turbine systems, are together with investigating competitors, suppliers, customers, and substitutes relevant activities for creating the initial list of requirements.

For conceptualizing the system architecture, an emphasis is put on the value proposition in this case, since this (sub-)system is the most relevant for the manufacturing SME. The value proposition is defined by the tower system. The conceptualization phase is coined by the following activities. A structural load hypothesis for rated operation and storm operation of the wind turbine mainly resulting from wind forces, rotor shearing forces, and weight forces is carried out. The relevant main and supporting functions for the different domains of the value proposition are determined. The main functions are mapped according to principal solutions using morphological analysis. Promising design variants for the overall tower system are selected and evaluated. In terms of conceptualizing the value network and distribution, the following activities are conducted. Hypotheses for the domains of the value distribution and the value network are created. Critical cost drivers are identified. They are linked to the quantities of materials used as well as to the manufacturing and assembly technologies and process used for manufacturing the tower system.

5.2.3 Domain-specific design and system integration

The domain-specific design aims at developing the domains of the (sub-)system based on the SoS architecture created during the system design phase. Designing the different domains of the value proposition covers the design of the hardware system with its mechanical structure, electrical and electronics, software, and services as relevant artifacts of the tower system. The dimensioning of the tower segments through optimizing the static and dynamic load of the mechanical structure is at the core of the hardware design. Finite element simulations of parameterized CAD models of the mechanical tower structure are used for making iterative design improvements toward a lightweight and modular design (Figure 10). Hereby, the design of the connecting elements is highly relevant since they essentially contribute to the stability of the whole tower. For this reason, different design variants of flanges are created and iteratively improved based on a finite element simulation of the mechanical stress for each of the variants. Additionally, the ground-based azimuth bearing, as well as the secondary function carriers, are designed e.g., the cladding, the elevator, the lighting, the cable routing, etc. The electrical system is designed based on mapping the automation, measurement, and control functions with principle solutions for sensors and actuators. Subsequently, specific sensors, and actuators for wind tracking of the tower system, avoiding cable twists, breaking the movement motion of the tower system, and measuring the vibrations, for safety and maintenance are evaluated and selected. The design of specific services or software systems is not the focus of the SmarTower project. However, the SME intends to carry out the maintenance services related to the tower and azimuth bearing over the use phase of the system.

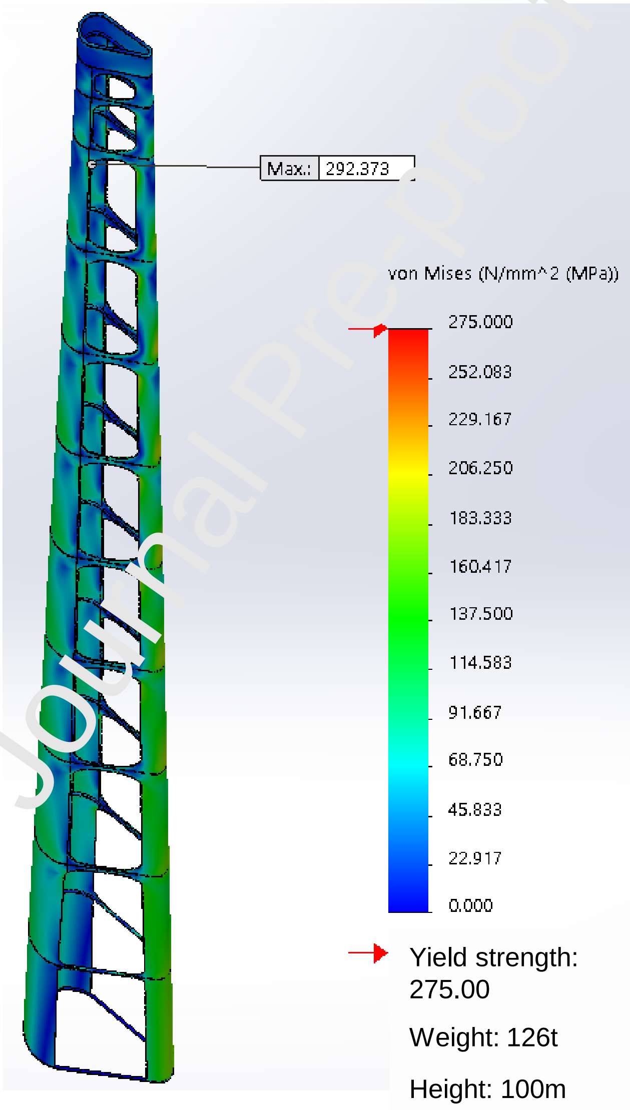
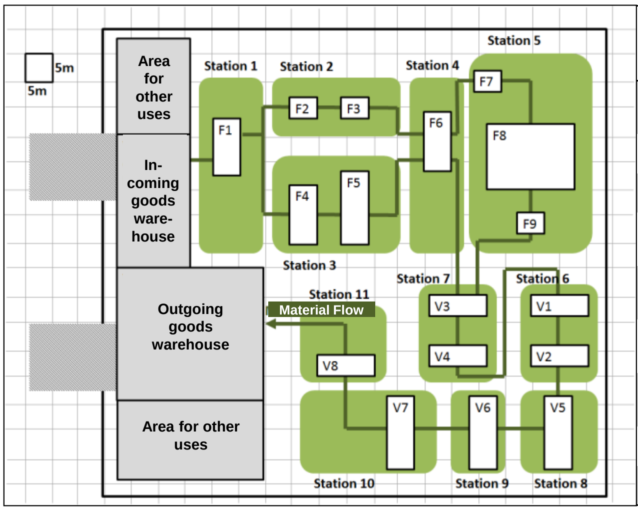


Figure 10. Design solution of the mechanical tower structure

The design of the different domains of the value creation network is essentially addressing the design of the manufacturing process chain and factory layout including the on-site assembly processes chain, and the transportation concept from manufacturing to the assembly site. The manufacturing process chain is designed together with the tower and its components in an integrated manner. The process chain covers the sequence of manufacturing processes to manufacture the selected design variants of the tower segments and the bearing. Subsequently, the layout of the manufacturing site is determined (Figure 11). This includes the decision on the material flow of components and semi-finished parts, aggregating manufacturing processes to manufacturing stations, and defining the space for the stations and warehouses. The average throughput time of one tower system is estimated at 81,5h.



Steps (components)	Manufacturing processes	Steps (for both components)	Galvanizing processes
F1 (Segment/ Flange)	Plasma cutting	V1	Pickling
F2 (Flange)	Finishing	V2	Rinsing
F3 (Flange)	Profile bending	V3	Degreasing
F4 (Segment)	Finishing	V4	Rinsing
F5 (Segment)	Roll bending	V5	Fluxing
F6 (Segment/ Flange)	Stress relief heat treatment	V6	Galvanizing (furnace)
F7 (Flange)	Submerged arc welding	V7	Galvanizing (zinc bath)
F8 (Flange)	Drilling	V8	Cooling
F9 (Flange)	Finishing		

Figure 11. Manufacturing layout (adapted from [13])

The on-site assembly includes the description of process steps which need to be conducted on the construction site from topsoil work up to the assembly of the bearing and tower, the installation of the nacelle, as well as all required electrical installation and commissioning (Figure 12).

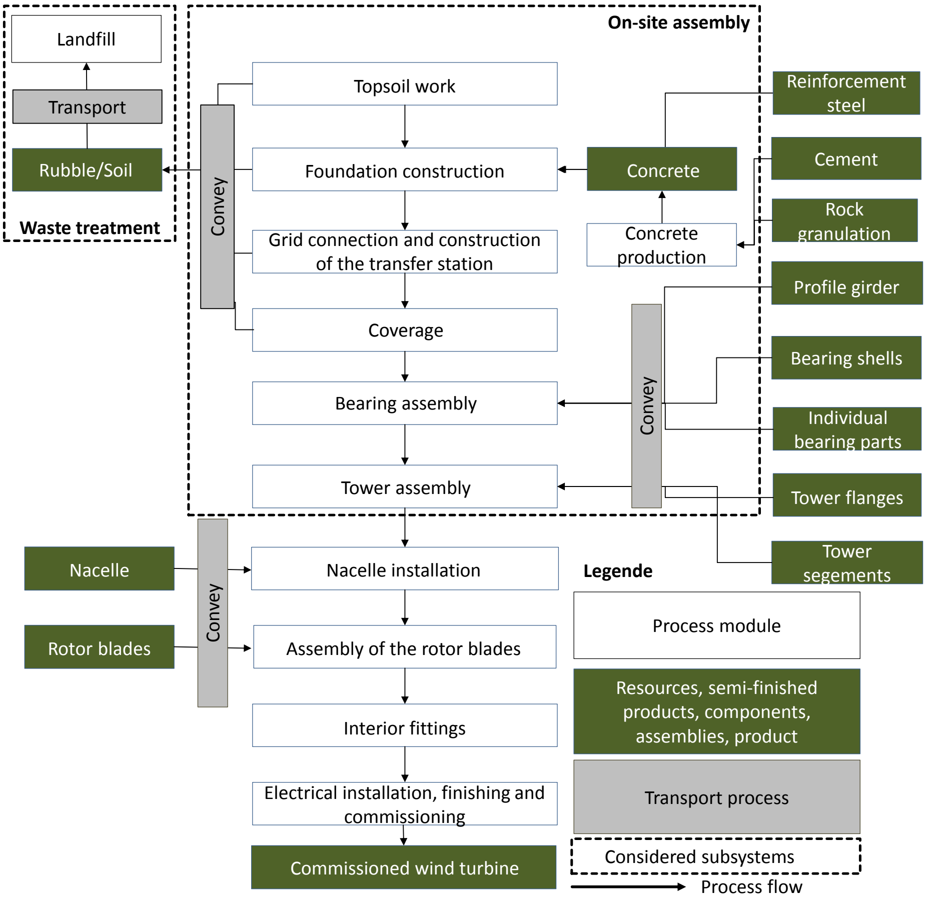


Figure 12. On-site assembly process (adapted from [13])

Figure 13 shows the key process steps for assembling the tower system on-site. The tower assembly is thereby dependent on the selected design variants for the flanges since they are providing the function of connecting the bearing to the tower segments, connecting tower segments to segments as well as connecting the nacelle to the tower. Eventually, the maximum process times for manufacturing and on-site assembly of the tower system are approximated at 96h. The design of a transportation solution for bringing the tower system to the location of the on-site assembly especially focuses on adjusting the design of all tower components to the dimensions of an ISO-40-foot container. In other words, all components of the tower need to fit inside the container for transportation. This aspect is for the SmarTower of high relevance since the standardized and cost-reduced transportation of the whole system is one of the imported value propositions of the innovation.

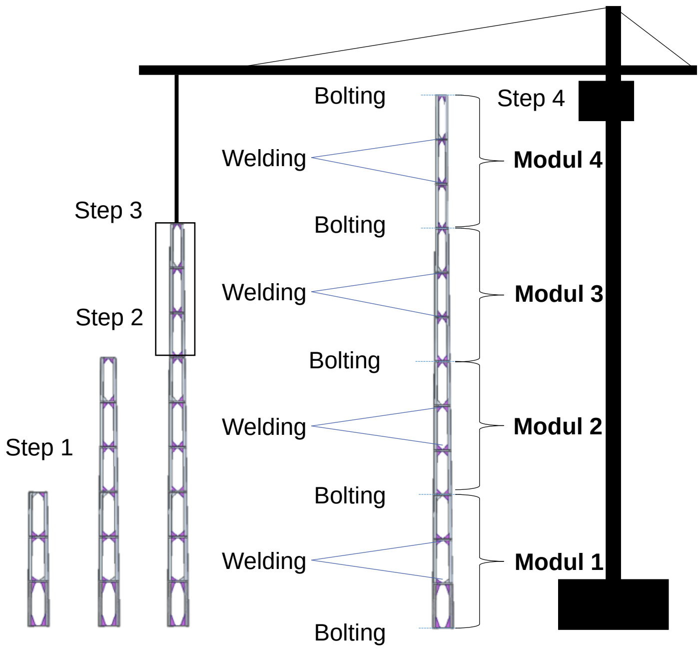


Figure 13. On-site tower assembly

The design of the cost domain is the most relevant activity linked to designing the value distribution (sub-system). An analysis of competitors' products revealed the target costs for the tower system. Based on the design of the tower system, the selected manufacturing, assembly, and transportation solutions, the sourced components for the electrical system, and the production and transportation costs of the tower system are approximated and continuously updated according to new design iterations of all domains. A profound design of the channels, customers, and sales is not conducted as part of designing the value distribution system since it is not the focus of the project.

The design of the domains requires continuous integration of the design solutions. The system integration is based on creating experiments for testing the interfaces and the intended interplay between the individual design solutions generated in the specific domains. Integration is conducted continuously throughout the whole system design phase. In terms of the tower system, the integration of solutions is essentially important for adjusting the manufacturing process chain and assembly processes to the design of the tower segments and bearing as well as for keeping the design of the tower and bearing within the technological boundaries of the manufacturing and assembly processes. Another important integration activity is to ensure that the tower segments and the bearing can be transported with an ISO-40-foot container. The stacking of the assemblies in the container is tested by using digital models. Another example of continuous integration is the adaption of the cost model according to the recent design solutions for the value proposition and value creation networks and their domains. The system integration eventually aims to identify faults and challenges as well as to verify the properties of the overall SoS. The system integration continuously runs in parallel to the domain-specific design process until the innovation has reached a maturity level where it can be released to the market.

5.2.4 Hand- and footprint of the SmarTower during its life cycle

The Life Cycle Assessment (LCA) approach according to ISO 14040 [59] provides the theoretical foundation for determining the hand- and footprint of the system. The relevant stages of an LCA are depicted in Figure 14.

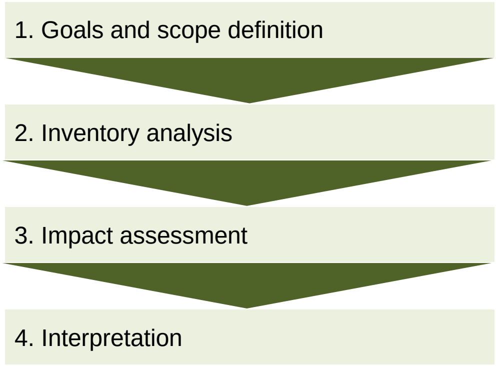


Figure 14. Stages of an LCA [59]

Determining the product system of the SmarTower with its relevant life cycle phases (Figure 15) is essential for the goal and scope definition of an LCA. The handprint i.e., the positive impacts of the innovation on society and the environment, resulting from achieving 30% material savings and 30% savings in transportation efforts compared to conventional tower systems for wind turbines as well from realizing a 30% longer use phase, due to reduction of the dynamic load and the yield loss from the windward wind jam when the rotor blade passes the tower system. The footprint is determined by the negative environmental impacts.

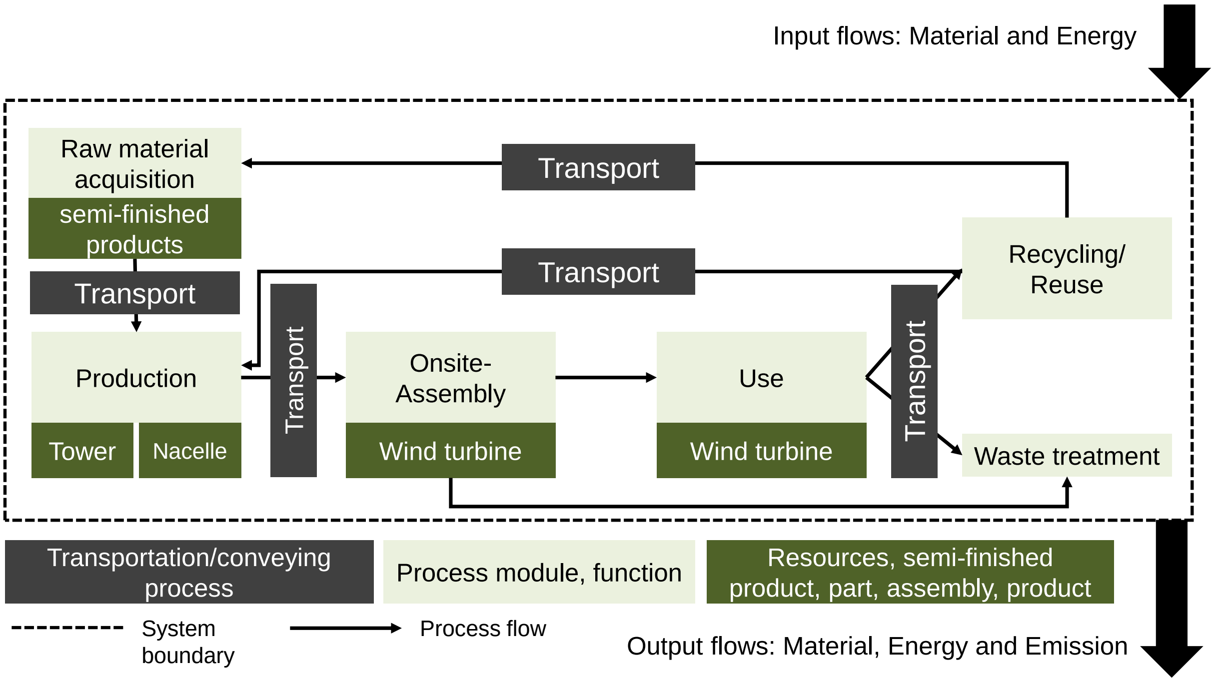


Figure 15. Product system of the SmarTower

For analyzing the footprint, relevant material and energy input and output flows and related CO2 emissions are calculated for each of the life cycle phases (Table 4 and Figure 16) as part of the inventory analysis stage of the LCA.

Table 4. Environmental footprint – Materials

Product component	Material	Mass [kg]]	Quantity

Flange (tower)	Structural steel (S355)	400	28
Tower segment (tower)	Structural steel (S355)	10.000	14
Concrete (foundation)	Concrete	1.300.000	1
Reinforcement steel (foundation)	Structural steel (BSt500)	50.000	1

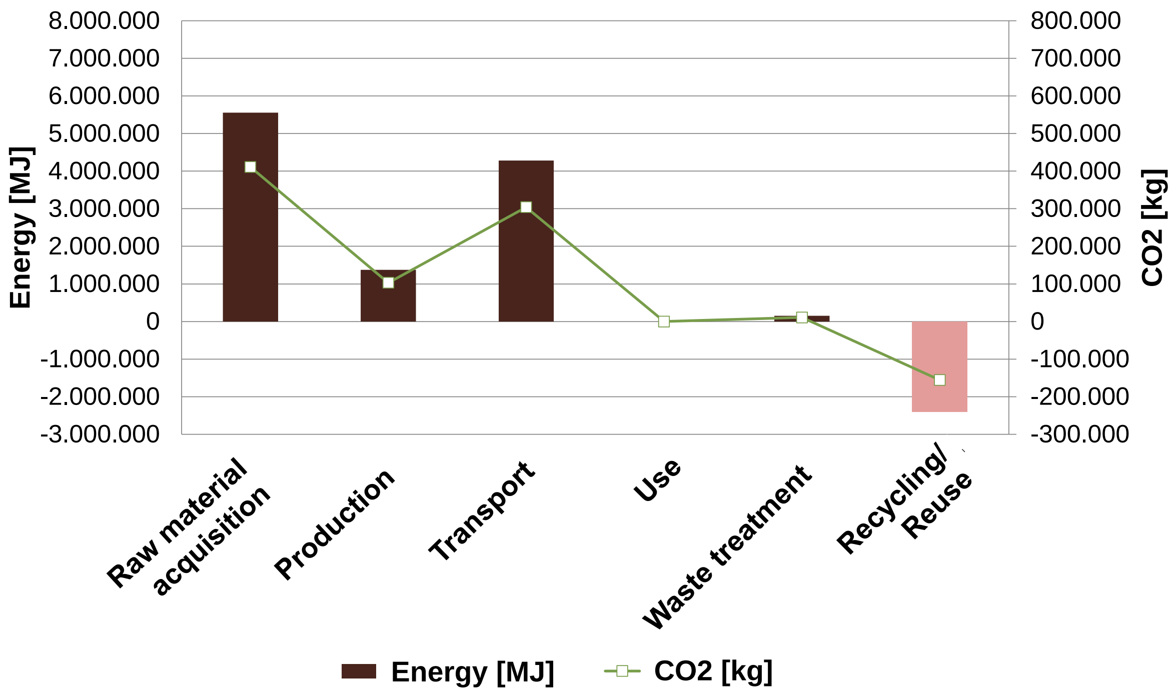


Figure 16. Environmental footprint – Energy

The input and output flow provides the building block for the impact assessment and the subsequent interpretation. The results of the impact assessment and interpretation stage of the LCA are shown in Table 5. This stage includes an evaluation of the relevant impact categories through a weighted scoring method. The scores and weights for the individual impact categories are created based on a joint discussion of the engineering team.

Table 5. Evaluation of the impact categories

Impact category	**Weight**	**Score (1-10)**	**Weighted score**
Impact on ecosystem			
Physical damage	0,05	5	0,25
Recycling capability	0,1	7	0,7
Change in the landscape	0,05	3	0,15
Impact on living beings			
Danger for living beings	0,1	4	0,4
Human toxicity	0,15	9	1,35
Impact on Lithosphere (soil)			
Space requirement	0,05	5	0,25
Scarcity of abiotic resources (without water)	0,1	8	0,8
Scarcity of abiotic resources	0,05	8	0,4
Emissions (entering ground)	0,1	8	0,8

Impact on Hydrosphere (water)			
Scarcity of water	0,05	8	0,4
Emissions (entering water)	0,1	8	0,8
Impact atmosphere (air)			
Emissions (entering air)	0,1	9	0,9
Overall evaluation			**7,2**
Score: 1 – very poor, …, 10 – very good			

Next to the more environmental-oriented LCA, also a social LCA is conducted. This includes the identification of relevant stakeholders and the analysis of potential risks for them. Table 6 shows an example excerpt of the risk assessment for different stakeholders. Relevant direct stakeholder groups are value chain actors, workers, customers, local communities, and society. Examples of indirect stakeholder groups are national organizations such as public authorities, labor associations, or commerce and trade associations. However, a quantitative assessment of social impact categories is often difficult due to a lack of data [60]. For this reason, an emphasis of the social LCA is put on examining social acceptance as the main impact category. Societal acceptance describes the reception and adaption of the SmarTower tower system by the direct and indirect stakeholders that are influenced by the tower system during its life cycle. The focus of the study is put on the use phase of the tower, especially focusing on the acceptance of the local community towards the novel design and appearance of the tower system. The social acceptance of individuals, in this case, is evaluated through a survey asking different people about the aesthetics of the SmarTower compared to a conventional tower system.

Table 6. Example of a risk assessment for stakeholders

Stakeholder	Potential risk	Worst case consequence	Possible causes
		Society	
	Dwindling acceptance of wind turbines in general	Decrease in the number of new wind turbines (WT) built per year	Changes in the preferences of society caused by "negative campaigns" or lobbying
	Energy generation shifting to substitutes (e.g., solar energy, gas)	Decrease in the number of new WT per year/dismantling of existing wind turbines	Problems with grid connection; reduction in guaranteed feed-in tariff; overcapacity; change of federal government policy; technology leaps of substitutes
		National organizations	
Lobby groups	Lobbying against wind energy	New regulations for the approval of the operation of a WT; exclusion of specific regions for WT use (e.g., forest areas).	New scientific findings; changes in legal framework; increase in organized wind energy opponents.
Federal Wind Energy Association	No acceptance of the SmarTower system	No demand for the tower system among wind turbine operators and manufacturers	Insufficient marketing, lobbying

The acceptance of companies or local communities who act as operators of wind turbines is also driven by economic interests such as cost and revenue. The life cycle cost (Table 7) and life cycle revenue (Table 8) are calculated for a wind turbine that is using the novel SmarTower as a tower system. The revenue is thereby dependent on the feed-in tariff as well as on the location of the wind turbine.

Table 7. Life cycle cost (adapted from [13])

Product Development (Development, Supply, Manufacturing)	
Project Planning and Product Design	96.950 €
Manufacturing Tower and Foundation	503.000 €
Manufacturing Nacelle and Rotor Blades	1.472.691 €
On-site Assembly and Transport	370.000 €
Total Costs Product Development Phase	2.442.647 €
Use (20 Years)	
Operation	54.000 €
Maintenance	30.000 €
Total Costs Use Phase	84.000 €
End-of-Life	
Total Costs End-Of-Life Phase	78.000 €
Life Cycle	
Total Costs Life Cycle	**2.604.674 €**

Table 8. Life cycle revenue for use phase of 20 years (adapted from [13])

Feed-in tariff [Cent/kWh]:	5	9	12
Onshore	2.608.233 €	6.688.233 €	9.748.233 €
Coastal	3.383.233 €	8.083.233 €	11.608.233 €
Offshore	4.858.233 €	10.738.233 €	15.148.233 €

Continuously determining the hand- and footprint for the solutions developed throughout the different (sub-)systems of the innovation allows reveal and track relevant positive and negative life cycle impacts qualitatively and quantitatively. The hand- and footprint also enable the prioritization of impacts in terms of their degree of severity as well as the identification of "low-hanging fruits" for subsequent improvements of the manufacturing SoS.

5.3 Micro cycle

5.3.1 Stakeholders and problems

The stakeholder phase of SPADE includes the continuous search for, identification of, and engagement with relevant stakeholders. The hand- and footprint of the innovation provide the starting point for mapping the values for the different stakeholder categories including the environment. For this purpose, the value mapping tool [47] is applied to continuously track the captured, destroyed, missed, and wasted values, as well as value opportunities. Subsequently, a TRIZ-inspired approach, following the concept from [13], is selected to unravel contradictions of the current design solutions to the essential ideas of the global pathways of innovation (Figure 4) and their related principles (Table 3). The contradictions eventually create a set of problems for the development of sustainable solutions. Figure 17 shows the process for deriving relevant problems related to global pathways of innovation based on the hand- and footprint of the tower system.

Some relevant contradictions of the tower system to the synergetic innovation pathway are:

- The subsequent use and reuse of the tower foundation as well as of the tower and bearing modules is unclear during the end-of-life phase.
- Regional stakeholders (residents, and communities) are not involved in the design of the tower system, and its characteristics; especially safety aspects of the novel tower system, are not communicated to the stakeholders.
- Substantial changes in the landscape are resulting from sealing the ground and the overall physical appearance of the tower.

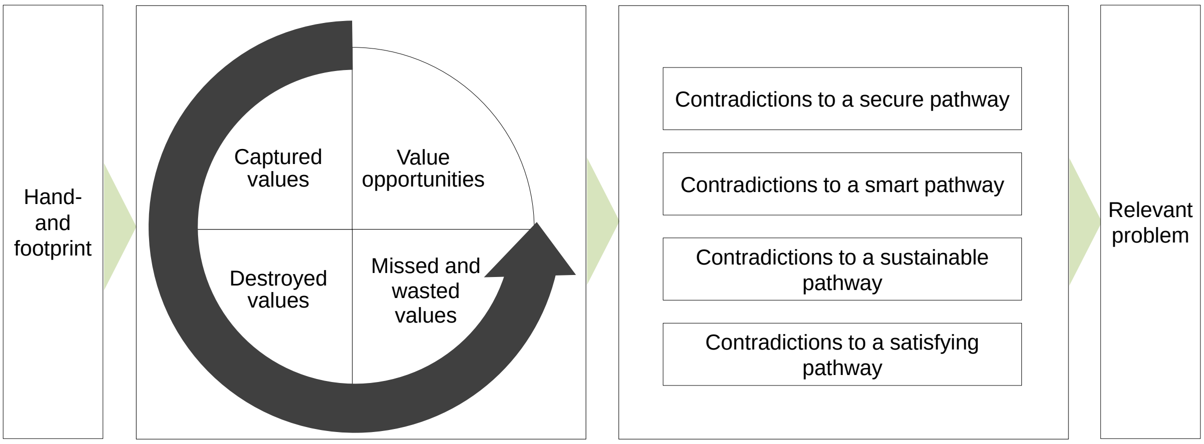


Figure 17. Process for deriving relevant problems related to global pathways of innovation inspired by the TRIZ approach (following the ideas from [13, 47])

A pertinent contradiction to the synergetic innovation pathway is the not existing approach for the end-of-life of the tower foundation, which in turn has a significant impact on the material footprint of the SoS. The contradiction is:

- “Closed-loop life cycles for system artifacts” (principle 23 (Table 3)) versus “present solution for reusing or recycling the foundation”

This contradiction can be deconstructed into a more basic value-oriented contradiction according to [19]:

- “Use of natural resources” versus “profit/economy".

In other words, the contradiction specifies that the use of natural resources within the end-of-life phase might be improved while the profit might be deteriorating if the present solution will be changed due to the increasing complexity of the value creation.

5.3.2 Alternatives

To overcome and resolve the contradiction, alternative system solutions are designed. In this case, alternative solutions are targeted at improving the profit while also trying to realize a closed-loop material flow. Figure 18 shows an alternative solution that is based on an industrial symbiosis approach in a way that the waste stream linked to the concrete of the foundation serves as valuable input for another value creation step i.e., as crushed sand for the road construction and as recycled concrete for concrete manufacturing. This solution leads to an increase in profits while also contributing to the realization of closed-loop life cycles, and by doing so, it overcomes the initial contradiction.

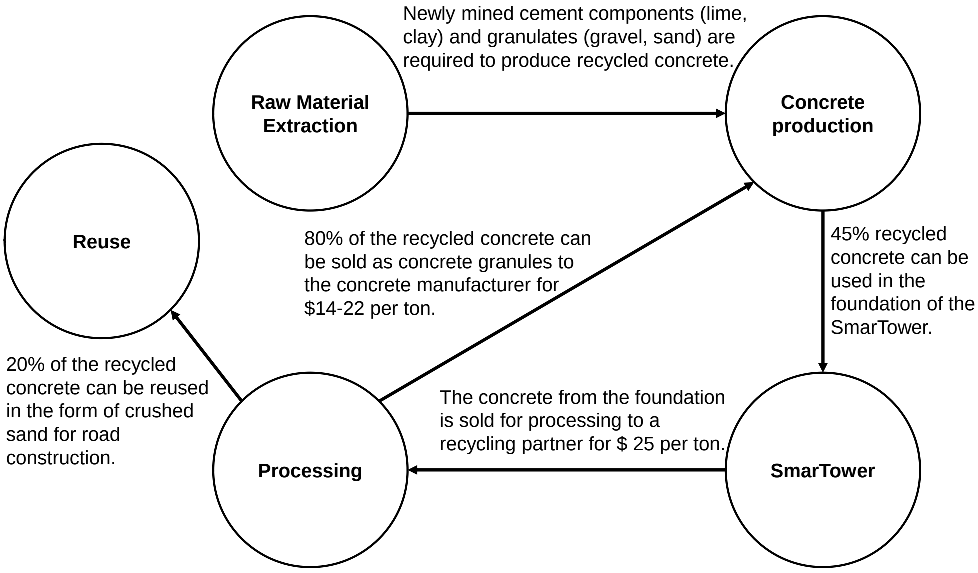


Figure 18. Alternative solution for the end-of-life of the tower foundation (adapted from [13])

5.3.3 Decision and evaluation

The decision-making sets out the action plan for integrating the industrial symbiosis approach into the respective (sub-)systems and domains of the innovation. In this case, the value network with its subsystems is mainly affected by the new industrial symbiosis solution. For example, the identification of possible recycling partners who agree to further process the concrete of the foundation is a relevant follow-up action.

Evaluation is continuously carried out to adopt alternative solutions to new learnings and to integrate stakeholders' feedback. In the case of the SmarTower, the evaluation of the solutions’ contribution to ensuring and increasing the SME's competitiveness is of utmost importance. For this purpose, the evaluation scheme highlighted in Figure 1 is applied. The scheme shows competitive advantages linked to global pathways of innovation. For the selected alternative solution, the profit increase and cost reduction resulting from the industrial symbiosis approach for improving the end-of-life of the concrete are direly contributing to increasing the competitiveness of the innovation.

5.4 Critical reflection

The SmarTower case study shows that the procedure of the macro cycle offers principal efficacy for designing a complex innovation in manufacturing. The systems engineering approach allows shaping the relevant (sub-)systems and domains of the manufacturing SoS linked to the value proposition, value network, and value distribution. The micro cycle reflects a suitable procedure for improving the hand- and footprint over the life cycle of the innovation by ensuring the design solutions that improve the integrated value of the SoS. For this purpose, the case study presents the application of a TRIZ-inspired tool for solving system contradictions related to the global pathways of innovation and their relevant principles for sustainable innovation (Table 3).

Since the case study only covers the design of one exemplary innovation of a manufacturing system, with a focus on large-scale products, it has some limitations in terms of its transferability to the design of innovations with different characteristics, for example, more process-, service-, or software-oriented innovations, or innovations addressing rather small-scale products. Yet, the authors believe that the proposed systems engineering approach offers an efficacious guideline for innovating manufacturing SoS in general due to the generic nature of the macro and micro cycle. However, for the design of mere software- or service-oriented innovations, specifically tailored design and engineering approaches might be more suitable for realizing an effective and efficient innovation process.

The case study only allows a limited quantitative evaluation of the efficacy as no measurable performance indicators have been predefined for the design process of the innovation. A metric to quantify the numerous indicators might be helpful and should be considered a relevant aspect of future research. However, all intended design results and artifacts, e.g., FEM simulation or CAD files, for the SmarTower are realized. Eventually, a comparison of the proposed systems engineering approach, with its macro and micro cycle, with other design procedures was not in the scope of this research.

6 CONCLUSIONS

The research presented a novel systems engineering approach for creating sustainable innovations in manufacturing systems. The approach aims at supporting manufacturing companies in coping with the global challenges while maintaining and improving the competitiveness of the companies' value creation. Against this backdrop, the research paper first discussed the concept of integrated values and global pathways of innovation for setting the scope and practical relevance of the research. Subsequently, the state-of-the-art based on a literature review for the earlier and later phase of the sustainable-oriented innovation process was described, and the resulting research gap, contribution, and novelty was specified. Then, the novel systems engineering approach for creating sustainable innovations in manufacturing systems, based on a specific macro and micro cycle was explained. The macro cycle determines the important design phases for the life cycle of the innovation while the micro cycle provides a process for finding sustainable solutions during the design process. For this purpose, the micro cycle utilizes specific sustainability principles which have been derived from the idea of integrated values and global pathways of innovation. A case study based on an innovative wind turbine tower system was introduced to verify, validate, and evaluate the proposed systems engineering approach. Eventually, the principal efficacy and limitations of the research were discussed taking into consideration the findings of the case study. The case study showed that the procedure of the macro cycle demonstrates a principal efficacy for the design of complex innovations in manufacturing, while the micro cycle offers a suitable process for improving the sustainability aspects over the life cycle of the innovation. However, the case study only covered the design and prototypical implementation of a specific, large-scale wind turbine tower system and did not address the actual implementation of the final tower system within a real business case. The methodology has some limitations in terms of its transferability to systems with different characteristics, for example, more process-, service-, or software-oriented innovations or small-scale product systems. In the future, the authors plan to apply the presented systems engineering approach within more industrial settings to also gather more information and feedback about the relevance for manufacturing companies to cope with the future global challenges.

7 ACKNOWLEDGEMENTS

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: