Sustainable Value Creation by Applying Industrial Engineering Principles and Methodologies

vorgelegt von

Dipl.-Ing. Pinar Bilge

geb. in Istanbul

von der Fakultät V – Verkehrs- und Maschinensysteme –

der Technischen Universität Berlin

zur Erlangung des akademischen Grades

DOKTORIN DER INGENIEURWISSENSCHAFTEN

– Dr.-Ing. –

genehmigte Dissertation

Promotionsausschuss:

Vorsitzender:		Prof. Dr.-Ing. Henning Jürgen Meyer
I.	Gutachter:	Prof. Dr.-Ing. Günther Seliger
II.	Gutachter:	Prof. Dr. I. S. Jawahir
III.	Gutachter:	Prof. Dr.-Ing. Jörg Krüger

Tag der wissenschaftlichen Aussprache: 25.05.2016

Berlin, 2017

To my beloved parents

Abstract

The world already exhausts its limited resources in economic, environmental and social manner. This limitation forces engineering to handle conflicting goals of technology and management in global value creation networks. As manufacturing determines the ratio between input as resources and output as functionality, the reasonably demanded sustainable value creation utilizes dynamics of competition and cooperation for stimulating processes of innovation and mediation. Sustainable value creation in manufacturing applies following principles: selling functionality instead of products in economic dimension, processing resources in multiple life cycles and substituting non renewables by renewables in environmental dimension and increasing awareness and motivation about sustainability in social dimension.

Sustainable value creation is coined by the integration of technological and management methodologies based on projects. In order to cope with the sustainability challenge by developing and implementing technological solutions within the frame of regional conditions, engineers can widen the solution space. This requires a change of thinking habits in engineering and action plans in order to transform educational programs.

Two educational case studies demonstrate the transformation of interdisciplinary programs in industrial engineering according to the requirements of local academia as well as the implementation of project based courses with industrial partners. Shaping sustainable value creation is achieved by developing innovation, entrepreneurship and creativity in emerging markets.

Three technological case studies demonstrate how transformed programs based on sustainability challenges in higher education enable engineers to create sustainable value in developed and emerging countries through synergies between technology and management. International interdisciplinary students and scientists implement transformative engineering within the three case studies. Hybrid energy generation and water supply in agricultural production increases resource efficiency. Redesigning handling equipment for remanufacturing of turbine blades as components of gas turbines improves ergonomics and quality. Simulation-based redesign of the maintenance and repair network for vehicles as part of service fleet for waste collection and cleaning increases productivity. The depth of sample implementation in manufacturing is combined with the breadth of systematic analysis and synthesis along the economic, environmental and social sustainability dimensions.

Kurzfassung

Die begrenzten Ressourcen der Erde werden gegenwärtig über jedes ökonomisch, ökologisch und sozial verantwortbare Maß beansprucht. Für die Ressourcennutzung in globalen Wertschöpfungsnetzen ergibt sich ein Spannungsfeld zwischen Technologie und Management. Bestimmt die Produktionstechnik das Verhältnis zwischen Nutzen und Ressourcenverbrauch in der industriellen Wertschöpfung, so wird die rational gebotene Nachhaltigkeit unter Nutzung der marktwirtschaftlichen Dynamiken von Zusammenarbeit und Wettbewerb durch technologische Innovation ermöglicht. Prinzipien der nachhaltigen Wertschöpfung sind der Nutzen- statt des Produktverkaufs in ökonomischer Dimension, die Ressourceneinsparung durch Kreislaufführung und Substitution nicht nachwachsender durch nachwachsender Rohstoffe in ökologischer Dimension sowie die Vermittlung der Nachhaltigkeitsperspektiven in sozialer Dimension.

Der vorgestellte Ansatz ist auf nachhaltige Wertschöpfung durch Integration von ingenieur- und wirtschaftswissenschaftlichen Methoden über Instanziierung in Projekten gerichtet. Indem technologische und organisatorische Lösungen in der Wertschöpfung nach Maßgabe regionaler Rahmenbedingungen entwickelt werden, können Ingenieure Lösungsräume zur Bewältigung der Nachhaltigkeitsherausforderungen erschließen. Hierzu bedarf es einer Wandlung der ingenieurwissenschaftlichen Denkmuster und der damit einhergehenden Maßnahmen in Aus- und Weiterbildung.

In zwei bildungsorientierten Fallbeispielen werden interdisziplinäre Studienprogramme für Wirtschaftsingenieurwesen entsprechend den Anforderungen der regionalen Hochschullandschaft konzipiert sowie durch projektorientierte Lehre und Forschung mit der Industrie instanziiert. Ziel ist die Gestaltung nachhaltiger industrieller Wertschöpfung durch die Erschließung von Innovation, Initiative und Kreativität in Zukunftsmärkten.

Drei technologieorientierte Fallbeispiele demonstrieren, dass an Nachhaltigkeits-anforderungen angepasste Aus- und Weiterbildungsprogramme Ingenieure dazu befähigen, in Industrie- und Schwellenländern durch Synergien zwischen Technologie und Management in ökonomischer, ökologischer und sozialer Dimension nachhaltige Wertschöpfung zu erschließen. Internationale interdisziplinäre Gruppen von Studierenden und Wissenschaftlern bearbeiten hybride Energie- und Wassergewinnung zum Abbau ökonomischer und ökologischer Grenzen bei agrarwirtschaftlicher Produktion. Ein flexibles Werkzeug für Handhabung und Transport verbessert Ergonomie und Qualität bei der Wiederaufbereitung von Turbinenschaufeln. Im Bereich der Wartung und Reparatur von Fahrzeugen von Stadtreinigung und Müllsammlung wird durch simulationsgestützte Neugestaltung eines Instandhaltungsnetzes die Dienstleistungsproduktivität erhöht.

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°C	Degree Celsius as a unit of temperature on the Celsius scale
3D	Three-dimensional
ABET	Accreditation Board for Engineering and Technology
acatech	National Academy of Science and Engineering, in German: Deutsche Akademie der Technikwissenschaften
app	Software application for mobile devices
APS	Agricultural production system
ASIIN	Accreditation Agency for Degree Programs in Engineering, Computer Science, Natural Sciences and Mathematics
BMBF	German Federal Ministry of Education and Research, in German: Bundesministerium für Bildung und Forschung
BSC	Balanced Scorecard
CAD	Computer-aided design
CAE	Computer-aided engineering
CNC	Computerized Numerical Control
CO_2	Carbon dioxide
COP21	21st Conference of the Parties or Paris Climate Conference
CRC	Collaborative research center
CURO	Centrifuging Ultrafiltration Reverse Osmosis
DAAD	German Academic Exchange Service, in German: Deutscher Akademischer Austauschdienst
ECTS	European Credit Transfer and Accumulation System, reads as credit points according to ECTS
ERP	Enterprise resource planning
EU	European Union
EUR	Unit specified by the European Union
FIFO	First-in-first-out
FMEA	Failure mode and effects analysis

GDP	Gross domestic product
Georgia Tech	Georgia Institute of Technology
GPEM	Global Production Engineering and Management
i.e.	in Latin: id est, in English: that is
IoT	Internet of Things and Services
ISO	International Organization for Standardization
IT	Information and communication technologies
IWF	Department of Machine Tools and Factory Management, in German: Institut für Werkzeugmaschinen und Fabrikbetrieb
KAIST	Korea Advanced Institute of Science and Technology
kg	Kilogram as a unit symbol of mass according to the International System of Units
KW	Kilowatt as a unit for measuring power, equal to 1.000 watts
kWh/m^2	Kilowatt-hours per square meter per a defined amount of time (e.g., day or year) as a unit symbol of average irradiance
LCA	Life-cycle assessment
m	Meter as a unit symbol of length according to the International System of Units
m/s	Meter per second as a unit symbol of speed according to the International System of Units
m^3	Cubic meter as a unit symbol of volume according to the International System of Units
MAUT	Multi-attribute utility theory
METU	Middle East Technical University
mm	Millimeter as a unit symbol of length according to the International System of Units, equal to one thousandth of a meter
MRP	Material requirements planning
MRP II	Manufacturing Resource Planning
MTBF	Mean time between failures
MTBR	Mean time between repair
MTM	Methods-time-measurement
MTTR	Mean time to repair

MW	Main workshop of a municipal maintenance network
No.	Number
OECD	Organization for Economic Co-operation and Development
PDCA	Plan-Do-Check-Act
PPC	Production planning and control
PSS	Product-service system
QFD	Quality Function Deployment
SME	Small- and medium-sized enterprises
STEM	Science, Technology, Engineering, Maths
SWOT	Strengths, weaknesses, opportunities and threats
TDU	Turkish-German University, in German: Türkisch-Deutsche Universität
TPS	Toyota Production System
TRNC	Turkish Republic of North Cyprus
TU Berlin	Berlin Institute of Technology, in German: Technische Universität Berlin
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
VCF	Value creation factor
VGU	Vietnamese-German University
W	Workshop of a municipal maintenance network
YÖK	Council of Higher Education, in German: Türkischer Hochschulrat, in Turkish: Yüksek Ögretim Kurumu

1 Introduction

1.1 Initial Situation and Motivation

The United Nations Educational, Scientific and Cultural Organization's (UNESCO) General Conference has adopted the Declaration on the Responsibilities of the Present Generations Towards Future Generations in 1997. The first article of the declaration highlights that "the present generations have the responsibility of ensuring that the needs and interests of present and future generations are fully safeguarded" [UNE-97]. Maslow has introduced the hierarchy of human needs for present and future generations ordered from lower-level to higher-level needs. Hierarchy of needs involves (1) biological needs such as air, food and water; (2) safety needs such as physical and psychological security; (3) social needs such as need for affiliation, friendship, belongingness; (4) esteem needs such as need for achievement, success, recognition; and (5) self-actualization needs such as need for creativity, self-expression, integrity and self-fulfillment [Sir-86, p. 331].

The greater the need satisfaction from lower-level to higher-level needs, the greater the living standards of a society and development level of a country. Until now, the lower-level needs are not satisfied worldwide equally. The present global population of 7.3 billion is expected to grow to a predicted 8.5 billion people by 2030, 9.7 billion by 2050 and 11.2 billion by 2100 [UN -15, p. 1 f.].

Access to food, "water and energy as resources per se is not a global problem. The situation changes significantly when local availability" of resources is considered. Today, "more than 10% of global population is undernourished due to lack of food [WWA-14, p. 54], while 30% do not have access to safe water and 20% still lack access to electricity" [WWA-14, p. 13]. "85% of the world population lives in the drier half of the planet" [UNE-13].

A wide range of growing threats to living standards include wars, political and ethnic conflicts, terrorism, environmental and natural phenomena, industrial accidents, occupational injuries, and crime. Caused by natural phenomena and human activity, the acceleration of climate change has already affected human lives and economies worldwide. Climate change damages properties and infrastructures, and results in lost productivity, mass migration, and security threats.

Only 20% of the global population live in developed countries [PRB-15, p. 3] and hold 60% of world's gross domestic product (GDP) [IMF-15].1% of the global population own 46% of all global assets, while another 50% of the population own only 1% of the assets [Sho-13, p. 95]. Thus, the majority of the global population seeks to move from a lower-level need toward a higher-level need. "Globally, 70% of the water supply is utilized by the agriculture sector, while industry uses only 22% today" [WWA-14, p. 23]. "The agricultural production and supply chain sectors account for about 30% of total global energy consumption" [WWA-14, p. 4].

The working-age population aged between 18 and 67 years has declined by 0.4% annually worldwide since 2010 having the potential to significantly impact the economy [EU -15]. While 17% of the population is under 18 in developed countries, the share of children and teenagers in emerging and developing countries is almost double [UNF-14, p. 3 ff.]. Food demand is expected to increase by 60% [WWA-15, p. 3], "while energy demand from hydropower and other renewable energy resources will rise by 50% by 2050" [WWA-14, p. 70]. World manufacturing energy consumption is projected to increase by 56% between 2010 and 2040 [EIA-13]. "The Intergovernmental Panel on Climate Change predicts with high confidence that water stress will dramatically increase in central and southern Europe, and that by 2070, the number of people affected by the water scarcity will double". Water scarcity emerges from a combination of hydrological variability and high human activity, which may in part be mitigated by storage infrastructure [WWA-16, p. 18]. California in the United States of America (USA), which is situated within the same circle of latitude as many regions across the Mediterranean Sea, "is already facing major water shortage, an alarming trend which exemplifies the forecasted impacts for central and southern USA and Southern Europe" [IRE-15, p. 31].

Most of the developed countries are already involved in global value creation and cooperate with international stakeholders. There is a positive correlation between participation of public and private institutions in global value creation, particularly in manufacturing, and the growth rates of GDP per capita [UNC-13, p. 10]. This can also cause challenges, as crises can be transmitted across borders quickly. Furthermore, a deeper gap regarding the resource generation and consumption has increasingly evolved among developed, emerging and developing countries. Developed countries create the most value, having a decreasing benefit on global well-being [CIA-13]. Since the second half of the 20^{th} century, emerging countries have grown quickly to accommodate the consumption needs and aspirations of developed countries, often allowing an increase in irresponsible resource consumption [Bil-16b, p. 516 f.]. Thus, developed and emerging countries need opportunities to maintain and enhance their living standards while reducing their environmental footprint [Sel-11a, p. 25]. Concurrently, emerging and developing countries need opportunities to ensure and improve their living standards according to Maslow's hierarchy of human needs [Sel-11b, p. 4].

A well-educated population is essential for local and global well-being, and sustainable development. Education and intense training play key roles in providing people with the capabilities needed to contribute to the sustainable development of the economy, environment and society. The lack of capacity and the challenges facing agricultural, industrial and service sectors require the enhancement of capabilities of workforce and societies. When young people are empowered and supported, they can contribute to meet the challenges by creating new solutions [UNF-15b, p. 86]. Educated, healthy, and safe, they can become powerful drivers of sustainable development [UNF-15c, p. 8].

The Paris Agreement indicates the first truly global agreement on efforts for mitigating climate change, and is signed by 55 countries, which account for 55% of global emissions, at the 21st Conference of the Parties (COP21) in 2015 [UNF-15a, p. 31]. Following this agreement, the industry and research communities are keen to position themselves as enablers of technological advances, in particular with a lower carbon energy mix, bigger competitive advantages and societal advances [WEC-15b, p. 6]. In general, engineering explores opportunities for useful application of scientific principles. For example, a car-size exploration rover landed on Mars in 2012 [Gre-16], while we all communicate wirelessly on a vast worldwide network. Achievements in engineering underlie many innovations in value creation and raise the question: How can engineering contribute to sustainable development to satisfy human needs from lower-level to higher-level needs globally?

Production, as a specific field in engineering, is concerned with the creation of tangible and intangible products and the provision of services in order to distribute wealth. Manufacturing, as a specific field in production, starts from human thinking and imagination, acquiring new knowledge about natural scientific phenomena through physical utilization of materials and resources towards value creation via products, processes and systems using technology and management. While value creation in manufacturing is dominated by engineers, those looking to improve upon value creation have embraced the methodologies in technology and management, mostly combined and used by industrial engineering. Industrial engineering, as a dynamically developing field of manufacturing, has risen to the top of production, services, and other areas of value creation in many developed and emerging countries [Els-99, p. 416] [Lu-07, p. 629].

1.2 Research Goal and Outline

This research discusses the question of how industrial engineering can contribute to sustainable value creation through manufacturing. The goal is the development of a new architecture to change value creation towards sustainable manufacturing. Changes require shaping, creatively manipulating, configuring, diffusing and utilizing new and sustainable solutions in practice. A new framework is required to upgrade industrial engineering, whose application in education and training should enhance industrial engineering to gain leverage for satisfying the human needs – from lower-level to higher-level needs – of any given society sustainably.

The research structure for establishing industrial engineering as a change agent [Lu-07, p. 629] towards sustainability is outlined in Figure 1-1. Where necessary, the structure is divided into two parts regarding (1) value creation in practice and research, and (2) engineering in education and training.

The state-of-the-art review of capabilities for sustainable manufacturing in Chapter 2 is divided into these two parts:

- A review of the state-of-the-art value creation is presented showing what principles and methodologies are currently applied for implementing sustainable manufacturing. Selected methodologies are analyzed to determine to what extent they contribute to creating sustainable value in practice and what fields exist for further research and development. Gaps and potential win-win situations among sample countries with different development levels are identified regarding competitiveness and the sustainability of local value creation in manufacturing as well as education and research.
- Various engineering disciplines and capabilities are reviewed to specify their potential leverage to exert a great impact on satisfying human needs towards sustainable manufacturing by exerting any change of value creation. Based on best practice programs in developed countries, the potential contribution of industrial engineering to sustainable manufacturing and currently applied attributes for engineering education and training are identified.

The deficits of existing industrial engineering programs are summarized in Chapter 3. Deficits are established by the extent to which the existing programs provide the necessary capabilities to narrow gaps of value creation in manufacturing at different development levels. Advanced capabilities are required to operationalize principles of sustainable manufacturing in training and practice. In conclusion, the needs for enhancing capabilities and upgrading industrial engineering are emphasized.

A novel architecture for sustainable value creation in manufacturing is developed in Chapter 4 through research for applications including education and training. The architecture aims to cope with the challenge of implementing sustainable manufacturing principles in practice. In manufacturing, value creation flows from analysis to synthesis iteratively. The methodology of how to apply the architecture in order to contribute to sustainable manufacturing is described in three sections:

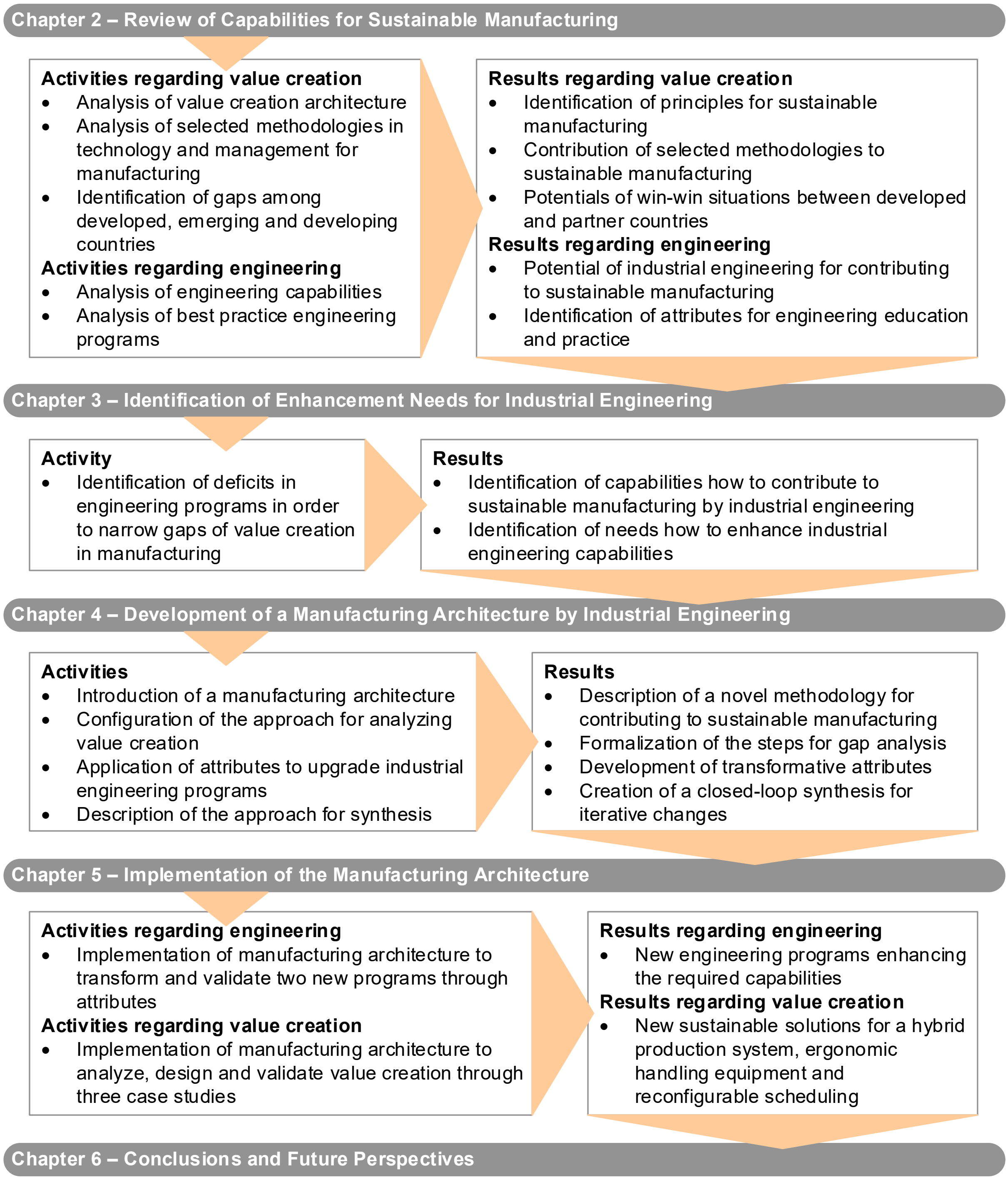


Figure 1-1: Research structure

- An approach for analyzing gaps of value creation is configured based on existing methodologies of gap analysis. All steps of the analysis are formulated. The commitment to the principles of sustainable manufacturing is verified and mostly called into question due to deficits in required capabilities.

- Due to the major needs for enhancing industrial engineering, new transformative attributes are developed to upgrade education and training programs. A new framework is proposed to transform industrial engineering in higher education by applying the transformative attributes in order to provide enhanced capabilities.

- A closed-loop synthesis approach is introduced to establish new solutions creating sustainable value in manufacturing through iterative changes of value creation.

The architecture is implemented in five case studies to identify the impact of transformative industrial engineering on sustainable value creation for achieving and maintaining competitive advantage in manufacturing in Chapter 5:

- Two new educational programs in engineering are transformed following the framework of industrial engineering. They are verified to test whether they meet the requirements and compared with existing best practice programs through the identified and proposed new attributes to highlight the enhancement of required capabilities.
- Application of transformative attributes in education, training and research is tested through three case studies as research projects and project-based courses. By applying the architecture for sustainable manufacturing, each case study analyzes, synthesizes and verifies a certain value creation in practice. New solutions such as a hybrid production system, ergonomic handling equipment and reconfigurable scheduling are designed and compared according to their contribution to sustainability.

Conclusions regarding the results of implementing the architecture for sustainable manufacturing including the framework for transformative industrial engineering are presented in Chapter 6. Some recommendations for research and practice are given to discuss potentials for future work.

2 Review of Capabilities for Sustainable Manufacturing

Research and development are characterized by increasingly complex research fields that require the combination of knowledge and skills from different disciplines [Wan-16, p. 1 f.]. This section is divided into two subsections to (1) investigate a state-of-the-art review for sustainable value creation in practice and research as well as (2) categorize engineering disciplines and capabilities provided in education and training according to their potential contributions to sustainable value creation.

2.1 Sustainable Value Creation

The state-of-the-art review for sustainable value creation is divided into three subsections. The first subsection explores the value creation architecture based on the research activities within the international Collaborative Research Center (CRC) 1026, which “intends to demonstrate how sustainable manufacturing embedded in global value creation proves to be superior to traditional methodologies of technology and management” [CRC-16]. The second subsection summarizes requirements, which must be fulfilled, and principles of sustainable manufacturing to contribute to sustainable development of the economy, environment and society. The third subsection presents selected methodologies for how to contribute to the superiority of sustainable manufacturing to current manufacturing practice.

2.1.1 **Architecture**

This subsection is divided into five subsections:

- In order to describe the degree of efforts and benefits within the frame of requirements and current conditions, the term “value” is introduced.
- The background of the term “sustainable development” is investigated to express the wide scope of its relevance for different regions, disciplines and contexts worldwide.
- Development levels are assigned to countries based on their living and working standards according to statistical data. Shaping value in the economy is devoted to the primary, secondary and tertiary sectors of groups of public and private institutions.
- The historical changes from an agrarian and handicraft economy to a by industry and manufacturing dominated economy lead to a virtually planned and controlled value creation today, which should be shaped sustainably.

- Sustainable manufacturing is identified as an enabler for value creation within the secondary and tertiary sectors of production and service provision in an environmentally, socially and economically acceptable manner [Sel-08, p. 60 ff.].

2.1.1.1 **Value**

Value is defined as “regard or usefulness that something is held to deserve” [Oxf-16b]. The term “**value**” is approached by various scientific disciplines such as philosophy, economics, psychology, engineering and ecology throughout history. From an engineering perspective, value is a measure of economic, environmental and social benefits created by the transformation of raw materials or applied services [Ued-09, p. 682].

The value creation is interpreted as a transfer function describing the inputs and outputs in primary, secondary and tertiary sectors. A **sector** is a grouping of professional value creation activities based on their main economic function, product, service or technology [EU -08]. The distribution of value creation into the three sectors describes the individual contribution of agriculture, industry, and services to value creation. The **primary sector** describes value creation in agriculture which includes farming, fishing, forestry and mining. The **secondary sector** describes value creation in production industry, which is divided into manufacturing, energy generation and process industry. The **tertiary sector** describes services covering governmental activities, communications, transportation, finance, education, cleaning, maintenance and all other activities in value creation that do not produce material goods [CIA-13]. The added value is the output of value creation in a product as a service including all intangible activities or as a part or whole system including all tangible objects.

“In manufacturing, value is created by changing the ratio between input and output in terms of raw, auxiliary and operating materials and resources by applying physical and chemical processes [Seg-14b, p. 828]. **Conditions** form boundaries of value creation, and are determined by, for example, natural limitations and governmental regulations, which engineering cannot directly change. **Requirements** fulfill goals, for example, meeting customer needs and other stakeholders’ demands. Solutions fulfill the requirements within the frame of conditions [VDI-00, p. 5 ff.]” [Bil-16a, p. 455].

Value creation must be interpreted not only in economic but also in environmental and social terms. In order to describe the degree of efforts and benefits to which they are useful for the economy, environment and society within the frame of current conditions, Kanji Ueda introduced the term “**sustainable value**” [Ued-09, p. 685]. Solutions which contribute to sustainable development are called sustainable solutions and create sustainable value.

2.1.1.2 **Sustainable Development**

“Graedel identifies similarities between the behavior of biological organisms and the behavior of industrial organisms. He proposes that the classic way in which biological organisms interact with other biological organisms can be transferred to industrial organisms and their interactions” [Gra-96, p. 76] [Eme-15, p. 1809]. Following Graedel’s lead, this research aims to design new solutions for sustainable production systems which mirror the interactions of ethically-driven biological organisms.

A **system** consists of at least two interacting stakeholders and environmental factors, which shape the stakeholders’ economic, as well as social freedom of action [Pah-07, p. 27 ff.] [VDI-00, p. 25]. The primary environmental factors are the availability of energy and water resources, the climate, including auxiliary materials, which shapes the soil, establishes the topography, and imposes limitations. Local opportunities, as characterized by Bloch, are (1) the ability for value creation within the frame of current conditions and (2) “value creation considering the unknown factors and forecasting for climate”, as well as availability of energy and water [Eme-15, p. 1809]. The relations between ecosystem, market economics and decision-making are summarized as “**Think global, act local**” by Geddes in 1915 [Agu-11, p. 2298 f.]. Geddes’ requirement implies that the knowledge to assess which values under global limitations determine the preferences for local action. The overall goal to perform actions for local value creation without compromising current and future global well-being is derived from Kant´s categorical imperative. However, the scope for action, the conditions and the preferences are not specified. Acting locally presupposes an understanding of the limitations of the ecosystem. To this extent, Geddes proposed three steps for the development of regional actions: (1) preparation of a local questionnaire; (2) analysis of the questionnaire regarding the implementation; and (3) development of an action plan [Eme-15, p. 1809]. These three steps are integrated within the approach for analysis in Section 4.2.

The Club of Rome promoted the study “The Limits of Growth” in 1972, which paved an international attention for effective and efficient resource utilization. The “Brundtland Commission Report” of the United Nations introduced the term “**sustainable development**” in 1987 and promoted the change of technological, economic and social systems [Bru-87, p. 16 f.]. This change intended to extend the individual focus from economic growth to environmental limitations or human development. “The report stipulates that sustainable development is the overall goal of the United Nations, governments, research” and private institutions [Eme-15, p. 1809]. The UNESCO’s General Conference has adopted the Declaration on the Responsibilities of the Present Generations Towards Future Generations in 1997 and stated that “the present generations have the responsibility of ensuring that the needs and interests of present and future generations are fully safeguarded” [UNE-97].

Building upon the concept of sustainable development, the Enquete Commission of the German parliament introduced the triple bottom line of economic, environmental and social **impacts** of **sustainability** in 1998 [Ger-98, p. 24 ff.]. Sustainable development signifies the process of "meeting needs of the present generation without compromising the ability of future generations to meet their own needs" [Sel-11a, p. 25] Further, increased human well-being should benefit the majority of the society. This overarching and global goal calls for competitive advantages in the frame of sustainable manufacturing as the enabler for new solutions for products, services and processes [Jov-08, p. 644]. Sustainable development can promote technological advances through new solutions to ensure human survival and further development in spite of limited resources, while stimulating global well-being.

The global population growth rate, coupled with changing environmental conditions triggered by climate change, puts pressure on value creation. This situation decreases the competitiveness of conventional institutions within the primary, secondary and tertiary sectors in some regions. Sustainable development must be conceived as a common goal of institutions and countries, while maintaining a superior position in the market through the achievement of intended individual goals [Eme-15, p. 1810].

2.1.1.3 **Gaps among Countries**

After the world wars in the 20th century, some countries such as Japan have rapidly developed. The activities of national governments and intergovernmental organizations like the Organization for Economic Co-operation and Development (OECD) led, in the 1960s and 1970s, to an immense interest in reasons why national growth rates and competitiveness differ. However, differences in industrial sectors, education and research systems of countries have led to different development levels until today. Some innovative countries combined universities and research institutions with industrial research and experimental development as well as with other fields such as production, customer service and marketing [Lun-02, p. 214 ff.]. Due to the lack of suitable approaches for sustainable development and regional limitations over the years, gaps have evolved between developed and emerging countries on innovation and technological development. Some countries are better prepared to cope with rapidly changing conditions than others when it comes to respond to new challenges. To distinguish regional limitations worldwide, this subsection unfolds gaps among countries.

Development levels are assigned to countries based on their living and working standards according to statistical data related to Maslow's hierarchy of human needs, education level, GDP and competitiveness. Issues such as public health, infrastructure, macroeconomic stability and mandatory education are excluded in this research. Countries are usually grouped according to their level of development in developed, emerging and developing countries, although there is no established convention for the designation of countries even in the United

Nations [WTO-14, p. 54]. The following designations are intended to explain differences exemplarily based on statistical data from the Global Competitiveness Report 2015-2016 published by the World Economic Forum, which is based in Switzerland since 1971 and co-founded by the United Nations. Six countries among 140 countries are selected to compare. The comparison of varying development levels is discussed in this subsection. Relevant data for the comparison is presented in Table 8-1 in Appendix 8.1.1 [WEC-15a, p. 87 ff.] [WTO-14, p. 73].

A **developed country** describes a sovereign state that has a highly developed economy and advanced technological infrastructure. Developed countries comprise all 27 member states of the European Union (EU), other non-EU western European countries, for example, Norway and Switzerland, Australia, Canada, Japan, New Zealand and the USA [WTO-14, 54, 73]. Developed countries' stakeholders focus on activity, confrontation, discourse, coexistence with nature, speech, articulation, self-assuredness, attempting to get more of everything, success, achievement, cherishing vitality of youth, retirement to enjoy rewards of work, communicating, lifelong learning and teachers as organizers, mentors, instructors, guides [Bad-12, p. 886].

For example, **Germany** is one of the leading developed countries worldwide (4th) and excels in the more complex areas of competitiveness with highly sophisticated businesses (3rd). The country’s innovation system (6th) is characterized by high levels of company spending in research and development (6th), and a supportive research environment, including industry cooperation with universities in applied research fields (10th). Germany is also a pioneer of the dual education system. This is supported by excellent professional training (8th) ensuring that engineers have enhanced capabilities to employ latest technologies in production (16th), and successful use of information and communication technologies (IT, 11th). The country uses its talent efficiently (11th), although more could be done to encourage greater participation of women in the workforce of engineering disciplines (43rd) [WEC-15a, p. 24 ff.].

The **USA** has rapidly recovered from the financial crisis in 2008 and countered the effects of lower energy prices. The country’s major strength as an advanced country (3rd) is its unique combination of exceptional innovation capacity (4th), large domestic market size (1st), and sophisticated businesses (4th). The country’s innovation capacity is driven by high availability of scientists and engineers (4th), and companies spending on research and development (3rd). The USA also benefits from flexible labor markets (8th) and an overall well-developed financial sector (5th) [WEC-15a, p. 24 ff.].

There are big differences between the most and least advanced economies among developed countries. For example, **Cyprus** is one of the least competitive economies worldwide (65th) with the highest unemployment rates within the European Union [WEC-15a, p. 150 f.]. The country fails to improve its value creation and workforce. Trade barriers, for example, production standards, technical and labeling requirements, limit the ability of exported goods to compete in foreign markets. Considering the restrictions imposed by trade barriers, the entrepreneurial freedom of action in Cyprus is extremely limited [WEC-15a, p. 16 ff.]. To overcome regional limitations and constraints, Cypriot value creation must change [Eme-15, p. 1818].

Germany and the USA share many advantages, such as benefitting from the world's best local suppliers, as presented in Figure 2-1. Both countries are well equipped to leverage the human factor to adapt their value creation to changes brought about by the fourth industrial revolution and to reap their benefits.

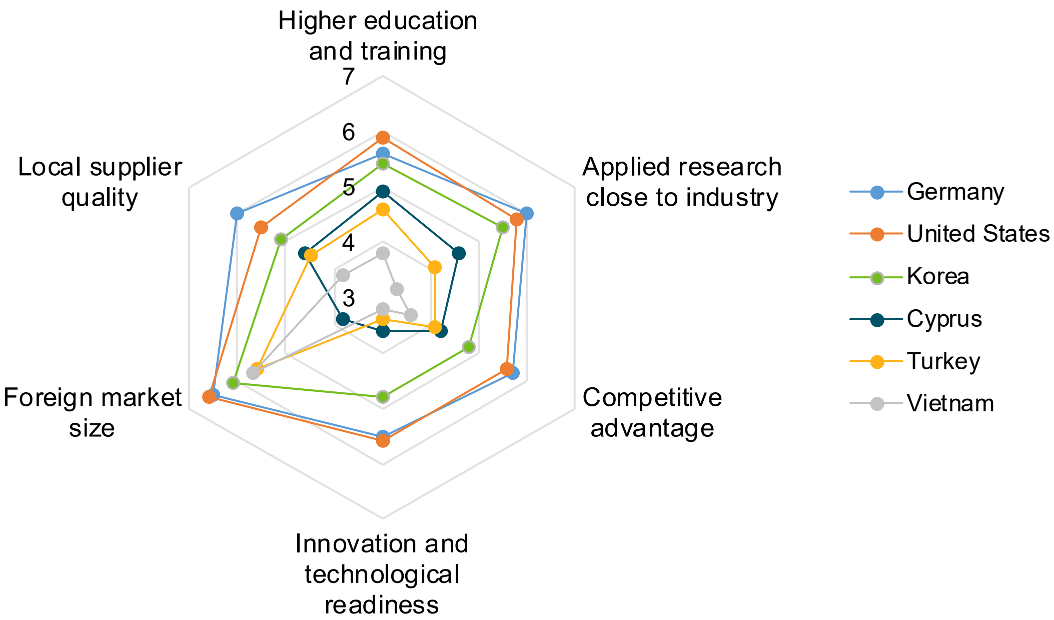


Figure 2-1: Comparison of countries based on Table 8-1 in Appendix 8.1.1

An emerging country is in the transition from a developing to a developed country. It has some characteristics of a developed country, however, it cannot meet all relevant standards. A developing country is in the procedure of industrialization, pre-industrial or almost entirely agrarian [WTO-14, p. 54]. **Emerging and developing countries'** stakeholders focus on acceptance, silence, meditation, consideration of others' feelings, content with less material assets, love of life, cherishing wisdom of years, retirement to be with family, teachers as lecturers of textbooks, hierarchical relations, coordination of group support, social and moral learning [Bad-12, p. 886]. Many emerging countries aim to improve their value creation by driving productivity and innovation by exposing companies to international markets, expertise, and technology. Hardly any country has developed successfully in modern times without opening its economy to international trade, investment, and the movement of people across borders [WEC-15a, p. 15].

For example, **Korea** is one of the countries in the upper level of emerging close to developed countries due to its rapid improvements in the last two decades. However, more needs to be done to leverage the country's human capital potential. The quality of the education system is lower than any other developed country (66th). Korea also lags behind most developed countries in innovation (19th). Although still high among emerging countries, its innovation potential has been gradually falling over the years [WEC-15a, p. 27 ff.].

Turkey, as one of the most competitive emerging countries in Europe, leads the Balkan region in technological and IT adoption. However, given the geopolitical uncertainty in the Balkan and Middle East regions, where the countries near to Turkey's borders are unstable, the country is engaged in a delicate political phase [Bre-15]. Investments which have been made to improve the transport infrastructure (23rd) and the relative production performance of the goods market (45th) only partially offset the lack of structural reforms that are indeed crucial to sustain Turkey's long-term competitiveness. Reforms and increased spending on education have so far generated a positive impact on educational attainment and schooling rates. However, significant problems remain over gender equality and the quality of education. Participation in higher education remains low by international standards [EC -15b, p. 32]. Reforms needed include improving the quality of education, strengthening the capacity for innovation by upgrading applied research. Turkey could also address high youth unemployment and female participation in labor markets (128th) by providing access to higher and professional education [WEC-15a, p. 30 ff.].

Vietnam is one of the countries on the upper level of developing close to emerging countries due to its high rankings (56th) among Asian countries. The country has a growing population with plentiful supplies of young workers and has improved notably in technological readiness in the last two decades [WEC-15a, p. 366 f.].

Korea and Turkey fall between the developed and emerging countries. Both countries change smoothly and develop slowly but continuously. They are also nicely placed geographically to take advantage of large markets nearby, with Korea close to China, and Turkey on the edge of the European Union. Korea and Turkey are growing quickly, in contrast to the aging and shrinking populations of developed countries which lead inexorably to slowing growth rates.

The Global Competitiveness Report 2015-2016 presents an overview to compare the consumption of resources on different levels of development with the competitiveness and living standards [WEC-15a, p. 3 ff.]. The results indicate that a worldwide increase in wealth based on current methodologies in technology and management with their consumption of resources would be fatal [CRC-16].

Developed countries support many emerging and developing countries, also called partner countries, with governmental funding to support people's survival and improve living standards including humanitarian, medical and educational aid. Besides emergency aid, development aid should support locals in meeting their needs from lower-level to higher-level needs as water, food, clothes, living and mobility by own competence and initiative, while complying with sustainable development. By achieving this goal, opportunities should be explored to essentially balance the uneven global distribution of wealth and create win-win situations among countries [CRC-16].

A sustainable concept to narrow gaps follows the Chinese proverb "give a man a fish and he eats for a day; teach a man to fish, and you feed him for a lifetime" [Seg-14a]. From the perspective of developed countries, cooperation with partner countries should promote **help for self-help**. Self-help indicates a self-guided improvement of the economy, environment or society through significant commitment to sustainable development. Cooperation promoting self-help includes offering teamwork between developed and partner countries as well as counseling partners on how to help themselves to attain particular goals.

In developed countries, the rate of population growth is low, and in some European countries it is even negative. For example, the average age of German engineers is currently over 50. Over the next ten years, more than one in two German engineers who work for German companies abroad, and almost one in four engineers who work in Germany, will retire. Because of this shortage of engineers in Germany, the labor market needs more than twice as many graduates annually as they have now, which accounts almost for 90,000 instead of 44,000 [VDI-14, p. 2]. Turkey, with a population of 77 million people, represents the second largest demographic population and – with an average age of 31 years – the youngest community in the European region [CIA-13]. Compared to that, Germany has the largest population with 81 million and the highest average age of 45. However, inefficient higher education, among other reasons, holds emerging countries such as Korea and Turkey back from fulfilling their potential.

Many countries receive governmental support from developed countries to improve their higher education and innovation systems. One possible way to create a win-win situation is to have emerging countries work closely with developed countries in education and research. By supporting higher education and research in partner countries, best practices are shared with nicely prepared presentations, lectures and plug-in solutions for a partner country. While a best practice can be plugged into a partner country with minor changes for implementation, in the partner country, the implementation's success depends heavily on its acceptance. Thus, the importance of active discussion with stakeholders from partner countries is often neglected. Rather than presenting one-sided best practices, respecting partners as peers and listening to what they think is essential to make effective decisions among academic staff and industrial experts from both countries [STE-15].

Upgrading educational programs depends on the active engagement of stakeholders in formulating and implementing new attributes in education, research and practice rather than only exchanging ideas and giving recommendations. In the context of a tailor-made model for a partner country, political and socioeconomic context must be thoroughly explored. Stakeholders with a management, coordination or execution responsibility from the developed country must be able to understand the legal system, the industrial structure, the regional economic situation and the social background. These stakeholders need to reflect such comprehensive aspects through exchange of ideas and engagement in joint activities with the local experts from the partner country. The stakeholders from the developed country must break down each element of its best practice programs. Their goal is to conform a good practice program to issues and challenges faced by partner countries. As a result, it is highly likely that the original model must be changed in order to upgrade the program. The new program has different characteristics after the change compared to the best practice of the developed country because every partner country needs to implement its own model.

Governmental stakeholders make decisions to fund and support development of new programs. While they do not have the disciplinary competence to make decisions about the content, form and outreach of new programs in higher education, the policies they advocate and the action plans they launch send important signals to public and private institutions of partner countries. A stronger push for shared decision making and bearing responsibility would also send a strong signal towards partners that governmental institutions respond proactively to the changing industrial environment such as Industry 4.0.

Stakeholders from partner countries would benefit from this cooperation by enhancing capabilities, upgrading labor forces, increasing knowledge sharing and access, having positive cultural impacts, long-term partnerships and strategic alliances [van-15b]. People who are educated and trained by developed countries can become ambassadors of sustainable manufacturing in their native countries in education, training, practice and research. For example, when companies from a particular sector are interconnected in geographically proximate groups speaking the same technical and organizational language in value creation, efficiency and effectiveness is heightened, greater opportunities for innovation in processes and products are created, and barriers to entry for new companies are reduced [WEC-15a, p. 37]. Developed countries also increase their influence in globally significant regions by assisting a partner country in developing their workforce by growing numbers of graduates who undertake engineering education based on the developed country’s best practice. The developed country mostly positions itself as the “best partner of choice” in the partner country [van-15a].

2.1.1.4 **Industrial Revolution**

In terms of the secondary sector, the developed countries are also called industrialized countries which have advanced their production industry through industrial revolutions and improved living standards earlier than the majority of countries worldwide. The secondary sector deals with value creation in production industry. **Production** is primarily the physical transformation of raw and auxiliary materials into semi-finished or finished products. **Industry** describes the production of goods and services by private institutions within the secondary sector [Oxf-16a]. **Manufacturing** describes “the entirety of interrelated economic, technological and organizational measures directly connected with the processing and machining of raw and auxiliary materials, i.e., all functions and activities directly contributing to the making of goods” [Seg-14b, p. 828]. The following industrial revolutions are related to manufacturing within production industry.

The changes from an agrarian and handicraft economy to an industry and manufacturing dominated economy describe the first industrial revolution. This revolution started in England with the introduction of mechanical manufacturing equipment, new chemical and iron production processes at the end of the 18th century [Com-13, p. 13]. The new technologies improved efficiency of water power and increased use of **steam power**. Engineering focused on solving detailed technical problems associated with supplying power and making reliable machinery [Bro-11, p. 174].

This second industrial revolution, which followed at the beginning of the 20th century, involved mass production of goods based on the division of labor [Com-13, p. 14]. Henry Ford reduced the amount of efforts required to assemble a black car, the Model T Ford, by 90% in 1913 by switching to continuous flow in final assembly. **Mass production** of goods, which were affordable by middle class, was realized by lowering costs through technical and business innovations [Wom-96, p. 22]. Concurrently, Frederick Winslow Taylor broke down the manufacturing into individual processes to produce components of a product and improved the efficiency of each process [Mar-01, 1.6]. **Division of labor** focused on standardized and interchangeable tasks and workers. Taylor’s **scientific management** was based not only on the scientific study of manufacturing but also on the scientific selection, education and training of workforce [Bro-11, p. 174] [Mar-01, 1.6].

After the second World War, Ohno visited automotive plants in the USA, where mass production was applied with substantial waste on the production lines. He introduced an approach of how to combine the advantages of mass production with the possibility of eliminating waste, referred to as **Muda**, and made changes along the production line. The goal was to adapt the production system to changing demands by saving resources. Ohno applied the principle of **lean thinking** at the Toyota Motor Corporation in Japan in the mid of the 20th century, which is known as Toyota Production System (TPS) today [Wom-96, p. 23].

The third industrial revolution began with the replacement of relay logic systems by the first programmable logic controller called the Modicon 084 by General Motors in 1969. Started in the early 1970s, the trend towards **digitalization** with electronics and IT has been followed to increase automation of processes in production systems [Com-13, p. 14].

A seamless transition from the third to the fourth industrial revolution has been achieved within the last two decades. Since the beginning of the 21st century, the **Internet of Things** and Services (IoT) have been integrated into production systems. IoT describes a combination of physical systems embedded with electronics, software and sensors that enables the system and its elements to collect and exchange data. This revolution has created opportunities to integrate physical systems into virtual systems including an instance of **cyber-physical systems**, which encompasses technologies such as smart grids, smart homes, intelligent transportation and smart cities [Com-13, p. 47 f.]. Given widespread recognition of these innovative ideas, many sectors intend to apply these technologies to improve efficiency, reliability and sustainability of value creation recently.

2.1.1.5 **Sustainable Manufacturing**

"The fulfillment of stakeholder requirements turns primarily economic values, but also environmental and social values, into **competitive advantage**. Processes as transformation procedures generate products as tangible objects, services as intangible activities or combinations of the two, representing the output for value creation in manufacturing" [Bil-16a, p. 455].

The strategic management of an ideal company is committed not only to economic growth and lean thinking in decision-making, but also, increasingly, to resource savings to protect limited natural resources. Aligning stakeholder requirements with environmental limitations leads to **green manufacturing** [Gut-05, p. 5 ff.]. Environmentally benign manufacturing encompasses the expenditure of resources with lower raw material costs using recycled wastes instead of virgin materials and more efficient processes with less energy and water consumption. By reducing non-renewable resource consumption, minimizing waste and pollution as well as recycling and encouraging reuse, green manufacturing promotes reducing costs and meeting environmental standards [Por-95, p. 127 f.].

However, sustaining changes through continuous improvement of lean thinking and environmental alignment is difficult due to lack of management involvement, workforce resistance and evolving company culture. Therefore, many scientists argue that lean thinking and green manufacturing are not sufficient to meet these challenges. Manufacturing actively seeks the integration of stakeholders to expand the decision-making concerns from economic and environmental to social [Bil-15, p. 290]. The CRC 1026 describes

- **sustainable manufacturing** as the creation of manufactured products that, in fulfilling their functionality over their entire life-cycle, cause a sustainable impact on the environment and society while delivering economic value [CRC-16], and
- **sustainable value creation** as the interplay of tangible and intangible transformation processes enabling the generation of useful products and services while accumulating intellectual capital and imparting the social and environmental configuration of global living environments [CRC-16].

An impact is called sustainable, when it benefits the economy, environment and society concurrently. Value creation through sustainable manufacturing leads to sustainable solutions. Sustainably shaped energy generation and processing also leads to sustainable value creation, especially in manufacturing. Any value creation through sustainable manufacturing can be modeled using the value creation architecture as presented in Figure 2-2 [CRC-16].

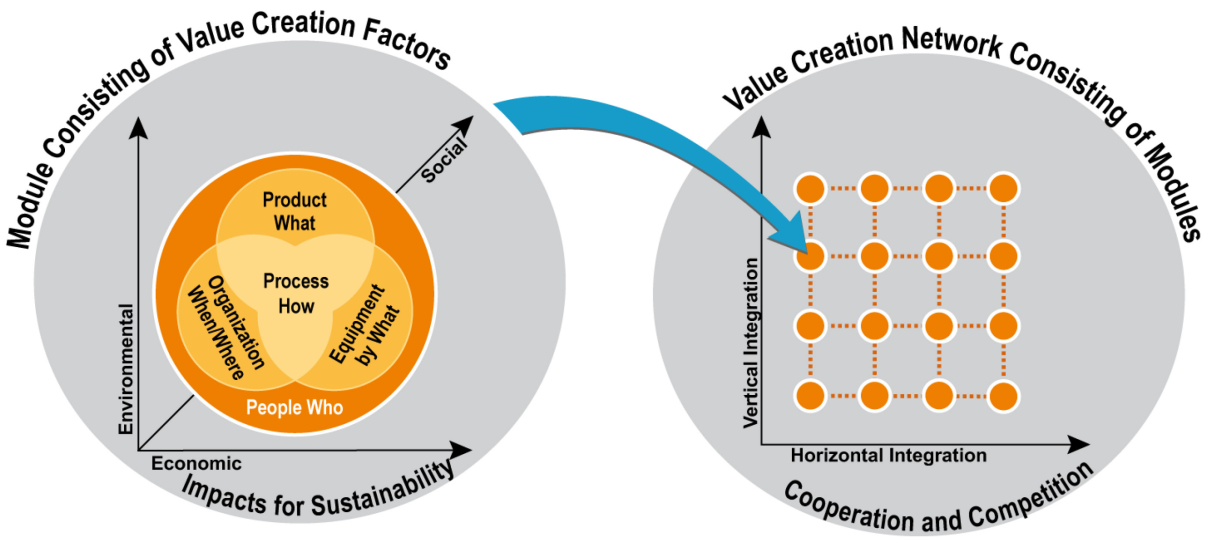


Figure 2-2: Value creation architecture [CRC-16]

Five **value creation factors** which are specified as product, process, equipment, organization and people, and their interactions constitute and determine a **value creation module** with a particular scope for a product, service or combination of the two [Sel-11a, p. 24]. Value creation modules are specified by various variables such as product type, production depth, production capacity and throughput time. The assessment of economic, environmental and social impacts of each value creation module determine the created sustainable value through implementation and adaptation of methodologies in manufacturing.

- What should be produced? – **Products** are classified into the levels of product portfolio, product, sub-product, workpiece, component and feature [Wie-07, p. 786]. Value creation covers all stages of product life-cycle: material extraction, pre-manufacturing, manufacturing, use and post-use [Jay-10, p. 144 ff.].

- How should it be produced? – **Processes** in manufacturing contain forming, shaping, reshaping, separating, joining, coating and material property modification processes [DIN-03, p. 7]. Further processes include assembly, storage, transport, recycling and maintenance [DIN-10, p. 9 ff.] [VDI-90, p. 2] [VDI-10, p. 3 ff.]. Processes can be classified according to their relevance to different industrial sectors, as presented in Figure 2-5. Institutions apply mostly new technological processes following the innovation life-cycle stages as innovators, early adopters, early or late majority or laggards [Rog-83, p. 205 ff.].
- By what means should it be produced? – "Machine tools, robots, transportation and hardware for information delivery represent typical **equipment**" [Eme-15, p. 1812]. Equipment is classified into the levels of network, factory, site, building, working area, cell, workplace, station, machine and tool [Wie-07, p. 785]. Life-cycle stages of equipment cover design, operation, maintenance and end-of-life activities [Bad-11, p. 62].
- When and where should it be produced? – "**Organization** addresses management and operational activities such as production planning and control. It includes the quantitative and capacitive flow of materials, energy, water, finance and information as well as supply chain management" [Eme-15, p. 1812]. Organization is leveled in conceptual design of production systems, value creation modules and factors, factory planning, production planning and control [Wie-07, p. 788 ff.]. Life-cycle stages of organizational management are planning, assessment and improvement [Boo-14, p. 821].
- Who should produce, supervise and manage? – **People** or human relate the assignment of tasks to and the involvement of stakeholders. Satisfaction of stakeholders' needs ensures the accomplishment of success and the achievement of long-term goals. Awareness, qualification and training of decision-makers, employees and operators are required to complete their tasks. Institutions including people as decision-makers and workforce are classified in governmental and non-profit institutions, education and research institutions and private institutions [Bil-15, p. 302].

Value creation modules consisting of these five factors are vertically and horizontally integrated into **value creation networks**. The value creation architecture provides a framework to simplify the complex dynamics of competition and cooperation in networks. This research focused on energy, production and mobility as areas of human living to investigate interactions among factors within multiple modules at different development levels of countries [CRC-16].

The value creation architecture enables the definition of appropriate production systems within a value creation network consisting of one or more value creation modules, each with five value creation factors, at every stage of abstraction, analysis or classification [Pah-07, p. 27].

2.1.2 **Requirements and Principles**

Although most companies address sustainability, many only emphasize environmental practices based on ISO 14000 standards in order to advance traditional economic impacts. Trade-offs between profits and environmental outcomes are navigated without considering social impacts. Lacking comprehensive decision-making to evaluate sustainability implications leads to inadequate exploration of opportunities for value creation. Most decisions within companies are neither specified by considering economic, environmental and social impacts simultaneously, nor based on relevant capabilities of stakeholders, especially decision-makers or operators [Bil-15, p. 300].

A comprehensive analysis of sustainable manufacturing should embrace three impacts simultaneously. Balancing sustainability impacts through manufacturing should be an overall goal by decision-making and acting in production and service industries. Companies should promote new opportunities to re-conceptualize manufacturing activities and support development of potential solutions. To support decision-making for sustainable value creation, requirements and principles that drive desired performance must be clearly described [Bil-15, p. 300 f.]. Recent research on shaping global value creation refers to several (1) requirements, which any production system possessing the five value creation factors should fulfill, as well as (2) principles for design and implementation that permit the fulfillment of such requirements. This subsection discusses a set of requirements which sustainable manufacturing should meet together with a set of principles for their fulfillment.

2.1.2.1 **Selected Categories of Requirements**

This subsection examines the requirements in manufacturing in order to determine how manufacturing can contribute to sustainable development. State-of-the-art review of sustainable manufacturing shows that some requirements are consistently addressed to justify competitive advantage or sustainability of any value creation.

Once the boundaries of a production system, scope of the analysis and goals are clearly defined, requirements can be identified to evaluate potential solutions. The data to quantify a complete production systems and analyze value creation modules and factors regarding the sustainability impacts is difficult to collect or estimate. Requirements from the economy, environment, or society form an interdependent value creation that involves trade-offs; almost all requirements influence each other by having either supporting or weakening effects. For the description of these effects as well as a systematic selection to identify and analyze the requirements for value creation in part or as a whole, an assessment methodology is selected in this research. Direct and indirect correlations between requirements can be addressed through complex system approaches in further research. Requirements can build on common ground and can vary according to different viewpoints [Bil-15, p. 301]. About 50 requirements are cited widely in the published literature for building sustainable value, as presented in Table 8-2 in Appendix 8.1.2.

Increased well-being of all stakeholders serves as the fundamental goal for competitiveness in companies. Overall goals such as sustainable development are, however, not easily measurable. Since the description of interactions between value creation factors and their effects on the whole system is highly complex, various supporting classifications are defined. Extracted from secondary data review, some categories of requirements are consistently addressed to satisfy customer needs and stakeholder demands such as functionality, productivity and resource efficiency. To support managerial decisions with operational sustainability goals, requirements are selected and summarized in categories [Bil-15, p. 301].

Categories should be clear, representative, complementary, unbiased and reasonable in terms of the number and context of requirements; cover the three impacts of sustainability comprehensively; and be applicable to a wide range of case studies. These categories should be applicable to value creation at all levels; with a capability of presenting multiple perspectives of value creation and enhancing efficiency, consistency and sufficiency through decision-making by all stakeholders. They must also enable the pursuit of a well-founded and reproducible assessment along the cause-effect relations to aggregate scores; address the trade-offs between different value creation factors, stages in the life-cycle and different impacts in an overarching and comprehensive way; and be assignable to quantifiable measures that avoid subjective or ad-hoc judgments. Moreover, in the case of qualitative requirements, they should be classified as low, medium or high to show the direction of change using, for example, a Likert scale [Bil-15, p. 301].

Appendix 8.1.2 presents also a catalog for six categories of requirements as gathered from secondary data for recent research in sustainable manufacturing. Each category is assigned

- to some value creation factors
- based on its most relevant impact on the economy, environment or society.

The catalog includes for each category

- a definition based on the well-acknowledged standards and scientific encyclopedias,
- a description, and
- some sample questions for evaluating the requirements

based on the instantiation of individual requirements within this research. Around 30 requirements r_i, represented by the number n, where $n \in [1, \ldots, 30]$, have been selected and assigned to six categories c_k, where $k \in [1, \ldots, 6]$, as presented in Table 8-3 in

Appendix 8.1.2. The assignment of three sustainability impacts to five value creation factors and six categories of requirements are exemplified in Figure 2-3 related to three sample case studies. To structure the evaluation procedure in each case study, the related requirements to each category are related to sustainability impacts; they are also assigned to value creation factors, showing only the most relevant interrelations to keep the illustration understandable.

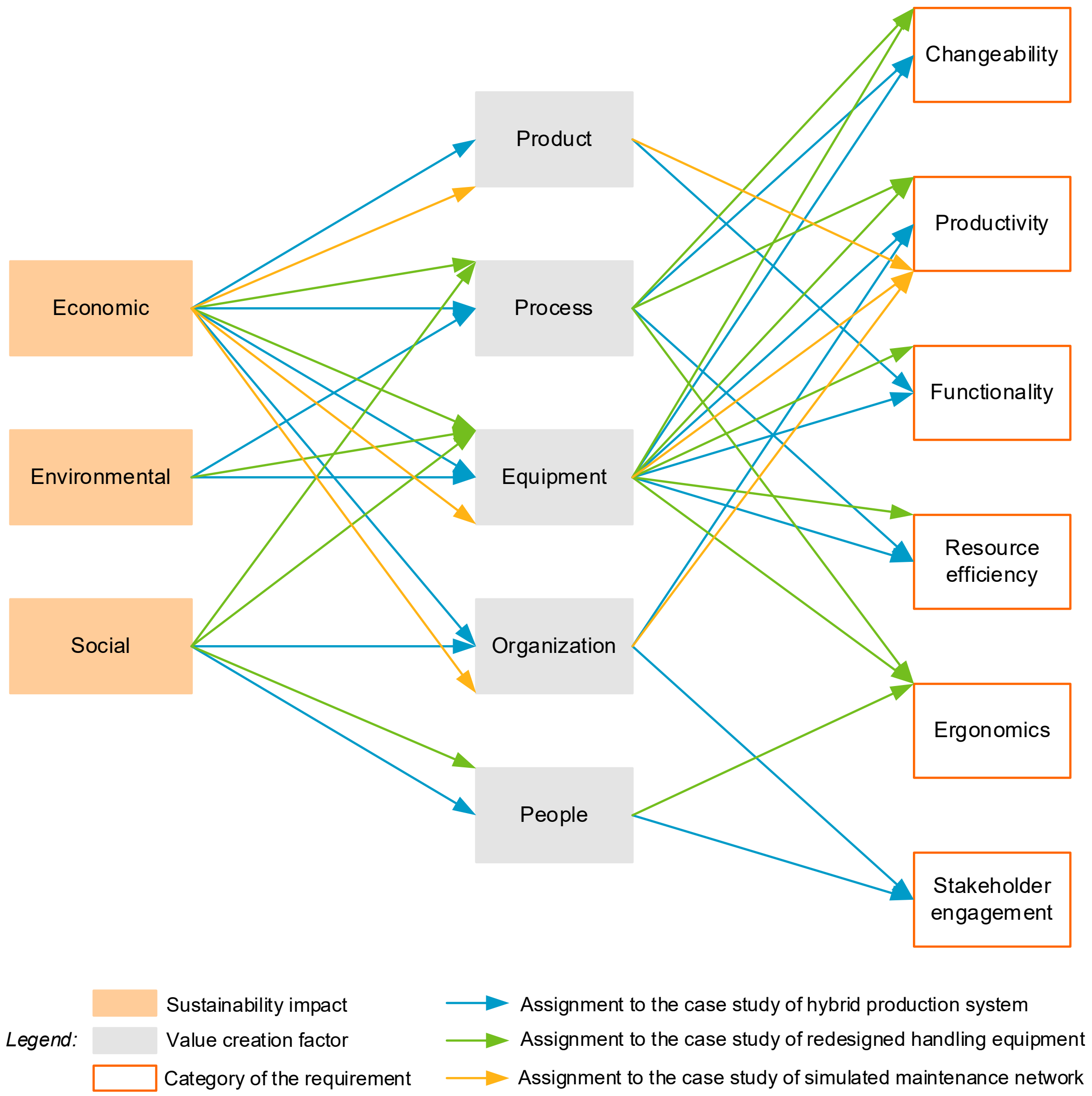


Figure 2-3: Sample assignment of impacts, factors and categories of requirements

Changeability describes the ability of a production system to economically accomplish early and foresighted adjustments of value creation modules and factors on all levels in response to changing impulses [EIM-14, p. 157 ff.]. Production systems including value creation modules and factors must be adapted to changing conditions, regions and goals as the dwindle of the natural resources, climate changes and growth of world population. Thus, economic, environmental and social challenges must be understood by decision-makers in the light of changing conditions in order to achieve a balance between conflicting or redundant goals. Changeability includes requirements such as scalability, modularity, mobility and compatibility.

- **Scalability** provides technical, spatial and personnel extensibility for variable volume of demands.
- **Modularity** follows the idea of standard interfaces for plug-in of variable input and output materials.
- **Mobility** ensures the unimpeded mobility of all production and auxiliary facilities including buildings.
- **Compatibility** allows various interactions within and outside the factory with other equipment by using standard interfaces.

For example, modular designed production systems can be created independently, then adapted and implemented with multiple functionalities following the approach "**local for local**" [Tse-14, p. 896] [Eme-15, p. 1814]. **Mini-factories** require high flexibility in order to be customized for various material and energy flows in different regions. The more adaptable the mini-factories are, the more independently they can operate locally and meet customer needs. Thus, a production system can be divided into several independent value creation modules in separate containers following the approach of mini-factories with scalable capacities [Pos-11, p. 183 ff.].

Productivity is a measure of production system or process output per unit of input, over a specific period of time, used as a metric to justify performance of production. Productivity of manufacturing activities increases by maximizing output. It can be related to different levels regions, companies and production systems, for example, to a certain equipment, organizational procedures for maintenance of the equipment or the entire production system. Productivity can be improved by increasing (1) efficiency through stipulating the amount of resources and time needed to reach particular goals or (2) effectiveness through questioning goals [Mak-14b, p. 1006].

- **Efficiency** is expressed as input-output ratio. It describes the extent to which time, cost, and resources are used. Efficiency seeks to produce more with less. Efficiency of value creation increases by minimizing input and waste through consumption of less resources or processing with higher speed, while creating the same output. Increasing efficiency reduces negative impacts "to do things right" in manufacturing [Her-15, p. 1 ff.].
- **Effectiveness** seeks to create intended value for human living. Increasing positive impacts needs radical changes towards effective utilization of resources, which calls for "doing the right things", and requires more awareness and efforts [Lan-13, p. 36]. Effectiveness increases by continuous review and improvement of goals to apply and adapt methodologies in technology and management. This can be learned and trained [Her-15, p. 1 ff.].

The impact of changes can be evaluated by specific measures, for example, by measuring throughput time, investment or life-cycle costs, capacity utilization or the use of resources such as energy, materials, labor, financial assets, as well as the output [DIN-09, p. 36 ff.].

In manufacturing, a function is interpreted as a specific action or task that a system or its part is able to perform. **Functionality** is the suitability or usefulness of an equipment which requires the fulfillment of the intended goal with the realized characteristics of a certain product, service or system under given conditions [VDI-00, p. 13].

For example, the **product-service system** (PSS) approach provides solutions, which comprises products, services and software in an integrated manner in order to deliver a particular value instead of a pure functionality to customers [Mei-10, p. 607 ff.]. A competitive advantage is achieved if a company gains a superior business position through an activity and outperforms its competitors [Por-98]. Enabled by IT, the PSS approach encourages a competitive advantage with less resource consumption. PSS provides more added value by selling functionality and services rather than tangible products [Sel-11a, p. 25 ff.] [Eme-15, p. 1810]. The impact of functionality can be evaluated by specific measures based on the provided value, potential damages, environmental pollution or service provision.

Resource efficiency measures to what extent the Earth's limited resources are consumed in a sustainable manner while decreasing negative impacts on the environment [EC -15a]. It is evaluated as an input-output ratio through the utilization of resources within one or multiple life-cycles. Resources as input correspond to the effort and goals to be achieved to the benefit of the output [Duf-14, p. 461].

The increasing usage of renewable raw, auxiliary and operating materials, such as energy, water, gas, chemicals, as well as the usage of technologies to reduce water scarcity and emissions can improve resource efficiency and mitigate environmental damage.

The application of **ergonomics** influences the design of work and working environment in order to provide equipment and processes which are compatible with the needs and physical limitations of the workforce [IEA-16].

In case of an equipment, ergonomic design must minimize the risk of injury during manual handling through an operator by avoiding inappropriate postures and movements. The information about how to use the equipment or handle the product should be visible, readable and accessible to the operators, for example, in form of workflow documentation, in order to complete the orders effectively.

Stakeholder engagement describes the involvement and empowerment of participating stakeholders and their concerns in decision-making and following actions for value creation

[Sta-05, p. 8]. It supports the continuing education and training of stakeholders and stimulates win-win situations through promoting competition and cooperation among them [IAP-07].

Through cooperation with individual and institutional stakeholders in a certain region, local changes can be initiated to compound economic, environmental and social impacts increasing personal living and professional working standards. Empowered stakeholders, especially decision-makers and responsible people in charge of value creation, are necessary to examine all requirements sufficiently.

2.1.2.2 **Principles Related to Sustainability Impacts**

Recent research suggests several principles that may be applied in order to create sustainable value in manufacturing. The following principles remain relevant for implementing sustainable manufacturing to fulfill several requirements within the six categories with positive impacts to the economy, environment or society [Eme-15, p. 1810 ff.].

Economically, relating mainly individual requirements of changeability, productivity and functionality,

- instead of tangible objects, functionality and use-based services should be created and sold, thus achieving more wealth with less resources, and
- people should act right, having decided on the right action by intense training of balancing impacts and adapting solutions.

Environmentally, relating mainly individual requirements of resource efficiency,

- non-renewable resources should be processed in multiple life-cycles through elements of the 6R approach rather than be disposed of after a certain life-cycle, and
- non-renewables should be substituted by renewables within the natural limitations of renewables regeneration.

Socially, relating mainly individual requirements of ergonomics and stakeholder engagement,

- higher living and working standards should be developed to increase equal distribution of global wealth, and
- people should be well-educated and trained to be creative in order to explore new opportunities for innovation and take initiative for implementation.

2.1.3 **Methodologies**

Several methodologies have been applied and adapted for contributing to sustainable development through manufacturing by applying the predefined principles that permit the fulfillment of the identified categories of requirements. This subsection investigates selected methodologies related to (1) technology and (2) management.

2.1.3.1 Technological Methodologies

In manufacturing, production systems are typically designed from **cradle-to-grave**, which involves suppliers and customers from resource extraction as cradle over the use phase to the disposal phase as grave. Such a value stream represents a single life-cycle for raw and auxiliary materials with an open loop. Sustainable manufacturing closes the loop from **cradle-to-cradle** with provision of multiple life-cycles [Jaw-06, p. 2].

Sample technological methodologies for manufacturing are demonstrated following the **equipment life-cycle stages**, which describes the life-cycle of physical objects or systems, representing value creation factor “equipment”. Four stages define the equipment life-cycle from an engineering perspective looking at value creation involved in integrating an equipment into a production system, using it and subsequent retirement at the end-of-life for this life-cycle [Bad-11, p. 62]. The life-cycle stages cover the time over which equipment is (1) designed including simulation, procurement, construction, installation and commissioning, (2) operated including scheduling, modeling and simulation, (3) maintained including repair, service, inspection and improvement, (4) decommissioned and disposed of including all methodologies of end-of-life approaches.

Design defines and describes the principles followed and features drafted for a production system, value creation module or factor. A **conceptual design** refers to a development procedure according to the identified requirements of a production system. It must be feasible and have the potential to fulfill requirements [Chr-14, p. 275] [Pah-07, p. 158 ff.].

For example, the **axiomatic design** approach describes a five-step design procedure: (1) Problem definition results in the definition of requirements and design parameters. (2) Requirements are mapped to design parameters as potential solutions. (3) Mapping results can be evaluated according to two design axioms to ensure a good design decision with potential solutions at each level of mapping. (4) The first three steps are iteratively repeated in a zigzag until a new solution can be conceived from the mapped potential solutions. (5) If all requirements reach leaf nodes, where the conceived match is clear and no further decomposition is necessary, the proposed solution is consistent with the problem definition. Physical integration of new solutions into the system leads to a final solution [Kim-14, p. 72 ff.] [Suh-98, p. 629 ff.].

In engineering and economics, **operation** refers to a collection of tasks that work together in order to produce specific outputs for specific inputs. People and equipment are involved in order to fulfill these tasks. Processes consume raw and auxiliary materials with a specific ordering of tasks across time and place [Ale-14, p. 973].

Operation of equipment covers all stages of product life-cycle: material extraction, pre-manufacturing, manufacturing, use and post-use. A life-cycle starts with **extraction of**

materials from natural reserves and **pre-manufacturing** through material processing. Materials are transformed through multiple production activities into raw materials and semi-processed materials for producing final products in **manufacturing**. These stages involve technological processes such as machining, forming, rapid prototyping, casting as well as quality checks, packaging, storage and transportation of the processed and semi-processed products. Assembly with manual or automated processing is also an integral part of the manufacturing stage. During the **use** stage of a product, consumers own or use the manufactured products. The major task of manufacturing companies is to provide satisfaction to all stakeholders, in particular customers, during this use stage. In the **post-use** stage, decommissioning and further end-of-life activities are performed. This stage includes realizing closed-loop material flow cycles, especially for non-renewable materials, by considering the total product life-cycle without disposal [Jay-10, p. 144 ff.].

Scheduling deals with the allocation of resources to tasks and sequencing of tasks over given time periods for all product life-cycle stages. Its goal is to optimize one or more goals [Ste-14a, p. 1092]. Modeling and simulation are used for verification of a suitable rule to sequenced tasks virtually before real assignments [Har-10, p. 304 ff.]. Models emphasize the main features of a system to clarify interrelations and ensure transparency [VDI-06, p. 11]. Simulation tools are widely used for production systems as well as services, defense, healthcare and public services [Jah-10, p. 3 ff.]. Value creation modules can be modeled at different levels of aggregation, for example, from a single station or workplace for a particular component or product in a regional factory as equipment [Wie-07, p. 785 ff.].

A **simulation** is defined with a simplified imitation of an operating system as it progresses for the purpose of better understanding and improving the whole system [Rob-04, p. 18 ff.]. Simulation methodologies are able to analyze the performance of any operating system without affecting the real system.

Discrete event simulation is a type of simulation where the operation of a system is represented as a number of labeled points in time in chronological order. Each of these points is defined as an “event” and signifies a change in an aspect of the system’s state. Each event is instantaneous. The state of the system is only determined when an event takes place at a time of the simulation, thus, the progress jumps from one event to the next. The interim state of the system can be either assumed to be unchanged or nondeterministic [Nas-14, p. 1120].

The European Federation of National Maintenance Societies defines **maintenance** as the “combination of technical, administrative and managerial actions during the life-cycle of a product, equipment or their parts intended to retain or restore it to a state in which it can perform its required function” [Kle-09, p. 3]. Maintenance should provide an efficient way to assure a satisfactory level of reliability during the use stage of a product or operation stage of an equipment. According to the DIN 13306, maintenance contains four methodologies to achieve several goals such as repair, service, inspection and improvement [DIN-10, p. 24 ff.]. Sample goals are increase in availability and reliability of a product or equipment for improving productivity and quality of production; decrease in downtimes including failure and breakdowns for boosting higher productivity through improving capacity, faster and more reliable throughput time, and reducing inventory; decrease in throughput time of maintenance; decrease in life-cycle and operating costs of equipment [DIN-10, p. 17 ff.]. Downtime is described as the termination of a product's or equipment's ability to perform an action as required [Smi-08, p. 19 ff.].

Various maintenance strategies have been proposed for production systems. The selection of an appropriate maintenance methodology, as standardized by the DIN 13306 [DIN-10, p. 24 ff.], for each downtime is crucial.

- **Periodic maintenance** is a preventive methodology involving mainly services with predetermined plans and schedules through a selected set of processes to keep a product or equipment available and reliable within a production system. This methodology is effective if the lifetime of a product or an equipment can be accurately determined [Sha-11, p. 6 ff.].
- **Condition-based maintenance** is a predictive methodology which implements innovative measurement tools and signal processing methodologies proactively to diagnose the state of a product or an equipment during operation in order to optimize the maintenance intervals. This methodology is effective when prognostics are available, however, is also more cost intensive. Sensors and software tools are used for monitoring and analysis of parameters of the desired product or its components [Sal-11, p. 68 ff.].

Preventive and predictive methodologies require intervening before the failure occurs in order to increase safety of workforce and customers as well as decrease economic and environmental consequences. These types of maintenance incur high costs based on spare parts, lost operation time, workforce and auxiliary material such as rags and lubricants.

- **Corrective maintenance** is a reactive methodology to comprise immediate, unplanned and unscheduled processes after the point of failure in order to return a product or an equipment to a defined operating state. Errors and breakdowns leading to downtime and corrective maintenance include components with random failure distribution, a lack of measurable deterioration or preventive measures that are infeasible or poorly performed. Additional costs arise in downtimes related to scrap, rework or overtime for recovery. A failure occurs when the system's performance falls below its required level and requests corrective maintenance. This methodology is more cost effective only if the failure has no critical consequence.

For example, **failure mode and effects analysis** (FMEA) is a methodology widely used for studying downtimes that might arise from malfunctions. It includes the review of multiple processes within a production system to identify failure modes, their causes and consequences. **Ishikawa diagrams**, as one of the most recognized instruments to show cause-effect relations, is selected to demonstrate the causes of specific failures as events in order to identify the most relevant causes and consequences. The most significant parameters of a component affecting the reliability and availability are determined using FMEA to justify maintenance types and schedules [Mar-13, p. 17 ff.].

Sustainable manufacturing closes the loop from cradle-to-cradle with provisions of multiple life-cycles for tangible products or their components at **end-of-life**. The **6R approach** enables closed-loop multiple life-cycles for products or their components including methodologies such as reduce, reuse, recycle, recover, redesign and remanufacture [Jaw-06, p. 4]. A closed-loop material flow diagram for the methodologies of the 6R approach and the four product life-cycle stages are presented in Figure 2-4 [Bil-16a, p. 456].

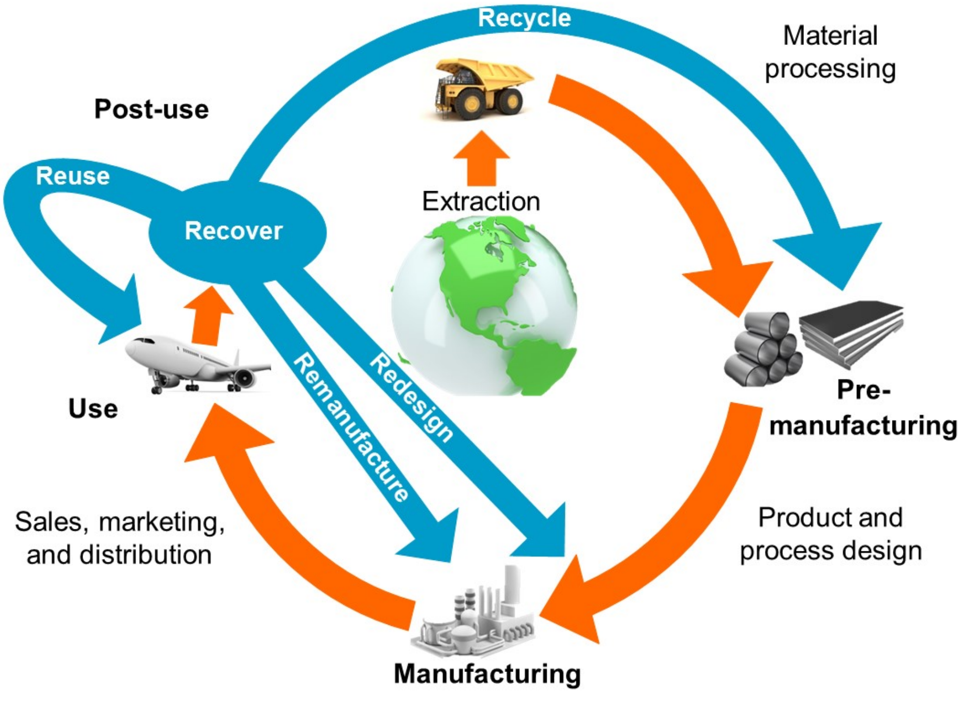


Figure 2-4: Material flow for the 6R approach within the product life-cycle [Jaw-16, p. 106]

- In the 6R approach, the methodology “**reduce**” mainly focuses on reduced use of energy, materials and other resources during manufacturing as well as mitigation of emissions and wastes during the use stage. Reduce increases resource efficiency.
- The process of collecting products at the end of the use stage, disassembling, sorting and cleaning for utilization in subsequent life-cycles is referred to as “**recover**”. Recovery is the main methodology in the end-of-life stage of a product providing the basis for generation of value streams for other methodologies within the 6R approach.

- The methodology “**reuse**” refers to the reuse of a product or its components after its first life-cycle in subsequent life-cycles to reduce the usage of virgin materials in order to produce similar products and components.
- The well-known “**recycle**” methodology involves the process of converting end-of-life materials that would otherwise be considered as waste normally heading to landfills into new materials for next-generation products.
- The “**redesign**” methodology involves the act of redesigning next-generation products, which would use components, residual materials and resources recovered from the previous life-cycle,
- while “**remanufacture**” involves the re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many components as possible without loss of functionality.

2.1.3.2 **Management Methodologies**

In manufacturing, management of production systems is mostly related to the value creation factor “organization” in order to coordinate efforts of people and accomplish goals by using available resources efficiently and effectively. The goal of management is to build and sustain competitive advantage through manufacturing for environmental protection and human advances. Management methodologies aim to support decision-making in spite of enormous amount of information including fields such as technology management, project management, innovation management, supply chain management, quality management, sales and after-sales services [Boo-14, p. 821]. There are many perspectives on the life-cycle of management, while many scientists agree that management goes through (1) planning including initiating a scope and conceptualizing a roadmap for production planning and control, (2) assessment including execution and monitoring of actions, (3) improvement including recommendations and conclusions.

Planning enables institutions to manage their technological advances to create competitive advantages. Initiating a scope and conceptualizing roadmaps support mapping technological methodologies to customer needs and other stakeholders’ demands. For example, analysis of **strengths, weaknesses, opportunities and threats** (SWOT) is a conceptually structured planning methodology to select opportunities among gaps. SWOT analysis selects opportunities among listed gaps to maintain, adapt or substitute existing solutions [God-01, 15.23].

Production planning and control (PPC) describes the short- and mid-term planning, operation and control of the entire production system, value creation modules and factors. It utilizes the resource allocation of tasks regarding raw and auxiliary materials, processes, capacity utilization of equipment and workforce, organization of workflows as well as prioritizing of orders. Following TPS, **material requirements planning** (MRP) was developed as an open-loop approach in the USA in the 1960s. MRP was implemented in production systems for material- and quantity-related planning and scheduling of operations as well as inventory control. **Manufacturing resource planning** (MRP II) was developed at IBM at the end of 1960s to coordinate the entire production, including all modules and factors, based on quantities and capacities. The goal of MRP II is to provide consistent data to internal stakeholders as the materials move through all stations within a production system. **Enterprise resource planning** (ERP) sums up all tasks within a company including the production system to plan and control the internal and external resources such as purchase, finance, sales, workforce and equipment efficiently [Sch-14, p. 472 ff.]. Recent ERP tools also have a simulation capability to answer “what-if” questions and an extension for closed-loop MRP and MRP II.

Whether a production system is able to ensure these goals is measured by its performance in managing the transition to sustainable manufacturing. “**Performance** describes the effect of how successfully a specified task is completed and an activity fulfilled [VDI-00, p. 15]. Measuring the performance of an activity supports decision-making. Assessment is the procedure of collecting, analyzing and reporting information about activities as they pertain to meeting requirements” [Sch-12, p. 602] [Eme-15, p. 1810]. Many companies and current research approaches work based on approximation to evaluate economic, environmental and social impacts [VDI-00, p. 31 f.].

A range of methodologies is available to evaluate **economic impacts**. For example, measuring profit quantifies the economic impact. **Assessment** in production systems is used at strategic, tactical and operational levels to support decision-making, and for each level, requirements and conditions must be declared [Ste-14b, p. 930 f.]. Two assessment methodologies which are broadly accepted in practice are selected. **Balanced Scorecard** (BSC) is an acknowledged assessment methodology based on financial and non-financial data. The BSC translates the company strategy into a set of qualitative requirements and quantitative measures that support future improvement, including goals and initiatives. The BSC is widely applied for the derivation of requirements from goals. **Quality Function Deployment** (QFD) is a qualitative methodology to rank solutions. This methodology demonstrates qualitatively how the effectiveness of a value creation factor, module or system would change iteratively according to high utilization of resources and cognition by stakeholders. The **house of quality**, as one of the most recognized instruments of QFD for gap analysis, is selected to translate significant gaps from existing solutions into opportunities for future solutions regarding identified requirements. The house of quality determines relations, targets, gaps, trade-offs, and redundancies between a set of requirements and solutions [Wal-01, 13.6–13.10].

Evaluation of environmentally benign manufacturing provides widely used guidelines to quantify **environmental impacts** such as tracking carbon and water footprints. **Life-cycle assessment** (LCA) methodologies evaluate the performance of life-cycles and provide measurable values, as well as data structure. ISO 14000 and ISO 14044 provide widely used guidelines for LCA and product carbon footprint studies [DIN-09, p. 14 ff.]. LCA measures mainly a set of indicators and calculates primarily the environmental, but also the direction of economic and social impacts quantitatively to provide evidence of efficient solutions.

The assessment of **social impacts** is introduced for supply chains, but only rarely for individual value creations factors such as products or processes. For example, the establishment of ergonomic workplaces for operators can be quantified by social and economic impacts. "Methodologies searching for an optimum, such as simultaneous planning, would typically fail since they disregard stakeholder preferences and the interactions among them" [Eme-15, p. 1810]. However, a multi-perspective view on potential solutions is needed for assessment in order to select the best fitting solution among the proposed solutions. Integral approaches should move beyond these separated impacts by focusing on the broader identification of technological potential and the increase of competitive advantage.

A set of **Pareto** optimal solutions is required which define a set of consistent solutions that make at least one individual better off without making any other individual worse off. Selection of potential solutions addresses first each solution under multiple requirements and then a set of solutions without degrading the fulfillment of at least one other requirement [Ste-14b, p. 930]. "**Multi-attribute utility theory** (MAUT) enables decision-makers to structure complex production systems in a hierarchical form as well as to assess measures in the presence of uncertainty [Smi-04, p. 567 f.]. MAUT manages trade-offs in value creation by combining different perspectives and quantifies individual stakeholder preferences" such as investment costs for ergonomic equipment versus improving working standards for the workforce [Eme-15, p. 1811].

Following the implementation of any methodology, value creation must be continually reviewed in order to identify opportunities for further developing technological solutions and creating more added value, while also meeting the recent requirements by changing conditions. Integral approaches can explore how existing solutions can be critically reviewed to provide feedback and **continuous improvement** for sustainable manufacturing. Companies must have the capability to adapt immediately to changing conditions in order to meet customer needs, keep production costs low and reduce waste. Practical adaptation promotes and increases the competitive advantage [Hol-07, p. 422].

A broadly accepted methodology which serves to continuous improvement is **Plan-Do-Check-Act** (PDCA) to measure and analyze manufacturing activities continuously. The PDCA describes an iterative cycle applying planning, controlling and quality management procedures to satisfy customer needs. The cycle starts with the establishment of a plan, referred to as “plan”, continues with its execution, referred to as “do” and monitoring, evaluation and results analysis, referred to as “check”. Corrective actions, referred to as “act”, to rectify performance are then implemented. The PDCA is used later to develop Six Sigma decision models for problem-solving based on changing requirements [Dem-00, p. 131 ff.].

2.1.3.3 **Morphological Analysis for Value Creation**

Morphology is the study of the shape and arrangement of an object’s parts. It describes how parts of a physical object such as factory or its parts, a social system of an institution or mental objects such as design concepts or simulation rules interact to create a whole system. Morphological analysis including charts, matrices and maps, are widely used in a number of scientific disciplines such as product development, zoology and geology to provide a structured search for problem-solving and for combining potential solutions [Kre-01, 6.45-6.50].

By applying the principles of sustainable manufacturing, engineering must focus on multiple interactions among value creation factors and their life-cycle stages [Bil-16a, p. 2]. To build a case-based scope addressing the interactions between factors and stages in this research, a morphological analysis is presented in Figure 2-5. The analysis maps different levels of value creation factors and their life-cycle stages to investigate interactions within a production system. Each value creation factor is divided into several aggregation levels, as presented in the previous subsections.

Using the mapping in Figure 2-5, for example, the product life-cycle stages can be mapped to equipment life-cycle stages. During the use stage of an industrial product such as a grinding machine, stakeholders within a company as users are required to ensure maintenance of the product as an equipment. Any selected mix determines a path for value creation and helps to organize information for further investigations. Selected levels of value creation factors and their interactions enable the identification of scope, exploration of opportunities and potential solutions, which support decision-making. For example, two manufacturing processes can be run at a workplace to produce a component within a cell equipped with three machines and four tools. The process can be planned on one of the machines by an operator.

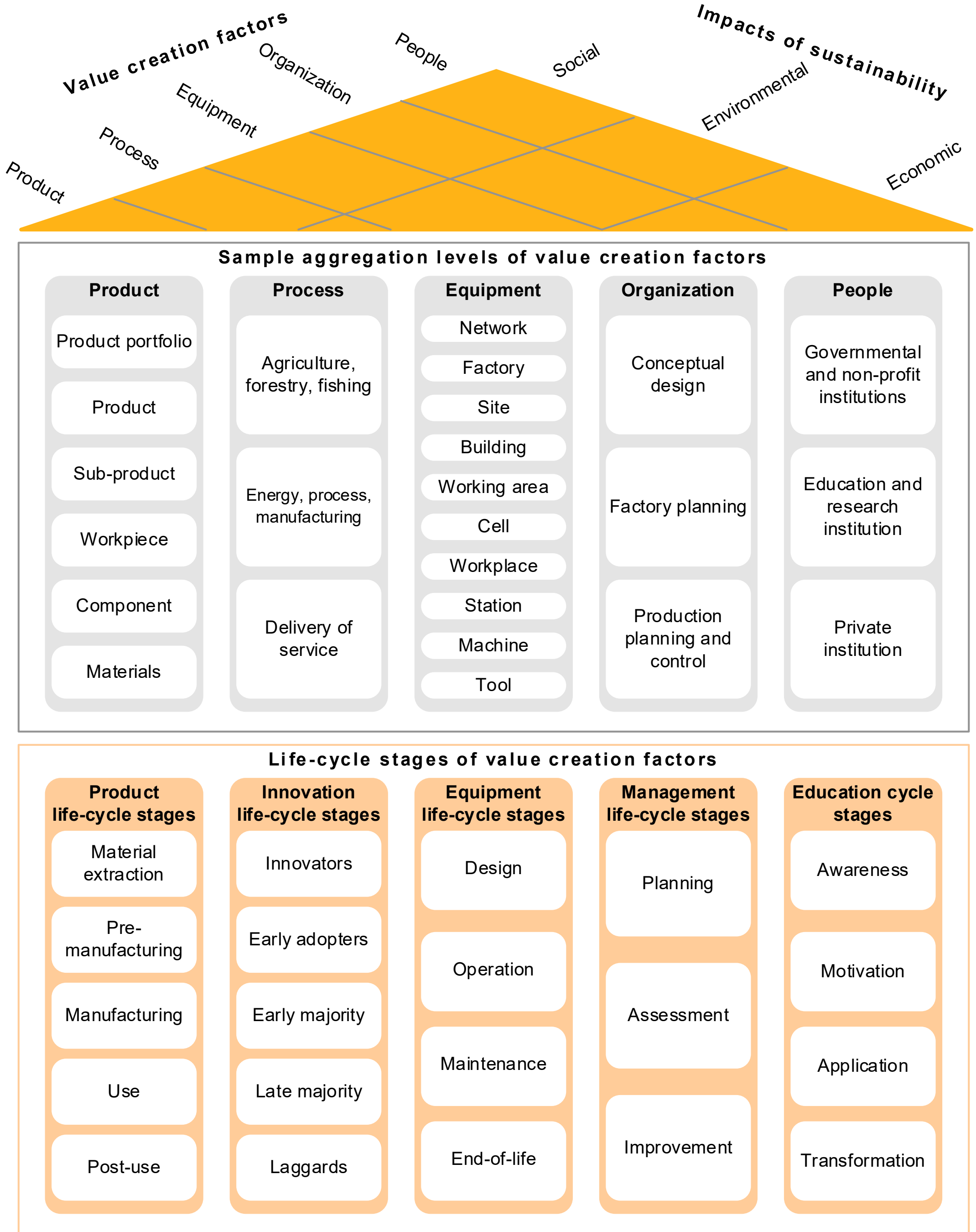


Figure 2-5: Mapping and integrating value creation factors and life-cycle stages

2.2 Industrial Engineering Practice

This section investigates engineering disciplines and capabilities provided in education and training according to their potential contribution to sustainable value creation. The investigation is divided into three subsections. The first subsection explores the current engineering capabilities which are provided through higher education and identifies potential engineering disciplines which can be useful for contributing to sustainable value creation in manufacturing. The second subsection presents relevant elements of selected best practice programs. The third subsection summarizes attributes which currently contribute to demonstrate the superiority of industrial engineering in manufacturing using methodologies in technology and management.

2.2.1 **Engineering Capabilities**

This subsection discusses (1) engineering capabilities based on higher education programs and (2) compares selected engineering disciplines to identify potentials which could easily address challenges of sustainable value creation in manufacturing.

2.2.1.1 **Capabilities through Higher Education**

A capability is defined as the ability of people to execute a specified task. It can be accompanied by an intention, as mainly used in the defense as well as production industry [Dep-16]. Students develop certain capabilities at universities for their future professional career; these capabilities are the result of an academic education. Universities frequently offer higher education programs at bachelors, masters, and doctoral levels as bodies of higher education, where formal, institutionalized and academic education and research is conducted. The **Humboldtian model** of higher education combines research and education. Following the European Qualifications Framework, engineering capabilities describe abilities to perform certain decisions and actions through a set of knowledge, skills and competence in various engineering disciplines, as presented in Figure 2-6 [EU -08].

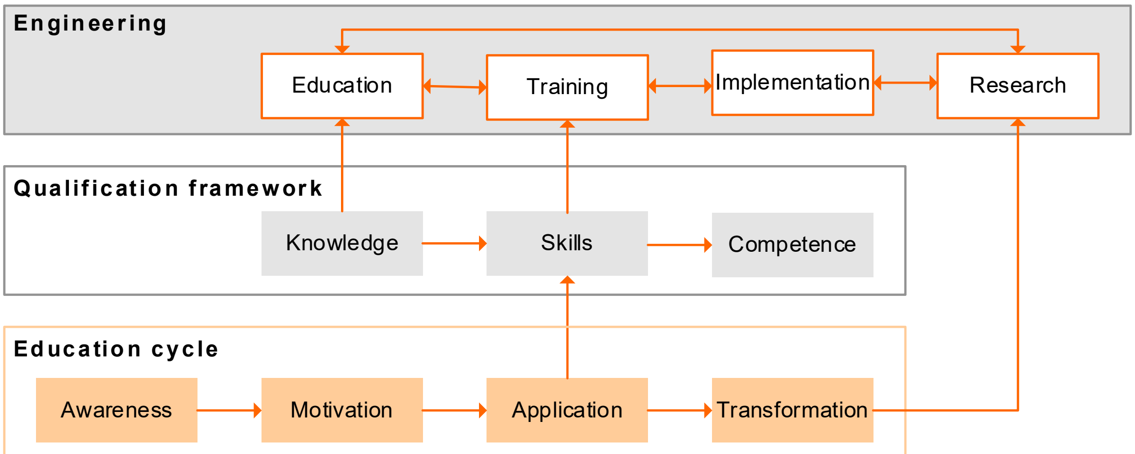


Figure 2-6: Engineering mapped to qualification framework and education cycle

Knowledge is the outcome of information assimilated and reproduced through learning. Students achieve academic knowledge through learning in higher education. Knowledge is a body of facts, principles and theories. The body of methodologies, instruments and tools builds methodological knowledge [EU -08].

Skills are the ability to apply knowledge, use logical thinking, and know-how to complete tasks and solve problems [EU -08]. Students train learned methodologies and tools in order to extend their methodological knowledge into practical knowledge, which then results in skills, i.e., skills describe practical knowledge as a result of intensely trained methodological knowledge. Training programs are structured, and are non-formal parts of academic education designed to impart skills through planned practical courses and real problems, in both research and practice. Practical courses usually follow the principle of "**learning by doing**," which was introduced by Dewey at the beginning of 20th century [Bru-12a, p. 1821]. Introduced for medical **problem-solving** in the late 1960s, problem-based learning focuses on existing issues in order to find solutions. For instance, if students identify the cause for an irregular state of a machine, they construct maintenance activities by generating potential solutions, collecting relevant information through interviewing the machine operator, analyzing historic data, as well as they test potential solutions and evaluate them [Sel-11b, p. 7].

During Kolb's four-stage **education cycle**, as presented in Figure 2-6, students are in the formal procedure of awareness, motivation, application and transformation. Focused determination inspires them to perform reflective observation and to engage in personally experiencing the surroundings. They frequently apply knowledge in order to form certain concepts and test these concepts in real situations [Gog-12, p. 1838].

Competence is the proven ability to use knowledge and skills in professional life by taking responsibility for activities and decisions [EU -08]. Performing knowledge and skills in professional life acquires and improves competence, which is a named practice [EU -13]. The active, unstructured and informal experimentation of knowledge and skills in professional and personal lives results in experience.

Experience, principles and motivation all influence ways of looking at, and watching certain situations during implementation of capabilities. **Critical thinking** is the structured procedure of analytic thinking, analyzing and synthesizing information, data, facts and experience around accumulating answers to questions. Using critical thinking in training and practice enables the application and transfer of knowledge to new situations and interpretation of data to make balanced decisions [Dan-14, p. 363]. Critical thinking is essential for engineers to think outside of the box, and to balance conflicting goals and trade-offs between the value creation factors and stakeholder requirements.

Transferring knowledge to new situations for the purpose of interpreting data builds concrete experience, which improves competence and later becomes a principle for decision-making in similar matters. The more the experience gained through application and transformation in practice, the greater the level of competence gained [Gog-12, p. 1838].

During the formation of higher educational programs, the pursuit of principles and standards guides all stakeholders, including instructors, lecturers, scientists, coordinators and designers of a program [Els-99, p. 417 ff.]. External accreditation bodies, which are authorized by the respective governments and professional societies, evaluate educational programs in order to determine if the governmental and intergovernmental standards are met. For example, the European **Bologna Process** aims to ensure comparability of the national standards and quality of higher education qualifications [EU -08]. Designers and coordinators take the initiative to adapt the programs to the regional conditions of any respective country. Feedback from industry, alumni, scientists, accreditation bodies, designers, coordinators, instructors and lecturers shapes new programs. When the accreditation bodies assess the revised programs, the accreditation criteria of, for example, the Accreditation Board for Engineering and Technology (ABET) in the USA and the Accreditation Agency for Degree Programs in Engineering, Computer Science, Natural Sciences and Mathematics (ASIIN) in Germany, guide the higher education institutions.

2.2.1.2 **Superiority of Industrial Engineering**

Until the second industrial revolution, problems tended to be in magnitude, spatial or temporal extent to analyze. In most cases, solutions could be found using methodologies from a single discipline such as mechanical or electrical engineering. Starting from the beginning of the 20th century, industrial issues become complex and were deemed unsolvable with mono-disciplinary capabilities and methodologies [Mad-07, p. 4].

This situation required engineers from different disciplines to cooperate in order to solve problems, which is called **interdisciplinary** cooperation. Since the advent of interdisciplinary problem-solving for complex issues, the focus lies on applying an appropriate methodology as well as identifying and bringing together the required mix of people from different disciplines [Mad-07, p. 4]. Furthermore, some issues required an extension to the contributing disciplines, thus, enriching single disciplines. New disciplines have emerged from such cooperation such as industrial engineering combining technology and management.

Despite required interdisciplinary cooperation, there is also a need to integrate multiple perspectives into decision-making and acting, when inadequacies or conflicts among goals such as time, cost and quality exist. In such cases, a trade-off is thought to involve losing one goal through value creation in return for gaining another goal. Trade-offs occur between various aspects of value creation. Sample trade-offs with two initially conflicting goals and potential complementary solutions for meeting the challenges of each trade-off are listed in Table 2-1.

Table 2-1: Trade-offs in value creation and potential solutions

Trade-offs in value creation	***Potential solutions for meeting the challenge***
Technology and management	Emerging technologies are cost-intensive in the development stage. Focusing on development of new technologies as a managerial decision can lead to emerging innovations which can overtake a current technology and create even greater benefits.
Practice and theory	Theoretical foundation is necessary to simulate new products under limited conditions, whereas practical demonstration of a prototype is essential to test it and improve iteratively.
Relevance and rigor	Research can implement both rigor and relevance. It is an explanatory science focusing on empirical describing, explaining and predicting and a design science focusing on case-based diagnosing, configuring and improving [And-04, p. 399].
Sustainability and competitiveness	The fulfillment of stakeholder requirements through sustainable manufacturing turns primarily economic values, but also environmental and social values, in competitive advantages. For example, decisions and actions to create sustainability-based new solutions are supported to ensure that a certain company gains economic advantages by investing in new forms of renewable energies for reducing its non-renewable energy consumption [Por-95, p. 128]. Meeting new regulations as an innovator can provide savings in energy costs and taxes.
Effectiveness and efficiency	Engineers should work efficiently, having decided on the right action by intense training of balancing impacts and adapting solutions.
Global and local	Engineers decide and act efficiently for local value creation without compromising current and future global well-being regarding environmental limitations and demographic challenges.
Interdisciplinary and mono-disciplinary	Disciplinary focus on single issues of a complex problem solves small pieces of the big picture, while interdisciplinary teams can approach complex problems from multiple perspectives together.
Top-down and bottom-up	A high-level goal such as sustainable development can be postulated, which is a creative top-down procedure, then revised and verified based on a bottom-up analysis of existing processes such as energy consumption of a machine. The bottom-up analysis can be made systematic in order to repeat it partly automatically and periodically [Pri-03, p. 462].

A comparison of major disciplines in selected educational programs shows that business and legal studies, social sciences, computer sciences, and mono-disciplinary engineering programs only barely cover successful management of trade-offs [Mad-07, p. 4 ff.]. An interdisciplinary engineering discipline can analyze a trade-off from multiple perspectives, evaluate cause-effect relations and consequences of all in order to create complementary solutions and new opportunities for the challenge. This requires engineers to become generalists, rather than specialists, in order to understand and manipulate value creation factors and modules interconnected in a production system.

In order to look at the big picture, rather than only ensuring that processes meet individual requirements, “**industrial engineering**” has emerged as a new engineering discipline during the second industrial revolution. The roots of the profession date back to the beginning of the 20th century. Taylor is well acknowledged as the pioneering management expert, engineer and the leader of the engineering movement in developing methodologies for improved efficiency in manufacturing without using the term “industrial engineering” [Mar-01, 1.5-1.6].

Following increasing industrialization in many countries, industrial engineering has been a fast-growing engineering discipline since then. According to the Bureau of Labor Statistics from the USA, higher education graduates from the educational group of Science, Technology, Engineering and Mathematics (STEM) used worldwide, especially from nine engineering disciplines, are the most required people in the labor market. Three out of these nine engineering disciplines make up two-thirds of the American engineering workforce [Wri-14]. (1) Mechanical and (2) industrial engineering as well as (3) electrical engineers and computer science engineers has accounted for the most jobs of any engineering discipline with around 270,000; 240,000 and 180,000 jobs out of 1.2 million engineering jobs in total in 2014 with an increasing trend of 23%, 20% and 15%, as presented in Table 2-2 [Com-16, p. 76].

Table 2-2: Comparison of job occupations and accredited programs in the USA

Engineering discipline	***Job occupations in 2014*** *[Com-16, p. 76]*		***Accredited programs until 2014*** *[ABE-15, p. 21 f.]*	
	Number	***Share***	***Number***	***Share***
Engineering managers	175,929	15%	19	1%
Aerospace engineers	70,195	6%	76	4%
Biomedical engineers	20,631	2%	107	5%
Computer hardware engineers	77,517	6%	330	16%
Electrical engineers & computer science	180,455	15%	314	15%
Electronics engineers	136,700	11%	579	27%
Industrial engineers	238,671	20%	148	7%
Materials engineers	25,280	2%	67	3%
Mechanical engineers	273,561	23%	485	23%
All engineering disciplines in total	1,198,939	100%	2,125	100%

In all three, 25% of currently employed workers are 55 years or older. Industrial engineers are vital to many companies that struggle to find the right technically oriented talent, so the aging workforce is a threat [Wri-14]. As industrial engineering has been already acknowledged from an industrial perspective, its potential to address challenges of sustainable value creation in manufacturing and balance sustainability impacts increases with adequate education and training.

In order to highlight the superiority of industrial engineering from both perspectives, its educational background is investigated briefly. Interest in industrial engineering as an educational program in higher education has grown steadily since 1901, when Hugo Diemer designed and offered the first industrial engineering course in the Department of Mechanical Engineering at the University of Kansas, USA [Mar-01, 1.7-1.8]. The Stevens Institute of Technology had the oldest American “Industrial Engineering Department,” established in 1908 at the School of Business Engineering. In Germany, Willi Prion, an economics professor was the first director to develop and manage a department, focusing on industrial engineering, at the Berlin Institute of Technology (TU Berlin, in German: Technische Universität Berlin) since 1926 [Sch-13, p. 9].

As of 2014, the ABET accredited around 3,600 programs distributed over more than 710 universities in 29 countries. The accreditation commission for engineering programs within the ABET reviewed around 2,100 engineering programs until 2014 [ABE-15, p. 3]. However, only 148, which accounts for 7%, were industrial engineering programs, as presented in Table 2-2 [ABE-15, p. 21 f.].

The comparison of job occupations and accredited programs in nine engineering disciplines in the USA in Table 2-2 assumes that all engineering programs have similar student intake capacities. (1) Mechanical and (2) industrial engineering as well as (3) electrical engineering and computer science accounts for the most jobs. While the share of occupations in the first and third ranked disciplines is almost the same as the accredited programs with 23% and 15%, industrial engineering presents a higher demand than educational programs. When only the USA is considered, the need of labor market for industrial engineers is almost three times more (20%) than the higher education programs can provide graduates within the accreditation area of ABET annually (7%).

2.2.2 **Best Practice Programs**

Although the relationship among innovation, sustainable development and competitive advantage is complex, they all rely heavily on the adequacy of the education system and the performance of the labor market. By educating, training and rewarding people appropriately, a country ensures that its workforce have the skills to attain productive employment and that it can attract and retain talent. It is true for all countries that talent generates ideas that in turn power innovation, and that advanced capabilities remain an important source of competitive advantage worldwide [WEC-15a, p. 17 f.].

This subsection investigates relevant elements of selected best practice programs in industrial engineering. A brief country profile for selected developed and emerging countries based on the Global Competitiveness Report 2015-2016 is given in Subsection 2.1.1. Developed countries such as Germany and the USA, are most likely to focus on higher education as well as readiness to develop and adopt new methodologies. Even in many emerging countries where higher education is almost universal, its quality can be mediocre and curricula are not adapted to stakeholder requirements [WEC-15a, p. 18]. The importance of innovation is also disregarded in many emerging countries compared to the most developed countries.

The German National Academy of Science and Engineering (acatech, in German: Deutsche Akademie der Technikwissenschaften) compared educational programs in industrial engineering from developed countries in 2014 [Sch-13, p. 22 ff.]. Widely acknowledged industrial engineering programs are offered at the Georgia Institute of Technology (Georgia Tech), University of Michigan and Purdue University in the USA as well as at the TU Berlin in Germany. The acatech also reports that the expanding diversity in rating methodologies and accompanying criticisms of each indicate the lack of consensus in rankings [Sch-13, p. 23].

The programs at the Georgia Tech and the TU Berlin are selected as best practice to be reviewed in detail. Major elements of both programs are illustrated in a framework in Figure 2-7, resembling a house based on a three-year industrial engineering undergraduate program with 180 ECTS. Shares of the categories are almost the same by well-acknowledged four-year American and three-year German industrial engineering programs with 240 and 180 ECTS [Sch-13, p. 19]. Most programs cover basic academic knowledge in both engineering disciplines and economics within the first two years. The upper level courses build on courses taken earlier in the program. Students receive training and develop methodological knowledge from the fourth to the sixth semester in order to combine and intensify their learned academic knowledge in engineering and economics. Graduates usually earn a Bachelor of Science degree.

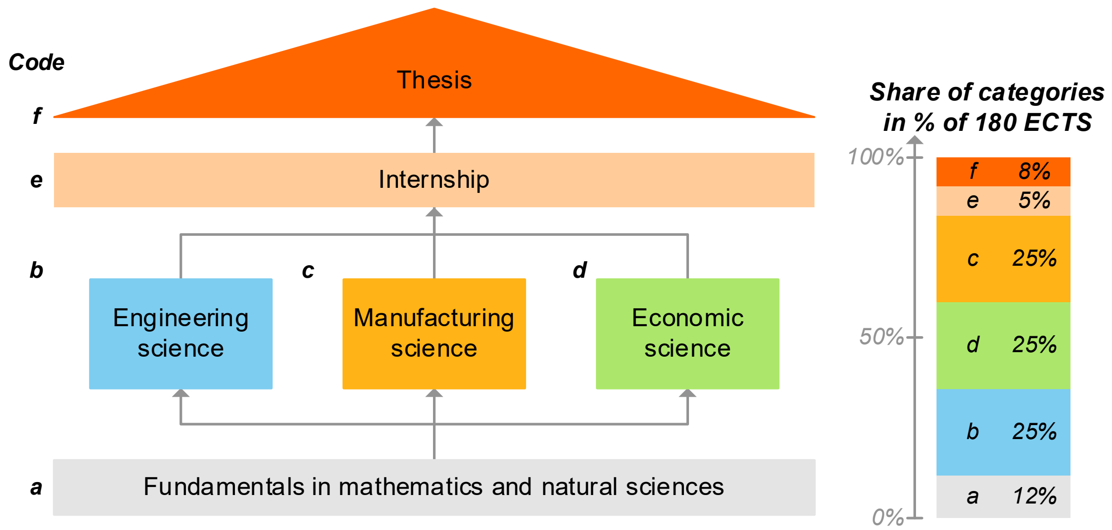


Figure 2-7: Framework of best practice industrial engineering programs

(a) The fundamental knowledge of engineering is in the formal and physical sciences. Most programs require several courses in the category “fundamentals in mathematics and natural sciences” in the first year, as presented by Figure 2-7a. Sample courses are mathematics through multivariate calculus, differential equations, discrete mathematics, calculus-based physics, an introduction in computer science to digitalize data.

(b) In the second year, physical sciences and technical courses related to fundamentals, particularly probability, statistics and stochastics, technical drawing, electronics, statics and solid mechanics, introduction in databases, business administration, accounting, and macroeconomics, build the necessary fundamentals, as presented by Figure 2-7b.

The upper level engineering courses in the third year, including thermodynamics, engineering tools and computer-aided design provide sufficient knowledge for the students to focus on manufacturing methodologies and tools in order to improve the efficiency of technological processes.

(c) Courses related to production and assembly technology, machine tools, automation, manufacturing processes laboratory and computer control of and simulation in production systems constitute a good portion of the program, as presented by Figure 2-7c.

(d) In the first two years, fundamentals in economics cover business administration, accounting, marketing and controlling. Based on this economic knowledge, in the third year, related courses such as factory information and technologies, quality and supply chain management follow. The third year economics courses focus on organizational and managerial aspects of value creation, as presented by Figure 2-7d [Els-99, p. 418 ff.].

(e) Many of the academic courses require laboratory experience in training and experimentation, modeling, simulation and interpretation of results. Students develop skills through internships, as presented by Figure 2-7e.

(f) Senior students write a bachelor thesis in the fourth year, which requires students to work, on occasions with industry and would involve science-based analyses, as presented by Figure 2-7f. The oral and written presentations associated with the internship and bachelor thesis require skills in both scientific and technical writing.

Following the “learning by doing” principle, the creation of technological solutions represents both merging action and experience of engineering students with projects. Projects address existing industrial issues of how to shape value creation via scientific approaches. Project-based courses have been established with students and researchers of universities in Botswana, Brazil, Chile, Germany, South Africa, South Korea and the USA within the CRC 1026 network since 2012, which is presented in Subsection 2.1.1 [CRC-16] [Eme-15, p. 1816] [Sel-11b, p. 7 f.].

2.2.3 **Attributes of Education and Practice**

Attributes are defined as characteristics, which indicate the current position or the direction and rate of change towards a particular goal [Bil-15, p. 301]. To teach and train students as well as create value in manufacturing, current industrial engineering applies the following three attributes.

- Industrial engineering is an **interdisciplinary** profession that contains two main knowledge domains: technology and management. Higher education in industrial engineering provides academic knowledge in both engineering and social sciences [Max-05, p. 6 ff.]. Interdisciplinary capabilities support engineers to understand situations from different perspectives, while increasing the efficiency of value creation [Mad-07, p. 4].
- IT enables the **digitalization** of information, data, and facts for many tasks and decisions. Access, storage, exchange, and manipulation are possible through the integration of telephone lines, wireless signals, computers, software, storage, and audio-visual systems. Education and practice have increasingly exploited IT in the last three decades. In education, courses focus on IT-based learning. In practice, IT-based applications have increasingly evolved in order to complete daily tasks such as planning, operation and monitoring of production systems [Jov-08, p. 647].
- In industrial engineering, **problem-solving** combines logical thinking with analysis and synthesis by applying methodological knowledge and skills [Bru-12a, p. 1821 ff.]. Interdisciplinary capabilities designate industrial engineers to recognize and infer single and common goals in complex production systems, abandon and communicate goals that are no longer relevant, identify conflicts among goals, and prioritize goals consistently for more competitive advantage in value creation. Ongoing efforts of industrial engineering in problem-solving aim to change value creation.

Designers of educational programs follow these attributes in order to create new programs, coordinators follow attributes in order to operate, scientists in order to research, instructors and lecturers in order to teach, and adapt educational courses, and students in order to learn. Graduates follow these attributes in their professional life by transferring and applying their academic knowledge to new situations. They accomplish tasks and make decisions in order to design, plan, operate, maintain, assess, and improve value creation activities. To acquire competence in these tasks, they combine knowledge and skills in both technology and socio-economics [Bil-16b, p. 519].

These attributes are applied to improve existing production systems towards resource efficiency in the circular economy and provide greater economic benefits, sometimes combined with environmental and social impacts. However, less attention is paid to understand the methodologies for next-generation manufacturing [Jaw-16, p. 107]. “Therefore, engineering must exceed the limits of economic impacts of single products and processes to open up to integrate all aspects of the economy, environment and society [Pet-94, p. 404]. To identify and conduct research for next-generation manufacturing, the USA National Science Foundation defines that **transformative research** involves ideas, discoveries, or tools that radically change understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education [NSF-15]" [Bil-16a, p. 456].

Many countries educate and train industrial engineers applying these attributes, however, they do not educate and train the required amount of engineers but also capabilities such as creativity, initiative, risk assessment and constructive management of changing conditions. Change of value creation, especially of production and consumption habits, is required in order to close the gap between developed and emerging countries. The lack of suitable approaches in education, research and practice between developed and emerging countries can be bridged by implementing a novel approach for adaptively developing best practices from developed countries, and the associated research methodologies, into the production systems in emerging countries. Integrating new approaches into education and later into the practice of industrial engineers offers opportunities to gain leverage on the required sustainable development. The next sections provide a closer look behind the scenes of industrial engineering in order to analyze how far industrial engineering can enhance capabilities for sustainable value creation, and to identify the prevalent gaps in industrial engineering.

3 Contribution of Industrial Engineering to Sustainable Manufacturing

A short review of the state-of-the-art architecture and methodologies for value creation showing what principles are currently applied in manufacturing for truly implementing sustainable manufacturing was presented in Chapter 2. Value creation can be modeled considering both, actual entrepreneurial activities in globalized markets and requirements of sustainable development. Dynamics of competition and cooperation in globalized markets can be utilized by technological and organizational innovation to cope with sustainability challenges [Sel-11a, p. 22 ff.].

The majority of existing methodologies in technology and management focus on analysis and improvement of separate parts of value creation rather than synthesis to develop integrated solutions. For example, the focus of increasing efficiency in welding lies mostly in individual projects aiming to decrease consumption of resources such as base or filler to cut costs. Another goal is to prevent injury through open electric arc or flame, and neurological damage generated through exposed dangerous gasses in order to increase safety of welders or other near-by-standers. Other research fields in welding are substituting conventional resources through new technologies such as laser-hybrid welding, increasing speed for higher productivity or assessing footprint to measure a new process's environmental impact on the ecosystem. However, there is little effort to integrate these efficient solutions into welding effectively.

A focused determination of stakeholders based on motivation, understanding of conflicting and redundant goals as well as experience with meeting sustainability challenges should promote and facilitate a holistic implementation of sustainable manufacturing. The implementation in training and practice involves technological and management methodologies for designing and producing, as well as managing, operating, and evaluating the impacts of products and services. Industrial stakeholders and scientists agree that the need for radical changes in ensuring competitive advantage, protecting the environment, and distributing wealth equally worldwide is urgent and imminent for sustainable development [PWC-15, p. 28]. The necessity to understand sustainability challenges and apply concepts to products, processes and production systems to meet them holistically require enhancement of engineering capabilities and information from different sources across the globe. While many disciplines such as economics, laws, and natural sciences focus on rigor, engineers focus on relevance and seek to find approximate solutions instead of an absolute ideal or optimal one. Developing and implementing new solutions often requires upgrading human capabilities and institutional abilities to interrelate technology and management as well as design and deploy sustainable solutions.

Industrial engineering is driven by case-specific conditions and requirements, which dictate how far initiative, creativity, hard work as well as management and social competence are required to fulfill a task. A new solution should be sufficient rather than being exactly the best one. Current industrial engineering capabilities can cope with many individual challenges in similar individual projects in manufacturing, as value creation flows from analysis to synthesis iteratively. However, current capabilities remain constrained due to the lack of transformative research for operationalizing principles of sustainable manufacturing in practice. Relevant research questions are:

- How can change of value creation through new solutions contribute to leverage multiplier effects on the economy, environment and society?
- How can industrial engineers be made capable to apply the principles of sustainable manufacturing?
- How can industrial engineers create new solutions in different fields of manufacturing integrating them into existing systems for a sustainable development of the economy, environment and society?

A closer look at industrial engineering provides insights into its practice and research can contribute to leverage the sustainable development of the economy, environment and society, as presented in Figure 3-1.

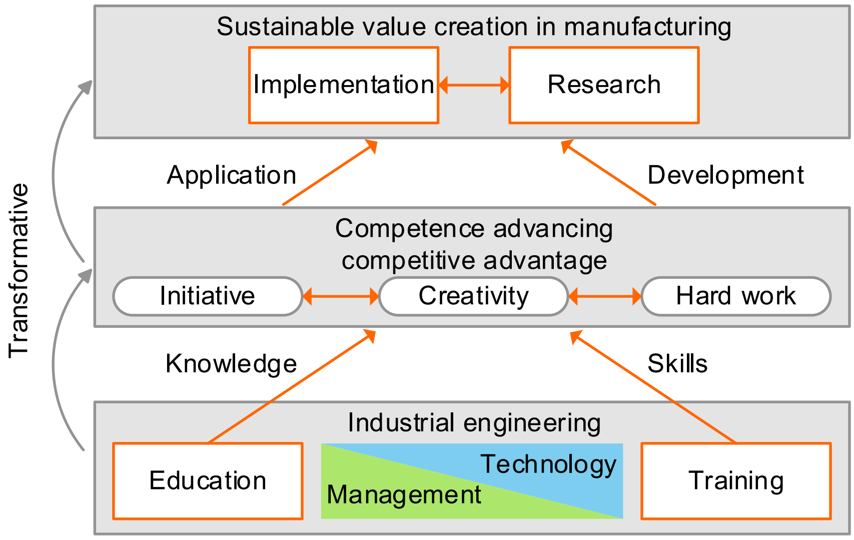


Figure 3-1: Contribution of industrial engineering education and practice to sustainability

Technological and organizational solutions can create sustainable value in manufacturing across the globe including developed, emerging, and developing countries, while at the same time helping to improve global well-being and environmental protection.

Industrial engineering education and training programs can provide the required knowledge, skills and competence in technology and management, and enhance capabilities for sustainable value creation in manufacturing. Integrating new attributes into higher education and later into the practice of industrial engineering offers opportunities to gain leverage for achieving the level of required sustainable development. If industrial engineering is to prosper in the future, it needs to serve the economy, environment, and society. New approaches for changing educational programs in universities and implementing an architecture for sustainable manufacturing are required. In order to contribute to sustainable manufacturing in these terms, industrial engineers should be empowered to become capable of

- maintaining an emphasis on connecting multiple methodologies in technology and management by following principles of sustainable manufacturing;
- changing the value creation in a sustainable manner that is aligned with the requirements of stakeholders who must continuously adapt the value creation to the changing conditions as the dwindle of the natural resources, climate changes, and growth of world population;
- understanding the economic, environmental and social challenges in the light of changing conditions in order to achieve a balance between conflicting or redundant goals; and
- designing a closed-loop architecture for sustainable manufacturing integrating stakeholders, regions, and disciplines into value creation.

These capabilities are only partially dealt within the current educational programs. However, they are essential for advancing abilities in industrial engineering beyond problem solving and toward synthesizing new solutions. Hardly any methodology to change industrial engineering in this regard is available yet. This research aims to fill this deficit by providing a new methodology for transforming industrial engineering in order to enhance the required capabilities for sustainable value creation.

New transformative attributes must be developed for application in new educational programs for industrial engineering education and training, and later for practice and research. A new architecture is required for sustainable value creation in manufacturing to cope with the challenge of implementing sustainable manufacturing principles. The architecture is developed through research for applications including education and training in order to enhance engineering capabilities, which can create sustainable solutions in practice.

4 Development of an Architecture for Sustainable Manufacturing

Current industrial engineering capabilities can cope with many individual challenges in manufacturing, however, they struggle to cope with many challenges at once. They remain constrained when it comes to the application of transformative research in order to operationalize principles of sustainable manufacturing in practice. How can industrial engineers be made capable of applying these principles in manufacturing?

4.1 Overview

The goal here is creating sustainable solutions by providing a roadmap with industrial engineering serving as an effective architecture for sustainable manufacturing. Figure 4-1 presents the proposed architecture, which is developed through research for applications including education and training in order to enhance industrial engineering capabilities.

A brief introduction to value creation terminology defined by the CRC 1026 [Sel-11a, p. 25 f.] using the architecture for sustainable manufacturing follows: Solutions for creating value in manufacturing demonstrate the value creation factor $VCF_1 = product$. In manufacturing, value creation flows from analysis to synthesis iteratively, as represented by $VCF_2 = process$. Industrial engineers, who represent stakeholders in terms of $VCF_5 = people$, must continuously justify why a technological or organizational opportunity provides a potential solution for creating sustainable value in practice. Enhancement of industrial engineering capabilities by educational and training programs to create sustainable solutions demonstrate the $VCF_3 = equipment$. This architecture connects value creation in manufacturing with industrial engineering education and practice. This connection builds the $VCF_4 = organization$.

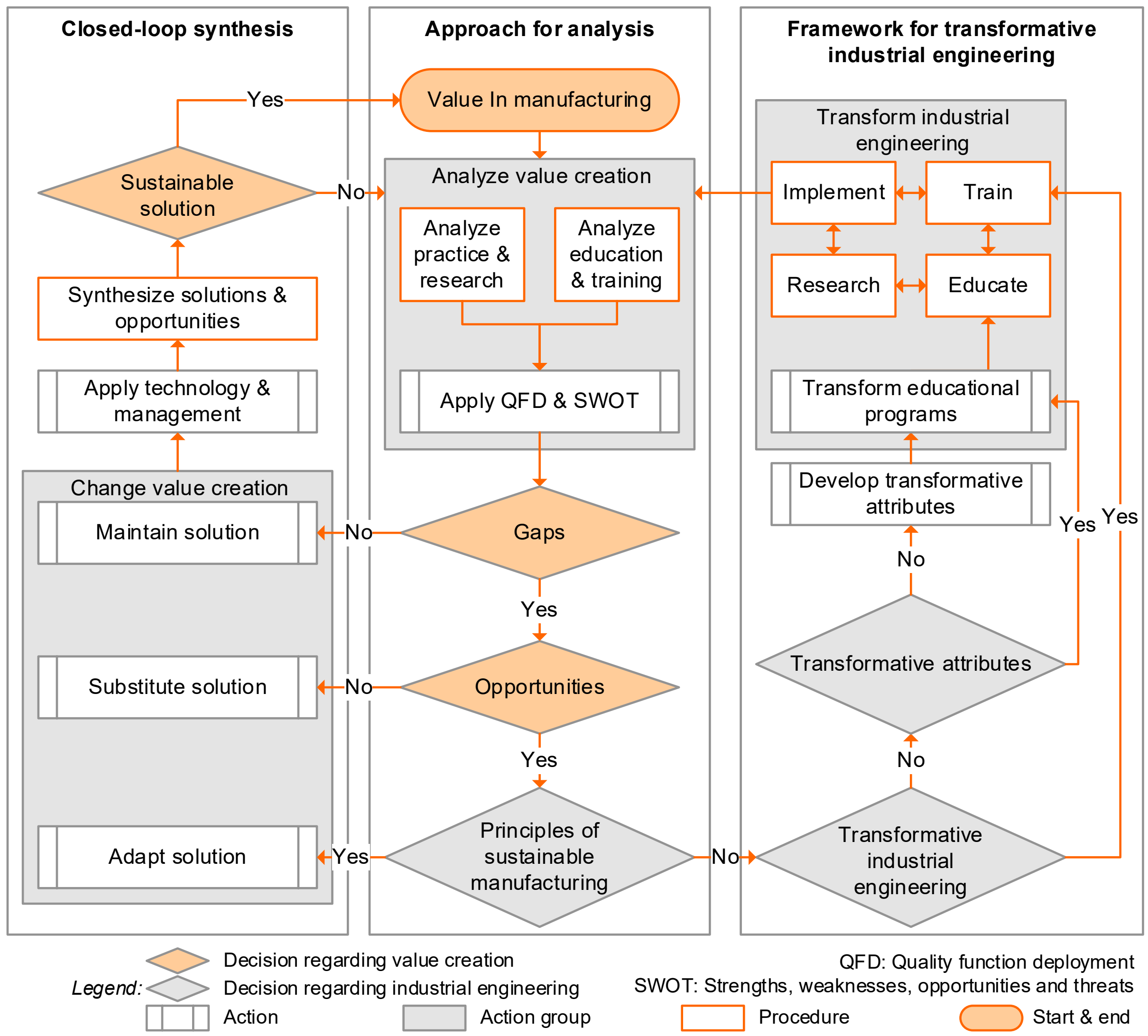


Figure 4-1: Architecture for sustainable manufacturing

The architecture for sustainable manufacturing illustrates in three sections how enhanced industrial engineering capabilities are operationalized in iterative cycles that industrial engineers can understand the existing solutions including their impacts, and accordingly create new solutions. Each section conceptually demonstrates the following:

- An **approach for analyzing** the current value creation in manufacturing: Starting at the top of the middle box in Figure 4-1, the created value in manufacturing is examined in Section 4.2 by methodologies such as QFD or a SWOT analysis describing strengths, weaknesses, opportunities and threats, if it satisfies requirements and balances economic, environmental and social impacts. If industrial engineers are aware of the principles of sustainable manufacturing, they can create sustainable value, while satisfying the requirements better than before.
- A **framework for transformative industrial engineering**: Starting at the bottom of the right box, Figure 4-1 shows that if industrial engineers have not already observed these principles, following transformative attributes can guide the transformation of higher

education and training programs to enhance capabilities in order to integrate these principles into practice, as presented in Section 4.3.

- A **closed-loop synthesis**: Starting at the bottom of the left box, Figure 4-1 shows that enhanced capabilities in industrial engineering promote the commitment to the principles of sustainable manufacturing. Thus, industrial engineers are capable of addressing opportunities, while changing the value creation, by methodologies in technology and management to synthesize sustainable solutions, as presented in Section 4.4.

4.2 Analysis

This section unfolds the proposed new approach for analysis of manufacturing. Analysis refers to gain a better understanding of how value is created, i.e., how a certain value creation factor, module or a production system is designed. Conditions and requirements of a certain factor, module or system are specified to answer the previous questions. The analysis provides a structure for ensuring that customer needs and other stakeholder demands are carefully heard, then translated directly into requirements. A QFD-based calculation approach and a SWOT analysis are selected to apply for analysis of value creation in this research to address the effectiveness of solutions qualitatively. Both methodologies are adapted for applications including education and training and are then combined to offer and monitor a continuous flow of information from requirements to shape new solutions for manufacturing. This combination guides industrial engineers in analyzing gaps, exploring opportunities, and then achieving the determined targets through the application of industrial engineering methodologies and principles. It is essential for industrial engineers to be committed to the principles of sustainable manufacturing in order to change the value creation towards sustainability.

4.2.1 **Procedure for Gap Analysis**

For aiding and fostering a better understanding, the procedure for the gap analysis is described in detail in this subsection. QFD describes “quality” as fulfilling the requirements what customers need and other stakeholders demand, and “function” as for how those requirements are to be fulfilled by focusing on principles to create sustainable value in manufacturing. “Deployment” encompasses industrial engineering capabilities by making the fulfillment happen to ensure both the required quality and function towards sustainability. The goal of QFD in this research is to explore possibilities, limitations and compatibilities, as well as to identify opportunities for transforming educational programs and implementation of analysis and synthesis.

The gap analysis as a combination of QFD and SWOT analyses proceeds through seven steps. It puts together a house of quality in the form of a schematic matrix in Figure 4-2 in order to analyze, justify and conclude results from any case study of value creation. After the selection of stakeholders in Step 1, stakeholders were asked two questions for conducting the analysis how value is created: (1) What is required by stakeholders within the frame of conditions? (2) What is available and possible? After the specification of requirements, the preferences of stakeholders for each requirement are determined in Step 2. After the existing solutions are specified in Step 3, the degree of fulfillment of each requirement by each existing solution is justified in Step 4. The question, that naturally follows, is whether the module fulfills the requirements effectively keeping with the conditions and balancing economic, environmental and social impacts. Comparing the scores of each solution with the targets in Step 5 leads to identification of its gaps in Step 6, which need to be narrowed down or closed. Steps 1 to 6 apply more QFD, while identification of opportunities in Step 7 focuses more on a SWOT analysis among scores and identified gaps to adapt existing and create new solutions.

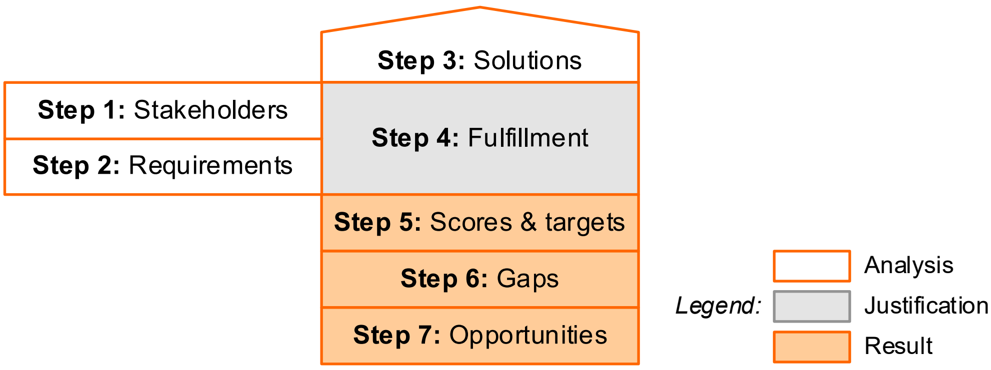


Figure 4-2: House of quality

4.2.1.1 **Step 1: Stakeholders**

In order for any company to stay in business, it must be able to create value in production and sales of their products or services, and be able to rely on repeat business. Competitive advantage can only be achieved with a backbone of continuous satisfaction of customer needs, as well as other stakeholders' demands. Stakeholders are divided into three groups according to Maslow's hierarchy of human needs [Sel-11b, p. 4 ff.]:

The first group consists of the public –governmental– and voluntary –non-governmental and non-profit–institutions and sectors serving the society. This group aims at protecting the society from actions by people with negatively impacts on their environment. These stakeholders determine policies, regulations, and standards to satisfy basic human needs such as air, water, and food, and preserve a good quality of life and education. This group focuses on regulative requirements, for example, for security and safety of all stakeholders, standardized and transparent processes, and environmental impacts of value creation. For example, legislators, administrators, and arbitrators fall into the first group.

The second group consists of education and research institutions in line with the Humboldtian model. For example, universities offer tertiary level qualification, as well as research and development activities. This group focuses on validation and verification of scientific concepts in practice, which includes demonstrating, and prototyping as proof-of-concept, for example, for newly developed products, human-centered automated processes, and equipment remanufactured through the 6R methodology [Jaw-06, p. 4]. Students, instructors, lecturers, designers and coordinators, and scientists fall into the second group.

The third group is the economic and private sectors, including the manufacturing and service sectors, which are run for profit as small, medium, or large companies along the supply chain, and people, including all taxpayers and consumers. Members of this group are cooperating and competing stakeholders with each other in production systems, including manufacturers, their suppliers, customers, shareholders, and competitors. To gain more competitive advantage, this group can focus on a variety of requirements, for example, greater functionality, improved quality, and uniqueness of the product, greater time-, and cost-efficiency of the manufacturing processes, effectiveness of organization, including logistics, and scope of manufacturing –global or local–, labeling, and distribution, after-sales services, and ergonomics of equipment.

4.2.1.2 **Step 2: Requirements**

The second step is the most critical part of QFD. It requires obtaining and expressing what the customers and stakeholders truly want from the value creation of the company, rather than what the designers and coordinators, named hereafter analyzers, think they expect. The requirements demonstrate the basic demands of stakeholders from the value creation [VDI-00, p. 5 ff.].

The information about the requirements to analyze any value creation usually comes from a variety of data. Some scientists concentrate on a selected set of requirements to prove their value creation approach theoretically; others select a set of case-based requirements to acknowledge the variety. Reliable data collection is essential for any analysis of primary and secondary references. Primary data is gathered from field research methodologies such as telephone or face-to-face interviews, postal or online questionnaires, as well as meetings, and workshops. All primary data collection methodologies use a set of questions. Stakeholders, for example, from the third stakeholder group, as presented in the previous subsection, are asked to answer these questions or discuss different perspectives. If the number of stakeholders is very large, the analyzers build a focus group by a few representatives out of this big group to discuss and debate the requirements concerned. Secondary data is gathered mainly from scientific literature, statistics, and reports of public and voluntary institutions, company reports and press releases, scientific, and commercial journals, and news.

Requirements are grouped into categories based on collected primary and secondary data by affinity diagrams. The interactions among categories and requirements are disregarded in the following calculations. Each requirement is assigned to the kth category c_k, which is most relevant for the fulfillment of this definitive requirement, where $k \in [1, \dots, u]$. In organizing the requirements, Equation (1) presents a sample for three categories based on their impacts on the (1) economy, (2) environment or (3) society:

$$c_k = \begin{cases} 1, & if\ the\ impact\ is\ primarily\ economic \\ 2, & if\ the\ impact\ is\ primarily\ environmental \\ 3, & if\ the\ impact\ is\ primarily\ social \end{cases} \quad (1)$$

Each category is expanded into individual requirements to obtain a more definitive list. r_i is the ith requirement, where $i \in [1, \dots, n]$. $c_k(r_i)$ ensures that the ith requirement is assigned to the kth category. n represents the total number of requirements, u the total number of categories.

Analyzers gather the requirements, including the rating of their importance by primary and secondary data [VDI-00, p. 6]. Stakeholders attach more importance to certain requirements than others. $p(r_i)$ represents the importance of the ith requirement for the stakeholders, which is the preference p of stakeholders for the ith requirement. To justify, if the fulfillment of the ith requirement has a high, medium, or low impact on value creation, and determine its importance, two hypothetical questions can be formulated, for example: a functional question, where the requirement has a positive impact on value creation; and a dysfunctional question, where the requirement has a negative impact. To reduce the possibility of potential inaccuracy in judgments, which is called Halo effect, and symmetric answers, the functional and dysfunctional questions are disposed in random order in a questionnaire. A third question, about the satisfaction with the current impact of the requirement, is also formulated to rate the importance. Table 4-1 presents an example of the three questions for the requirement "time efficiency" from the industrial engineering research conducted for this work.

Table 4-1: Sample questions to stakeholders about the requirement "time efficiency"

Question the impact of the requirement on the value creation		***Impact on value creation*** high	medium	low	not applicable
Functional question	Is the product delivered on time?	☒	☐	☐	☐
Dysfunctional question	Is the product not delivered on time?	☒	☐	☐	☐
Rate the importance of the requirement		***Impact on value creation*** high	medium	low	not applicable
Current satisfaction	Is the punctuality of the delivery correct?	☒	☐	☐	☐

The level of impacts specifies the level of importance. If delivery on time has a high impact on the requirement that the created value is highly time-efficient, then the preference is rated with a high importance. The respective value of the importance $p(r_i)$ is rated with a three-level scale, as presented in Equation (2):

$$p(r_i) = \begin{cases} 1, & \text{if the importance is low} \\ 3, & \text{if the importance is medium} \\ 9, & \text{if the importance is high} \end{cases} \tag{2}$$

Importance levels $p(r_i)$ of a set of requirements r_i forms a column vector P, as presented in Equation (3):

$$P = \begin{pmatrix} p(r_i) \\ \vdots \\ p(r_n) \end{pmatrix} \tag{3}$$

Table 4-2 presents a sample consisting of four requirements in two categories and three levels of importance. The left three columns –category, requirement and importance– of the Table 4-2 make up the vertical axis of the matrix for the house of quality, as presented in Steps 1 and 2 in Figure 4-2.

Table 4-2: Sample for the vertical axis of house of quality

Category	***Requirement***	***Importance***
$c_1(r_i)$	r_1	$p(r_1) = 1$
	r_2	$p(r_2) = 9$
$c_2(r_i)$	r_3	$p(r_3) = 3$
	r_4	$p(r_4) = 3$

Importance of the requirement for the stakeholders
1: Low
3: Medium
9: High

In reality, a set of requirements is tied together by analyzers and focus group. Table 4-2 contains sample requirements, as concluded in Subsection 2.1.2, to focus the gap analysis for sustainable manufacturing on changeability, productivity, resource efficiency and stakeholder engagement.

4.2.1.3 **Step 3: Solutions**

The next step in developing the matrix is to list–across the top horizontal row of the matrix, as presented in Step 3 in Figure 4-2–the current solutions of value creation through which requirements are fulfilled. The requirements tell the analyzers what to achieve, the solutions tell analyzers how it is currently achieved. Each solution is related to requirements, and must be selectively deployed to manifest itself in a product, service or combination of the two resulting in stakeholder satisfaction.

The current solutions demonstrate the characteristics of the AS-IS or existing state. Systematic, creative, and exhaustive analysis of each solution, based on the requirements, inspire the analyzers to create further expected solutions for the TO-BE or future state. The first and second step are usually conducted by the analyzers guiding other stakeholders to determine existing and expected solutions, which state the gap between TO-BE and AS-IS states. Usually, there is an abundance of potential solutions. In addition to the focus group and analyzers, more and more, customers and other stakeholders are asked to brainstorm the requirements for the value creation in order to generate further established or novel solutions that affect at least one of the requirements. How to achieve potential solutions, which are proposed for the future, can be explored in further research in greater detail.

The solutions are grouped into categories similar to grouping requirements. o_j is the jth solution, where $j \in [1, \dots, m]$. m represents the total number of solutions. $c_h(o_j)$ represents the category of the jth solution, where $h \in [1, \dots, v]$. Table 4-3 presents a sample consisting of two categories for two current and two future solutions.

Table 4-3: Sample for the horizontal axis

House of quality			***Category***			
			$c_1(o_j) = AS\text{-}IS$		$c_2(o_j) = TO\text{-}BE$	
			Solution			
Category	***Requirement***	***Importance***	o_1	o_2	o_3	o_4
$c_1(r_i)$	r_1	$p(r_1) = 1$				
	r_2	$p(r_2) = 9$				
$c_2(r_i)$	r_3	$p(r_3) = 3$				
	r_4	$p(r_4) = 3$				

4.2.1.4 **Step 4: Fulfillment**

This step builds the foundation to select solutions requiring change. Analyzers also rate the expectations of stakeholders for the future solutions. After labeling vertical and horizontal axes of the matrix, fulfillment of requirements by solutions are specified, as presented in Step 4 in Figure 4-2). The goal is to highlight the relative significance of the solutions, which represent the areas of greatest interest and highest satisfaction needed by stakeholders. This allows analyzers to follow how a solution is viewed by the stakeholders in fulfilling a particular requirement. $s(r_i, o_j)$ scores the significance between the ith requirement and jth solution.

Since there are varying degrees of fulfillment, a three-level scale is used to identify the significance of a fulfillment, as presented in Equation (4):

$$s(r_i, o_j) = \begin{cases} 0 \text{ or blank}, & \text{if the requirement is not applicable} \\ \bigcirc \text{ or } 1, & \text{if the fulfillment is low} \\ \text{◑} \text{ or } 3, & \text{if the fulfillment is medium} \\ \bullet \text{ or } 9, & \text{if the fulfillment is high} \end{cases} \quad (4)$$

The value 1 determines the minimum fulfillment level $s_{min}(r_i, o_j)$, and 9 the maximum fulfillment level $s_{max}(r_i, o_j)$. The analyzers carefully examine every intersection between a requirement and a solution. The assignment of fulfillment levels to a set of requirements and solutions is based on primary and secondary data. Absence of a value between a set, which is $0\ or\ blank$, indicates that a requirement is not addressed by a solution completely or has no significance. The fulfillment levels represent the current impact of the requirement on the value creation as responses to the functional and dysfunctional questions. Completing the matrix indicates if the current solutions fulfill the requirements and where the gaps are.

The significance of the requirements' fulfillment $s(r_i, o_j)$ forms a column vector $S(o_j)$ for the jth solution, as presented in Equation (5):

$$S(o_j) = \begin{pmatrix} s(r_1, o_j) \\ \vdots \\ s(r_n, o_j) \end{pmatrix} \tag{5}$$

Table 4-4 demonstrates a sample for the fulfillment of the requirements in the matrix.

Table 4-4: Sample for the fulfillment

House of quality			Category			
			$c_1(o_j) = AS\text{-}IS$		$c_2(o_j) = TO\text{-}BE$	
			Solution			
Category	**Requirement**	**Importance**	o_1	o_2	o_3	o_4
$c_1(r_i)$	r_1	$p(r_1) = 1$	$s(r_1, o_1) = 9$	$s(r_2, o_2) = 1$	$s(r_1, o_3) = 3$	$s(r_1, o_4) = 9$
	r_2	$p(r_2) = 9$	$s(r_2, o_1) = 3$	$s(r_2, o_2) = 3$	$s(r_2, o_3) = 1$	$s(r_2, o_4) = 3$
$c_2(r_i)$	r_3	$p(r_3) = 3$	$s(r_3, o_1) = 1$	$s(r_3, o_2) = 9$	$s(r_3, o_3) = 1$	$s(r_3, o_4) = 9$
	r_4	$p(r_4) = 3$	-	$s(r_4, o_2) = 3$	$s(r_4, o_3) = 3$	$s(r_4, o_4) = 3$

Blank rows or columns call for closer scrutiny because a blank row implies potentially unsatisfied stakeholders and the need to develop further solutions for this particular requirement. A blank column implies that the corresponding solution does not directly relate to, or affect, any of the requirements. At this point, solutions may have to be modified or supplemented to assure that all requirements are adequately addressed.

4.2.1.5 **Step 5: Scores and Targets**

Once the fulfillment levels have been established, the next step is to determine the scores and targets for solutions. Both are based on the importance and fulfillment of the requirements by the solutions, as presented in Step 5 in Figure 4-2.

Each score to be added is built by the multiplied combination of the importance $p(r_i)$ of all requirements r_i and its fulfillment $s(r_i, o_j)$ by a solution o_j. A score $S(o_j)$ presents a summed up score for the jth solution, as presented by Equation (6):

$$S(o_j) = \sum_{i=1}^{n}[s(r_i, o_j) * p(r_i)] \\ = s(r_1, o_j) * p(r_1) + s(r_2, o_j) * p(r_2) + \cdots + s(r_n, o_j) * p(r_n) \tag{6}$$

Step 5 also involves the development of targets for solutions. While targets bear no relation to what currently can be achieved by a certain solution in reality, they reflect the ideal minimum and maximum intention of the stakeholders and focus group to meet the requirements adequately by this definitive solution. Values for targets are calculated by considering the following aspects: The minimum and maximum targets should be oriented at the sum of the importance levels $p(r_i)$ for a requirement set r_i. The sum $P(r_i)$ is calculated according to the vector P following Equation (3), as presented by Equation (7):

$$P(r_i) = \sum\nolimits_{i=1}^{n} p(r_i) \tag{7}$$

To determine the limits of the targets $t(o_j)$ for the jth solution, the range between the lowest and highest limit for this solution is calculated. The sum of the importance levels $P(r_i)$ is multiplied by the minimum $s_{min}(r_i, o_j)$ and maximum $s_{max}(r_i, o_j)$ significance levels for the jth solution to calculate the limits for the targets $t(o_j)$ by Equation (8):

$$s_{min}(r_i, o_j) * P(r_i) < t(o_j) < s_{max}(r_i, o_j) * P(r_i) \tag{8}$$

For the jth solution, the minimum target $t_{min}(o_j)$ is smaller than the minimum limit as calculated by Equation (8) with $s_{min}(r_i, o_j) * P(r_i)$, and the maximum target $t_{max}(o_j)$ is smaller than the maximum limit as calculated by Equation (8) with $s_{max}(r_i, o_j) * P(r_i)$. The comparison is presented in Equation (9):

$$s_{min}(r_i, o_j) * P(r_i) < t_{min}(o_j) < \cdots < t_{max}(o_j) < s_{max}(r_i, o_j) * P(r_i) \tag{9}$$

The minimum target $t_{min}(o_j)$ is usually selected as a whole number around the minimum limit. If around 50% of the available intersections are scored, the minimum and maximum limits can hardly be achieved, thus the calculated maximum limit can be halved or quartered, and rounded to a whole number to determine the maximum target $t_{max}(o_j)$. The maximum targets for future solutions $t_{max}^{TO-BE}(o_j)$ are usually higher than those for current solutions $t_{max}^{AS-IS}(o_j)$ because of the higher expectations of the stakeholders and focus group, as presented by Equation (10):

$$t_{min}(o_j) < t_{min}^{AS-IS}(o_j) < t_{min}^{TO-BE}(o_j) < \cdots < t_{max}^{AS-IS}(o_j) < t_{max}^{TO-BE}(o_j) < t_{max}(o_j) \tag{10}$$

Table 4-5 presents a sample for the score and targets.

Table 4-5: Sample for the score and targets

House of quality			*Category*			
			$c_1(o_j) = AS\text{-}IS$		$c_2(o_j) = TO\text{-}BE$	
			Solution			
Category	*Requirement*	*Importance*	o_1	o_2	o_3	o_4
$c_1(r_i)$	r_1	$p(r_1) = 1$	$s(r_1, o_1) = 9$	$s(r_2, o_2) = 1$	$s(r_1, o_3) = 3$	$s(r_1, o_4) = 9$
	r_2	$p(r_2) = 9$	$s(r_2, o_1) = 3$	$s(r_2, o_2) = 3$	$s(r_2, o_3) = 1$	$s(r_2, o_4) = 3$
$c_2(r_i)$	r_3	$p(r_3) = 3$	$s(r_3, o_1) = 1$	$s(r_3, o_2) = 9$	$s(r_3, o_3) = 1$	$s(r_3, o_4) = 9$
	r_4	$p(r_4) = 3$	-	$s(r_4, o_2) = 3$	$s(r_4, o_3) = 3$	$s(r_4, o_4) = 3$
		$S(o_j)$	$S(o_1) = 39$	$S(o_2) = 64$	$S(o_3) = 24$	$S(o_4) = 72$
		$t_{min}(o_j)$	$t_{min}(o_1) = 18$	$t_{min}(o_2) = 18$	$t_{min}(o_3) = 36$	$t_{min}(o_4) = 36$
		$t_{max}(o_j)$	$t_{max}^{AS-IS}(o_1) = 60$	$t_{max}^{AS-IS}(o_2) = 60$	$t_{max}^{TO-BE}(o_3) = 90$	$t_{max}^{TO-BE}(o_4) = 90$

For example, the requirement r_1 and the solution o_3 receive a score of 3 according to Equation (11):

$$S(o_3) = p(r_1) * s(r_1, o_3) = 1 * 3 = 3 \tag{11}$$

The relation, comparison, and scoring of the solutions, and determination of the minimum and maximum targets from the fourth and fifth step of the gap analysis flow sequentially, and are hereafter referred to together.

4.2.1.6 **Step 6: Gaps**

The analyzers study the complete house of quality to identify gaps by comparing scores and targets of each solution (see Step 6 in Figure 4-2). Gaps describe a mismatch between fulfillment of requirements by solutions and expectations of stakeholders. $g(o_j)$ describes the difference between the score $S(o_j)$ and the maximum target $t_{max}(o_j)$ for the jth solution, as presented in Equation (12):

$$g(o_j) = t_{max}(o_j) - S(o_j) \tag{12}$$

Positive values for the difference $g(o_j)$ indicate gaps of the jth solution. Any gap can be specified in detail through the comparison of the real and expected fulfillment for a certain requirement.

4.2.1.7 **Step 7: Opportunities**

The gaps and targets, which are identified in the previous steps, guide how to identify and later explore opportunities in order to close the specified gaps, as presented in Step 7 in Figure 4-2.

This question can refer to multiple possible opportunities. At least one of those are highlighted in each iteration.

$f(o_j)$ describes the selection by a comparison of the score $S(o_j)$ for the jth solution with its minimum and maximum targets, as presented by Equation (13):

$$f(o_j) = \begin{cases} maintain\ o_j, & if \quad S(o_j) \geq t_{max}(o_j) \\ substitute\ o_j, & if \quad S(o_j) \leq t_{min}(o_j) \\ adapt\ o_j, & if \quad t_{min}(o_j) < S(o_j) < t_{max}(o_j) \end{cases} \tag{13}$$

Table 4-6 summarizes possible cases for a solution to map its gaps to a possible change, whether the maintenance, adaptation, or substitution should be the following action to perform for this solution.

Table 4-6: Actions by changing solutions

Solution is to / ***condition***:		***maintain, if …***	***substitute, if …***	***adapt, if …***
Gap	Mathematical function	$g(o_j) < 0$	$g(o_j) \gg 0$	$g(o_j) > 0$
	Match between fulfillment and expectations	high	low	medium
	Identified gaps	minor to none	major	major
Opportunity	Mathematical function	$S(o_j) \geq t_{max}(o_j)$	$S(o_j) \leq t_{min}(o_j)$	$t_{min}(o_j) < S(o_j) < t_{max}(o_j)$
	Match between gaps and opportunities	low	low	high
	Identified opportunities	minor to none	minor to none	major

The output of the gap analysis is recommendations how to change the solutions, as illustrated in Figure 4-3, which is an excerpt from Figure 4-1. Based on the identified gaps between the fulfillment of requirements and opportunities for the expectations, solutions are usually classified into three groups:

- The value creation remains as it is, if a solution satisfies the requirements and results in a score $S(o_j)$ higher than the maximum target $t_{max}(o_j)$. Only minor gaps are identified, and there is no need for any urgent changes. This solution matches with current expectations of stakeholders, and is to **maintain** in the subsequent analysis cycles. The solution is to examine in subsequent cycles if it can provide necessary characteristics to build a foundation for future changes. Each analysis cycle follows the same procedure with seven steps to put together a house of quality in order analyze the gap. For example, electric or hybrid vehicles have provided a sustainable solution for the road and rail transportation for over a decade. When research and development result in new solutions for batteries and storage, the vehicles must be analyzed to identify new opportunities for improving the next generation of electric and hybrid vehicles.

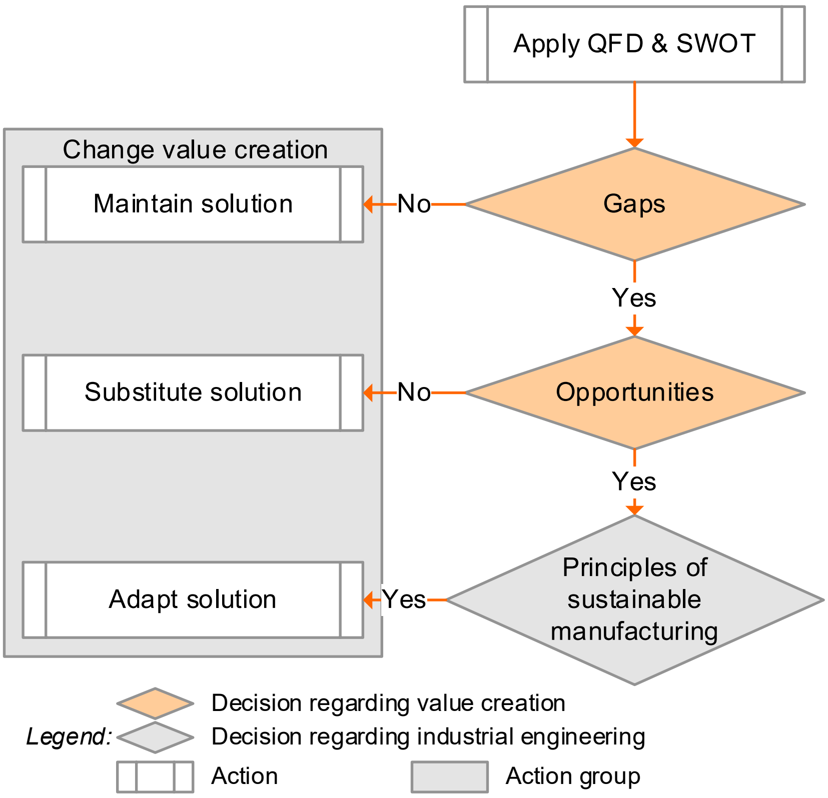


Figure 4-3: Changing solutions in value creation

- An existing or potential solution, which is analyzed in a certain cycle, is to **substitute** with a new solution if there is a mismatch between the gaps and opportunities, i.e., there is no adequate opportunity, which is identified within this cycle, to narrow the gaps. The existing or potential solution cannot be treated without further investigation. The solution does not satisfy the requirements and results in a score $S(o_j)$ lower than the minimum target $t_{min}(o_j)$. There is a big gap, which usually can only be closed through a range of changes after several iterative cycles and cannot be explored through the opportunities specified. The new solution should be analyzed in the subsequent cycles after creation. For example, energy generation by using renewable resource mitigates the emissions of greenhouse gasses in a production plant. The selection of the renewables to substitute the non-renewables depends on their availability in a certain region and must be investigated in detail.
- A solution is to be **adapted** partly or completely, if the opportunities provide potential solutions to narrow or close the gaps. The score $S(o_j)$ between the minimum and maximum targets implies that the change of this solution by exploring some opportunities increases the fulfillment of at least one requirement. The procedure to change the solution adequately for creating a sustainable solution is conducted with the next procedure following Figure 4-1. For example, American and European safety standards for

production plants can be adapted in an emerging country according to the governmental regulations to reduce safety incidents in manufacturing. By adapting the standards, the regional conditions and stakeholder requirements must be integrated into the analysis.

The gaps and opportunities of a product or a service are highlighted at end of the house of quality. As applied for the sample in Table 4-7, the outcomes are: o_3 needs substitution because it underlays the minimum target. There is room for improvement by o_1 and o_4. o_2 can be kept as it performs currently and maintained in the further analysis cycles.

Table 4-7: Sample for the score and targets

House of quality			***Category***			
			$c_1(o_j) = AS\text{-}IS$		$c_2(o_j) = TO\text{-}BE$	
			Solution			
Category	***Requirement***	***Importance***	o_1	o_2	o_3	o_4
$c_1(r_i)$	r_1	$p(r_1) = 1$	$s(r_1, o_1) = 9$	$s(r_2, o_2) = 1$	$s(r_1, o_3) = 3$	$s(r_1, o_4) = 9$
	r_2	$p(r_2) = 9$	$s(r_2, o_1) = 3$	$s(r_2, o_2) = 3$	$s(r_2, o_3) = 1$	$s(r_2, o_4) = 3$
$c_2(r_i)$	r_3	$p(r_3) = 3$	$s(r_3, o_1) = 1$	$s(r_3, o_2) = 9$	$s(r_3, o_3) = 1$	$s(r_3, o_4) = 9$
	r_4	$p(r_4) = 3$	-	$s(r_4, o_2) = 3$	$s(r_4, o_3) = 3$	$s(r_4, o_4) = 3$
		$S(o_j)$	$S(o_1) = 39$	$S(o_2) = 64$	$S(o_3) = 24$	$S(o_4) = 72$
		$t_{min}(o_j)$	$t_{min}(o_1) = 18$	$t_{min}(o_2) = 18$	$t_{min}(o_3) = 36$	$t_{min}(o_4) = 36$
		$t_{max}(o_j)$	$t_{max}^{AS-IS}(o_1) = 60$	$t_{max}^{AS-IS}(o_2) = 60$	$t_{max}^{TO-BE}(o_3) = 90$	$t_{max}^{TO-BE}(o_4) = 90$
		$g(o_j)$	$g(o_1) > 0$	$g(o_2) < 0$	$g(o_3) \gg 0$	$g(o_4) > 0$
		Gaps	major	minor	major	major
	Opportunities		major	none	minor	major
	to improve		$s(r_2, o_1)$ $s(r_3, o_1)$	-	$s(r_i, o_3)$	$s(r_2, o_4)$ $s(r_4, o_4)$
	to		adapt o_1	maintain o_2	substitute o_3	adapt o_4

4.2.2 **Commitment to the Principles of Sustainable Manufacturing**

Industrial engineering is committed to improving value creation in manufacturing to ensure that new concepts are implemented and something better than what existed before is realized. In this research, the principles and requirements of sustainable manufacturing are presented in Subsection 2.1.2. Gap analysis and target determination are designed as a sample for sustainable value creation in manufacturing by industrial engineering. Exploration of an opportunity has the potential to narrow or close a gap by creating sustainable value. Engineers aim to improve the fulfillment of an individual or multiple requirements by synthesizing a new solution out of opportunities, thus potentially changing the balance among economic, environmental and social impacts. There is a wide range of methodologies in technology and management to implement innovative ideas in manufacturing. Once a house of quality is completed in a certain cycle, the focus of the analysis moves on to the next question if the outcomes of the analysis, as solutions to be adapted, align with principles of sustainable manufacturing, as presented by Figure 4-4, which is an excerpt from Figure 4-1.

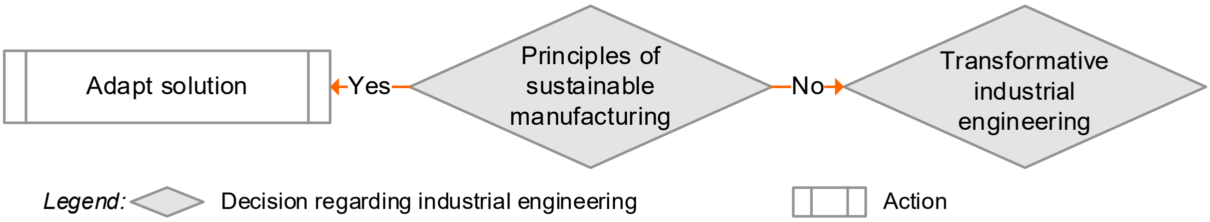


Figure 4-4: Commitment to the principles of sustainable manufacturing

Instead of looking at the implementation of individual elements, engineers must be aware of multiple interactions among value creation factors, life-cycle stages and the 6R approach by applying these principles to create sustainable value in manufacturing. Figure 2-5 illustrates the conceptual framework for mapping and integrating product and equipment life-cycles and the 6R approach with all five value creation factors.

The question that naturally follows is whether current industrial engineering provides the necessary capabilities to maintain, substitute, or adapt current solutions for value creation in order to balance impacts. Section 4.4 presents the next procedure which describes how to synthesize opportunities in closed-loops creating sustainable solutions, for example, by adapting existing solutions through the application of methodologies in technology and management. In addition to reducing resource consumption in all life-cycle stages, education and training of the workforce, especially engineers, play a central role to spread the application of end-of-life actions to post-use stages of products and equipment. Performing these actions and repetitive assessments of their impacts requires the development of new technological processes, organizational procedures and services for shaping sustainable solutions in different industrial sectors [Bil-16a, p. 456].

If industrial engineers still lack commitment to balance economic, environmental and social impacts, capabilities of industrial engineers must be enhanced to increase the awareness of and commitment to sustainable manufacturing. To foster a better understanding, Section 4.3 describes the procedure for development of new capabilities for industrial engineering in detail.

4.3 Transformative Industrial Engineering

The challenge of keeping a profession such as industrial engineering successful, as it enters its second century of practice, rests on the profession's ability to transform itself from what made it successful in the past to what it must be, to meet the new expectations of different stakeholders. Sustainable manufacturing is a challenge for applied engineering research in general, and for industrial engineering research in particular. Industrial engineering frequently does not fit comfortably within the scope of sustainable manufacturing, nor does it fare well wherever its education and practice are dominated by experts highly invested in current manufacturing paradigms. Consequently, industrial engineering education mentions, however, it does not focus on sustainable manufacturing. In order to shift the focus to sustainability, the ways industrial engineers do research, the ways they shape research projects, and the ways research interacts with education and practice, all call for radical transformations.

A new framework is developed for identifying and providing innovative capabilities, which lead to transformative industrial engineering to gain a better understanding of sustainable manufacturing. The term “transformative” refers to the urgent need to highlight the role of industrial engineers as enabler of sustainable manufacturing in this research. To identify and conduct research for new solutions in manufacturing, the USA National Science Foundation defines transformative research, as presented in Subsection 2.2.3 [NSF-15]. As transformative research often results from a new methodology, and is an interdisciplinary approach, the author adopts the following definition for characterizing transformative industrial engineering: **Transformative industrial engineering** challenges industrial engineering wisdom in research, education and practice, and raises awareness for sustainable manufacturing so that value creation can be made and improved through new capabilities towards sustainable solutions in manufacturing. Transformative industrial engineering enhances capabilities to transform the value creation factors, modules and production systems to a greater degree than the current industrial engineering practice in manufacturing to serve and enable sustainable development of the economy, environment and society.

If industrial engineers already have such transformative capabilities, and are still unable to apply principles of sustainable manufacturing in practice, they should be educated and trained to enhance their capabilities following the architecture for sustainable manufacturing shown in Figure 4-5 from bottom to top, which is an excerpt from Figure 4-1.

Transformative industrial engineering can emerge through two actions. The next question follows whether there are some transformative attributes to enhance industrial engineering capabilities through education and training. (1) Subsection 4.3.1 presents the development of transformative attributes. (2) These are applied in Subsection 4.3.2 to transform higher and professional education programs to educate and train industrial engineers.

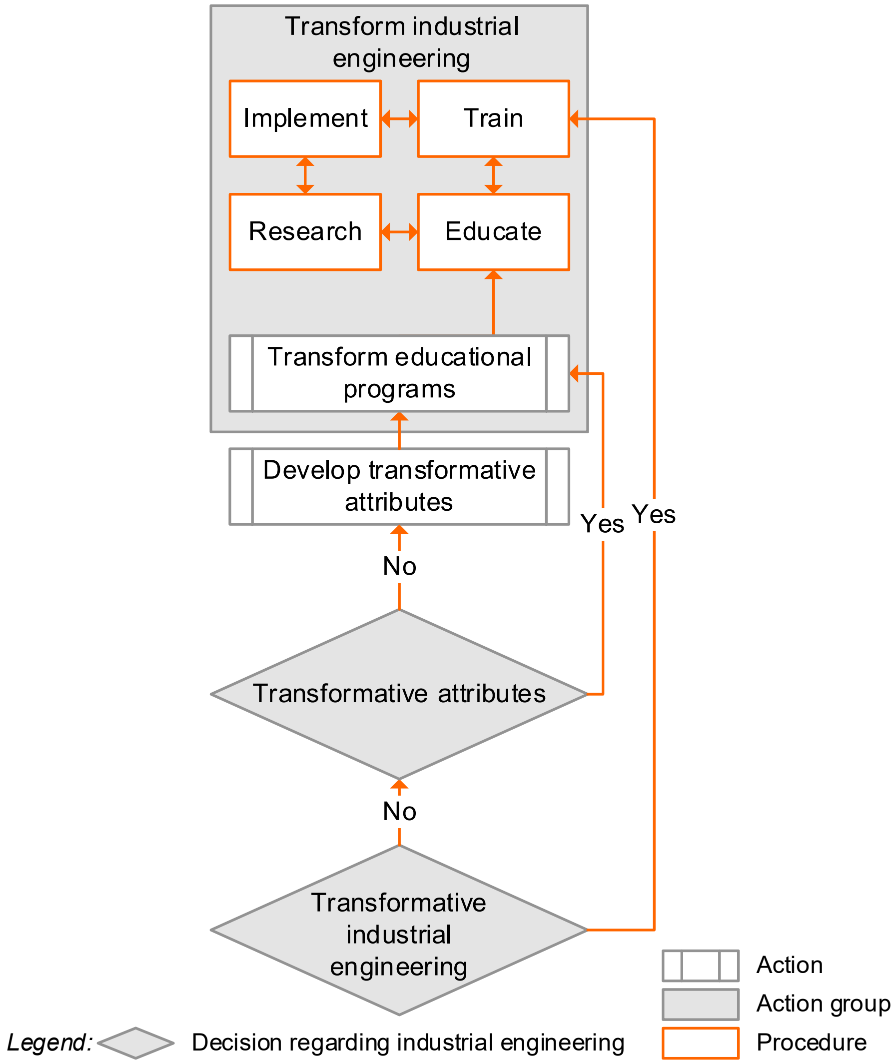


Figure 4-5: Framework for transformative industrial engineering

4.3.1 **Development of Transformative Attributes**

Industrial engineering undergraduate and graduate programs at different European and North American universities, especially in Germany and the USA, as well as emerging countries such as Korea, Turkey, and Vietnam, are analyzed in Section 2.2.2, with regard to identifying best practices in industrial engineering education, which combines engineering and management education. Existing attributes of industrial engineering practice, research, education and training are sound to create value in manufacturing, as presented in Section 2.2.3. There is no need to adjust or to modify the application of the interdisciplinary, digitalization and problem-solving attributes.

These attributes reasonably well contributed to the success of industrial engineering in the last century. The rapid rise of IT has simplified access to information within projects and allowed for focus on interactions among stakeholders, disciplines, and regions, when industrial engineers search for innovative and creative solutions. Although the clear intent of industrial engineering is to challenge and change current value creation in manufacturing by implementing various methodologies, existing attributes can only provide restricted specifications for sustainable manufacturing. Creating sustainable value in manufacturing requires specified efforts for transformative industrial engineering to discover opportunities for balancing impacts. Discussions in round tables and workshops with all three stakeholder groups, as well as interviews with individual groups of scientists, instructors and lecturers, questionnaires with industry experts, alumni, and students, are used to determine new attributes for transformative industrial engineering. In addition to the three conventional attributes in industrial engineering, three transformative attributes are proposed to ease the transition from conventional to sustainable manufacturing [Bil-16a, p. 457]:

- **Focus on projects** that incorporate problem-solving, interdisciplinary teamwork, and project management, while emphasizing that there is no individual optimal solution to any problem to increase effectiveness [Dan-14, p. 365].
- **Focus on sustainable solutions**, which balance impacts, is likely to improve the current products and services by designing, operating and assessing value creation in manufacturing.
- **Focus on glocalization**, which is a portmanteau, a made-up word coined from a combination of the words “globalization” and “localization”, which enables global environmental limitations determining the preferences for local actions and decisions [Hes-11, p. 6].

Applying transformative attributes in industrial engineering practice requires a change of thinking habits and understanding of challenges in production and consumption. The attributes of transformative industrial engineering build the necessary characteristics for developing a holistic integration of interests of all stakeholders, regions, and disciplines. A transparent framework for instituting transformative industrial engineering and appropriate methodologies for evaluating the impacts of value creation should be developed to empower and encourage maximum participation of industrial engineers.

The industrial engineering capabilities qualitatively describe which knowledge and skills the students and graduates need to apply, evaluate, implement, and adapt the existing methodologies. For example, while many LCA methodologies are generic, a closer alignment of the economic, environmental and social impacts of value creation is needed to assess the impacts of case studies. Thus, updated LCA methodologies are needed. The new methodology can be implemented within regional case studies, constrained by different limitations, using a holistic assessment approach. This is an essential research area of advanced industrial engineering with increasing complexity and conflicting requirements. This area should be researched in detail before accounting for education and practice. In general, education and practice focus on adapting existing methodologies to create changes and innovation by utilizing the dynamics of competition and cooperation in global markets rather than on developing fundamentally new methodologies.

4.3.2 **Transformation of Educational Programs**

"Transformation" is a uniquely defined term, which calls for a need with impactful changes without altering the fundamentals. Educational transformation in the context of this research indicates an intention to realize a sustainable value creation, which is likely to result from this new era of thinking about a paradigm shift.

Transforming thinking habits and enhancing engineering capabilities close to application in industry requires a significant change of programs in higher education. In particular, industrial engineering needs to be changed to appreciate the importance of sustainable development across disciplinary and national boundaries, as well as sustainable manufacturing, and also the importance of more responsible behavior, and sustainable consumption. Embedding sustainable development into the higher and professional educational programs in industrial engineering includes (1) conducting workshops with lecturers and instructors to raise awareness; (2) reviewing and revising the curriculum to identify those courses that already include, or could readily incorporate, principles of sustainable manufacturing; (3) identifying needs of lecturers and instructors for teaching material and industrial cooperation about sustainable manufacturing; (4) identifying synergies for sustainable manufacturing with other departments of the institution and (5) introducing sustainable manufacturing courses for all engineering students.

Workshops address lecturers, instructors and experts from engineering disciplines who are experienced in the teaching and training engineering students, as well as practicing and managing engineering tasks. The goal of workshops is to increase the awareness and motivation of the participants to take more responsibility and establish sufficient authority to define, revise, implement, and achieve changes in educational programs. Although the clear intent of transformative industrial engineering practice and research is to support more sustainable manufacturing that challenges current manufacturing paradigms, existing industrial engineering education and training programs can only provide restricted capabilities for sustainable manufacturing, and apply only some of the six attributes to an unsatisfactory extent in higher and professional education and training. This is the fundamental bottleneck that industrial engineering education and training programs face in enhancing their support to provide capabilities, which are characterized by transformative attributes. The limitations of the current educational programs are summarized in Section 2.2.3 such as the focus on tools for problem-solving rather than on methodologies for balancing impacts by synthesizing multiple opportunities.

Shifting the focus of industrial engineers to sustainable value creation in manufacturing supports transformative industrial engineering. This requires the transformation of educational programs to provide future industrial engineers with the necessary capabilities for sustainable manufacturing in terms of technical-methodological knowledge, skills and competence. The review and revision of the best practice educational programs in industrial engineering result in the proposal of the framework for a transformed program in a curriculum combining categories of courses with the transformative attributes, as presented in Figure 4-6.

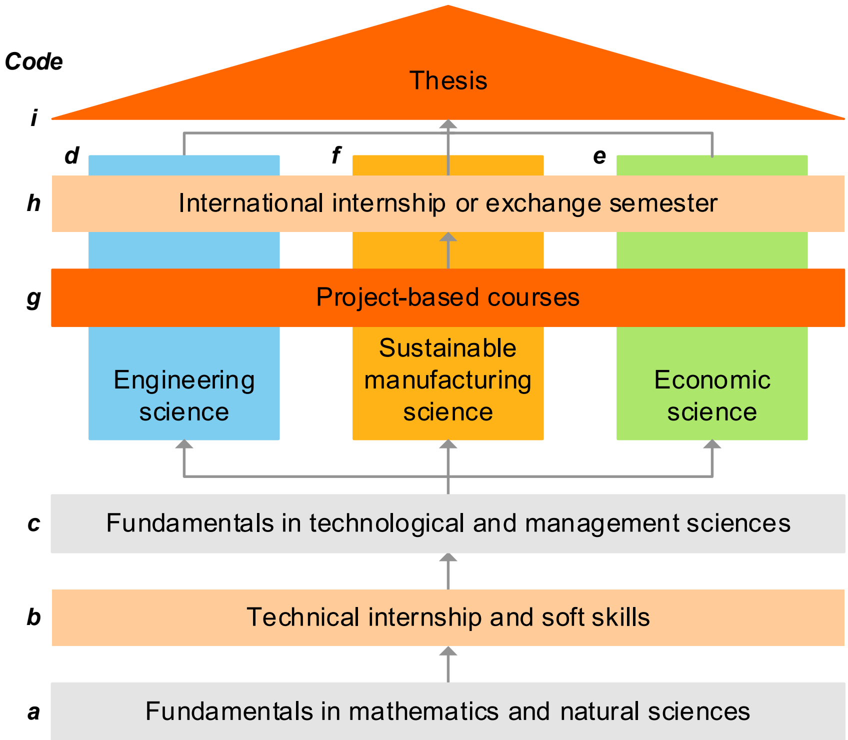


Figure 4-6: Framework for transformation of industrial engineering program

For example, the category of “manufacturing science” is revised to the category of “sustainable manufacturing science”. Project-based courses and an international internship or exchange semester are added to the program.

Six existing and transformative attributes present the requirements for future industrial engineering practice and research based on (1) interdisciplinary and (2) digitalized (3) problem-solving in (4) projects with focus on (5) sustainability and (6) glocalization, as described in Section 4.3.1. Figure 4-6 proposes categories of courses that are aligned to all attributes shown in Table 4-8.

(a) The courses in the category “**fundamentals in mathematics and natural sciences**” provide capabilities to apply interdisciplinary knowledge of mathematics through multivariate calculus, differential equations, discrete mathematics, calculus-based physics, an earth science, and an introduction in computer science to digitalize data.

Table 4-8: Alignment of course categories to attributes

Category of courses / Attributes based on	Fundamentals in mathematics and natural sciences	Fundamentals in technological and management sciences	Engineering science	Economic science	Sustainable manufacturing science	Technical internship and soft skills	International internship or exchange	Project-based courses	Thesis
Code	a	c	d	e	f	b	h	g	i
Interdisciplinary	●	●	○	○	◐	◐	◐	●	◐
Digitalization	◐	◐	●	◐	◐	○	◐	●	◐
Problem-solving	○	○	●	◐	◐	◐	●	●	●
Projects	○	○	○	○	◐	◐	●	●	○
Sustainability	○	○	○	○	●	○	◐	◐	●
Glocalization	○	○	○	○	●	○	●	◐	◐
Share in %	10%	10%	20%	10%	10%	10%	10%	10%	10%

Legend: ○ not directly applied; ◐ partly applied; ● completely applied

(b) The transformed program differentiates between two focuses for internships: technical and international. The **technical internship** serves to train practical knowledge and soft skills, based on problem-solving, for example, after the first year of an undergraduate program, to gain experience in methodologies such as metal forming and quality control and monitoring based on mathematics and natural sciences.

(c) The courses in the category "**fundamentals in technological and management sciences**", are analog to the first category. They advance industrial engineers to apply knowledge of sciences such as probability, statistics and stochastics, technical drawing, electronics, statics and solid mechanics, introduction in databases, business administration, accounting, and macroeconomics.

(d) The courses in the category "**engineering science**" prepare industrial engineers to apply skills of computer-aided design, thermodynamics, software, production technologies, machine tools, automation, and assembly to cope with technological challenges by analyzing, modeling, and designing physical objects consisting of solid and fluid components under given conditions.

(e) The courses in the category "**economic science**" prepare industrial engineers to understand the engineering relations between the management tasks of planning, organization, leadership, control, and the human factor in practice and research.

Advanced courses should also prepare industrial engineers to integrate appropriate management into a series of different regions and industrial sectors.

(f) The courses in the category “**sustainable manufacturing science**” provide skills in (1) materials extraction and manufacturing to be able to design processes that result in products or services to meet requirements; (2) process, assembly and product engineering to be able to design sustainable products, equipment, and services; (3) marketing to be able to create competitive advantage through manufacturing planning, strategy, quality, and control; (4) design of production systems to be able to analyze, synthesize, and control manufacturing using statistical methods; and (5) experimental or practical experience to be able to measure economic, environmental and social impacts.

(g) **Project-based courses** facilitate knowledge and skills in the areas of motivation, innovation, communication, teamwork, and writing business plans, in ways that encourage entrepreneurial behavior. Projects consist of the following elements: iterative decision-making and actions, pursuing solutions to real and nontrivial challenges by asking and refining questions, debating ideas, making predictions, planning investigations, collecting and analyzing data, drawing conclusions, communicating findings to others, and completing reports, models, computer programs, and video productions [Oku-06, p. 195 ff.].

(h) The **international internship** or an exchange semester, for example, after the third year of an undergraduate program, enhances industrial engineering capabilities to demonstrate innovations with a local adaptation to the specific requirements within the frame of an emerging country through implementation of methodologies in technology and management. Interns or exchange participants are exposed to challenges, as well as design, management, and planning of value creation in manufacturing while considering its impacts.

(i) The **thesis** is dedicated to develop and document sustainable solutions by applying innovation and entrepreneurial spirit to numerous interdisciplinary or regional issues. Subjects of a thesis can be as numerous as sustainability challenges in manufacturing.

Transformation of educational programs in higher and professional education contributes to the enhancement of capabilities for transformative industrial engineering. Such industrial engineers interrogate the current value creation in manufacturing and investigate the opportunities to adapt current solutions in order to promote and achieve sustainable value creation. When governmental stakeholders recognize the importance of an awareness of the sustainable development, they might introduce the transformative attributes in the accreditation criteria.

4.4 Closed-loop Synthesis

Transformative industrial engineering is committed to sustainable manufacturing by narrowing and closing gaps of existing solutions by adapting existing and creating new solutions. Engineers who practice industrial engineering contribute to accomplish a synthesis of sustainable solutions to create sustainable value in manufacturing, for example, using their analytical, computational, experimental, and methodological capabilities in technology and management. Synthesis refers to a combination of two or more parts, for example, an existing solution and an opportunity, that together create a new solution. Transformative industrial engineering applies enhanced capabilities for synthesizing new solutions. Industrial engineering applies transformative attributes following principles of sustainable manufacturing in order to:

- identify and develop know-how to implement any changes for performing an action or making a decision in practice, by taking account of the need to counteract negative impacts,
- analyze and interpret the collected data in balancing the focus on the economic, environmental and social impacts by simultaneously considering risks and uncertainties,
- design, develop, implement, and improve production systems that include people, materials, information, equipment and energy,
- use creativity and innovation to provide products, services and a combination of the two, which maintain and enhance the quality of the environment and community, and advantage competitiveness,
- encourage stakeholder empowerment, understand project management and the roles and responsibilities of governmental and non-governmental stakeholders pertaining to environmental policy and regulations, and
- narrow the gap between developed and emerging countries in order to reach an equal international distribution of social benefits and environmental burden.

Figure 4-7 presents how value creation can be changed based on the analysis results and transformative industrial engineering. Starting at the bottom of Figure 4-7, methodologies in technology and management are applied to change –especially substitute or adapt– a definite solution for exploiting multiple opportunities in order to synthesize a new solution.

Value, which is created in manufacturing, presents an end, if a solution is sustainable. The decision, if it is sustainable, is the input of value creation. A back-and-forth check of value creation from this input closes the loop. The analysis of this solution in the next cycle following the architecture for sustainable manufacturing within the frame of the Sections 4.2 and 4.3 should result in minor gaps and be selected to maintain. This net result closes the loop with positive feedback to the decision that the solution is sustainable, which creates also an output with a sustainable value in manufacturing.

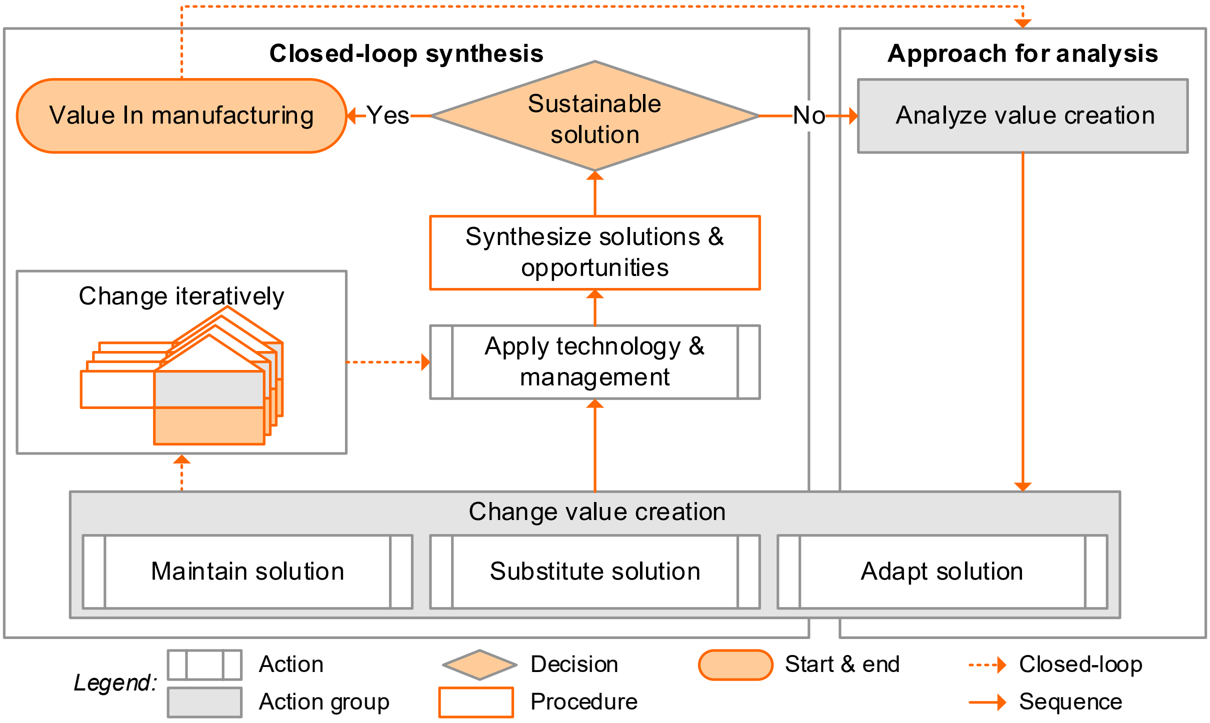


Figure 4-7: Closed-loop synthesis

In any other cases, the new solution is considered as a potential solution in the next cycle of analysis and should result in major gaps with minor or major opportunities. At least one of the identified major opportunities can be explored in the next cycle of analysis to change the potential solution by substitution or adaptation. The iterative cycles of analysis assure sequentially that different combinations of solutions and opportunities are explored to synthesize potential solutions. Scores of potential solutions are compared to select the most effective one for implementation.

The next chapter implements transformed educational programs by verifying the transformative attributes in two case studies to confirm the hypothesis that transformative industrial engineering contributes to sustainable value creation in other three case studies.

5 Implementation of the Architecture

The architecture, which is presented in Section 4.1, is implemented in this chapter to verify transformative attributes for industrial engineering and value creation in manufacturing. Starting at the middle box in Figure 5-1, the value creation in manufacturing is analyzed regarding (1) education and training, and (2) practice and research. The analysis approach, which is presented in Section 4.2, plays a central role in implementation and verification. Stakeholders, requirements and conditions are identified for each case study. The commitment of stakeholders to principles of sustainable manufacturing advances creation of sustainable solutions. By applying the transformative attributes, the goal of all case studies is to confirm through review and testing the hypothesis that a novel industrial engineering education and training can contribute to the implementation and research of sustainable manufacturing.

- The framework for transformative industrial engineering is implemented in two case studies in Section 5.1 to present how education and training programs are analyzed and transformed following Section 4.3. The transformative attributes are verified by new engineering programs for undergraduate and graduate education, which are established between a developed and an emerging country. A comparison is conducted to evaluate the extent to which each attribute is applied by the transformed programs.
- Following transformative industrial engineering and starting at the middle box in Figure 5-1, practice and research of value creation in manufacturing are analyzed. The closed-loop synthesis is implemented in three case studies in Section 5.2 to present how the gap of value creation narrows down by adapting and substituting existing solutions in iterative cycles. The case studies demonstrate how to apply and adapt methodologies to explore opportunities in regions with different limitations to improve value creation towards environmental protection and stakeholder empowerment, while providing economic benefits. The satisfaction of requirements is evaluated for the case studies according to their impact on value creation following Section 4.4.

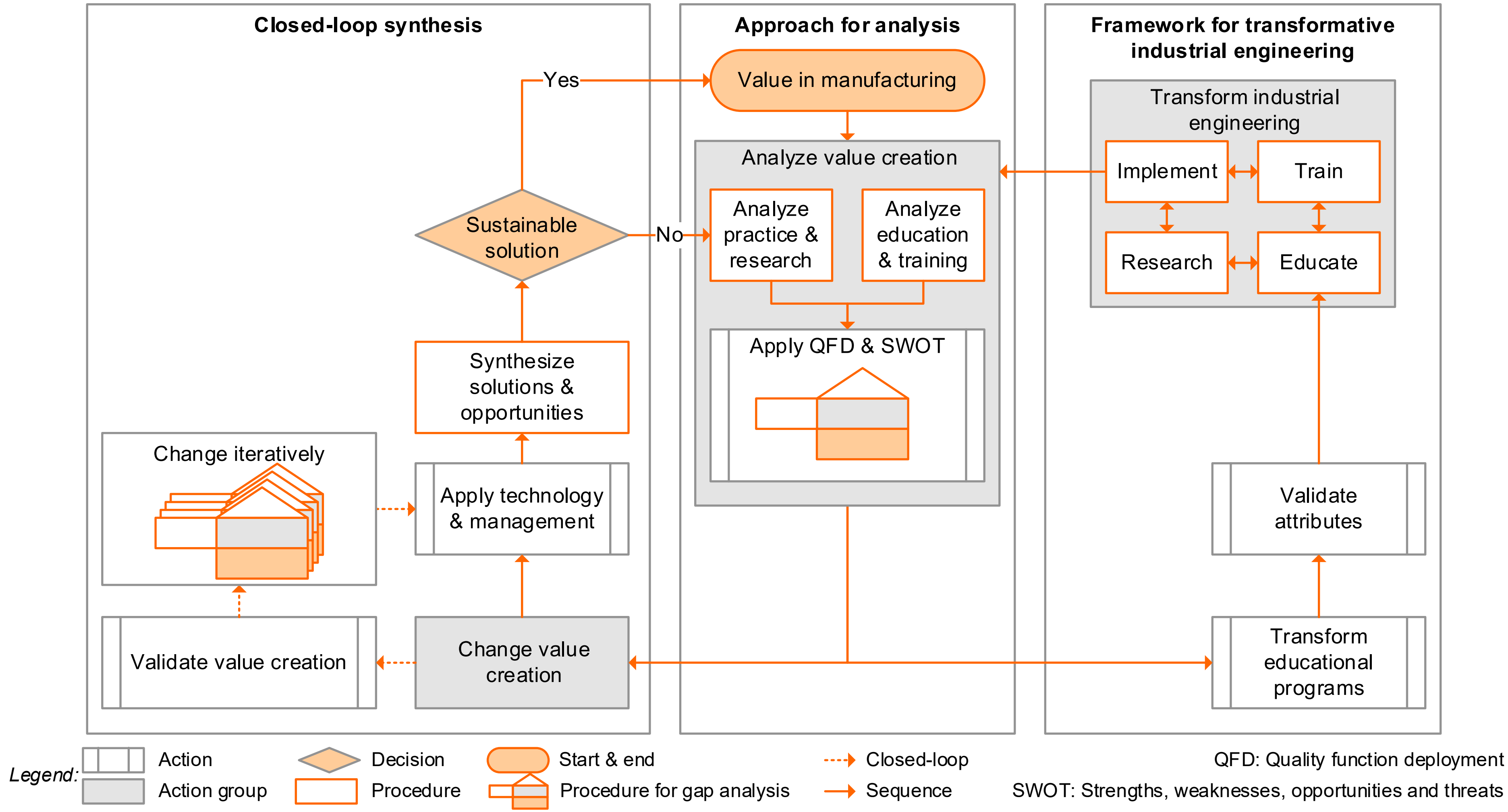


Figure 5-1: Implementation of the architecture for sustainable manufacturing

5.1 Verification of Transformed Engineering Programs

Many engineers, managers, and scientists have some form of sustainability responsibility in their professional lives. Demand for sustainability professionals, who can fully understand the role of sustainable development in any institution, grows in a range of production sectors. Within the framework of transformative industrial engineering, as described in Section 4.3, transformative engineering education can enhance necessary capabilities for sustainable value creation in manufacturing, thus enabling creativity, innovation and entrepreneurship as drivers for increasing global well-being. Transformative industrial engineering requires new educational programs and lifelong learning. Educational and training programs should provide the necessary capabilities to students, graduates and professionals to address challenges of sustainability in practice and research. The new programs should support industrial engineers in interdisciplinary learning, case-based problem solving, global exchange of knowledge, formation of social and scientific networks.

Educational programs can be transformed through the integration of all attributes into existing best practice programs following Figure 5-2. The application of transformative attributes in education challenges conventional engineering wisdom by changing value creation following the principles of sustainable manufacturing, as presented in Subsection 2.1.2. Many countries educate and train conventional engineers, however, they do not educate and train them in initiating changes of value creation towards sustainability. This section investigates if application of transformative attributes can change an engineering program to enhance the required capabilities for sustainable manufacturing. The proposed transformation is unique in having sufficient leverage to connect advanced methodologies in technology and management with unique approaches for the regional implementation of sustainable manufacturing in developed, emerging and developing countries.

The leverage obtained through industrial engineering education is presented in Section 5.1 for two sets of countries. The lack of suitable educational approaches in emerging countries can be bridged by adaptively applying transformative attributes and best practice programs from developed countries in emerging countries. A set of countries can be described based on their regional, sociopolitical and economic conditions. An educational transformation also depends on the active engagement of stakeholders in formulating and implementing requirements in education and training rather than only exchanging ideas and giving recommendations.

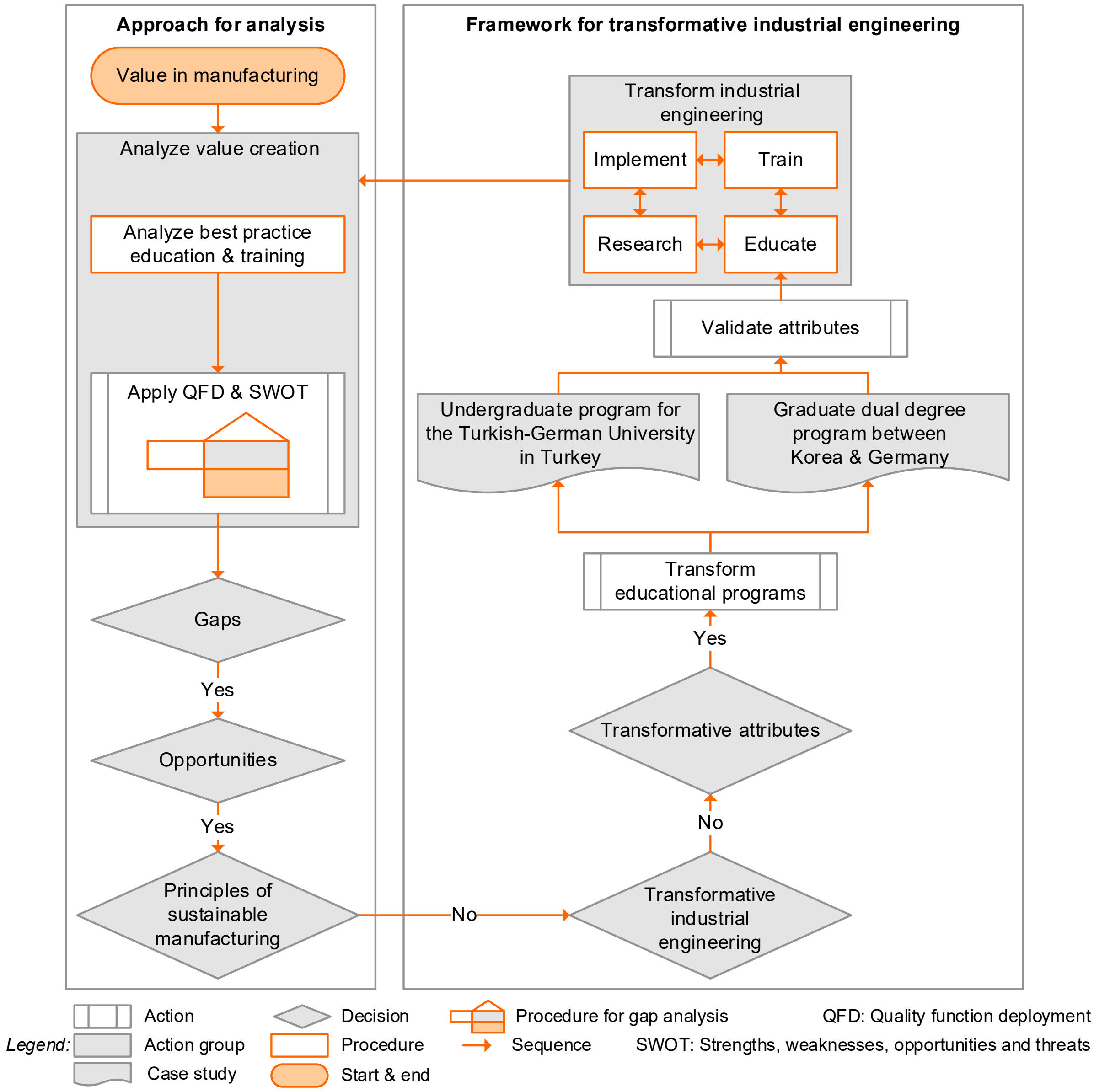


Figure 5-2: Verification of attributes through transformed engineering programs

Developed countries support partner countries with governmental funding to improve their higher education and research. Sociopolitical and economic conditions and requirements of both countries must be identified in detail in order to create a tailor-made model for a partner country. SWOT of best practice educational and training programs for the specific partner country, which are described in Subsection 2.2.2, must be analyzed according to the requirements following the procedure in Subsection 4.2.1. Stakeholders with a disciplinary responsibility in decision-making and operation from the developed country must be able to understand the legal system, the industrial structure, the regional economic situation and the social background of the partner country. The international stakeholders need to exchange ideas and be engaged in joint activities with the local stakeholders to break down the best practices into opportunities for a transformation of educational programs. To address the issues and challenges faced by the partner country, opportunities must be explored and combined to a new program. The new program has different attributes after the transformation compared to the best practice from the developed country. If the transformed program overlaps with the best practice in the developed country and with the requirements in the partner country without any major gaps, then it is called congruent with educational programs in both countries.

The following two case studies for implementing the architecture for sustainable manufacturing through transformation of educational programs focus on regional limitations of a partner country, while responding to the needs of the fourth industrial revolution, challenges and stakeholders in a developed country. An undergraduate program in industrial engineering is transformed for the Turkish-German University in Subsection 5.1.1. A graduate program in sustainable manufacturing between the Berlin Institute of Technology in Germany and Korea Advanced Institute of Science and Technology in Korea is transformed in Subsection 5.1.2. The undergraduate program is offered at a Turkish university in cooperation with German partners, whereas the graduate program is offered as a cooperation between compatible engineering programs at both institutions. The transformative attributes are verified through the case studies to ensure that the new programs meet the requirements in Subsection 5.1.3, i.e., to evaluate the extent to which each attribute is applied by the transformed programs. The existing and transformed programs are scored and compared based on the fulfillment of attributes as requirements.

5.1.1 **Undergraduate Program for the Turkish-German University**

This case study analyzes a program designer or coordinator who are studied holistically by the architecture for sustainable manufacturing to design, execute and evaluate the transformation of an educational program between a developed and a partner country. The goal of this case study is to test if the transformative attributes can be applied to private and public cooperation between Germany and Turkey in order to establish a new industrial engineering program.

5.1.1.1 **Gap Analysis**

The success of young universities depends on the support of its **stakeholders** such as well-established and experienced senior professors of the scientific community. Identifying talented young scientists and enabling them to participate in the scientific community will especially help to build a platform for future cooperation. Taking the dynamics of both society and politics into account, the scientific community supports to bridge the gap between both countries.

The idea of establishing a higher education institution between Germany and Turkey is described by Grothe for the first time in his book “Contributions to Knowledge of the Orient” in 1906 [Fra-14, p. 26 f.]. Almost a half century later, the Council of Europe opened an international treaty for signature to become a participating state in the Bologna Process and its European Higher Education Area in 1954. While 14 countries, including Germany, signed the European Cultural Convention in 1954 [Cou-16], Turkey followed in 1957. Three decades later, Germany's chancellor Kohl and Turkey's president Demirel made an attempt in the 1990s to found a German-Turkish institution for higher education, which failed for unknown reasons.

Almost two decades later, the initial idea of establishing a German-Turkish higher education institution was developed in 2008 by Cuntz and Süssmuth. Cuntz was the German ambassador in Turkey between 2006 and 2011. Süssmuth was the president of the German parliament between 1988 and 1998 as well as Federal Minister of Family Affairs, Senior Citizens, Women and Youth between 1985 and 1988. This initiative found broad support within a short period of time. Germany's chancellor Merkel and Turkey's prime minister Erdogan signed a “Memorandum of Understanding” in 2008 to enhance long-term cooperation in education and research between the Federal Republic of Germany and the Republic of Turkey. Both countries have agreed to expand cooperative efforts in higher education which include the foundation of a German-Turkish university in Istanbul, Turkey [Boz-09, p. 8 ff.].

The **Turkish-German University** (TDU, in German: Türkisch-Deutsche Universität) was founded as a Turkish state university in 2012. As designated by the Turkish government, the TDU aims to become a leading university focused on applied research in Turkey and the region. The TDU follows the successful German model and standards concerning the academic and administrative structure as best practice. Its strategy is to adapt excellent educational programs, taken from the strongest engineering areas, for example, of Germany and the USA, and to customize them to the needs of Turkish higher education.

The TDU is governed by many boards and committees which design and establish the academic, administrative and scientific activities, as presented in Figure 5-3. The stakeholders of the TDU are broadened to a German- and Turkey-wide network. The network is still expanding to include global leading universities and research institutions. The governmental stakeholders are the Turkish Council of Higher Education (YÖK, in German: Türkischer Hochschulrat, in Turkish: Yüksek Ögretim Kurumu) and German consortium including 33 German higher education institutions [TDU-16].

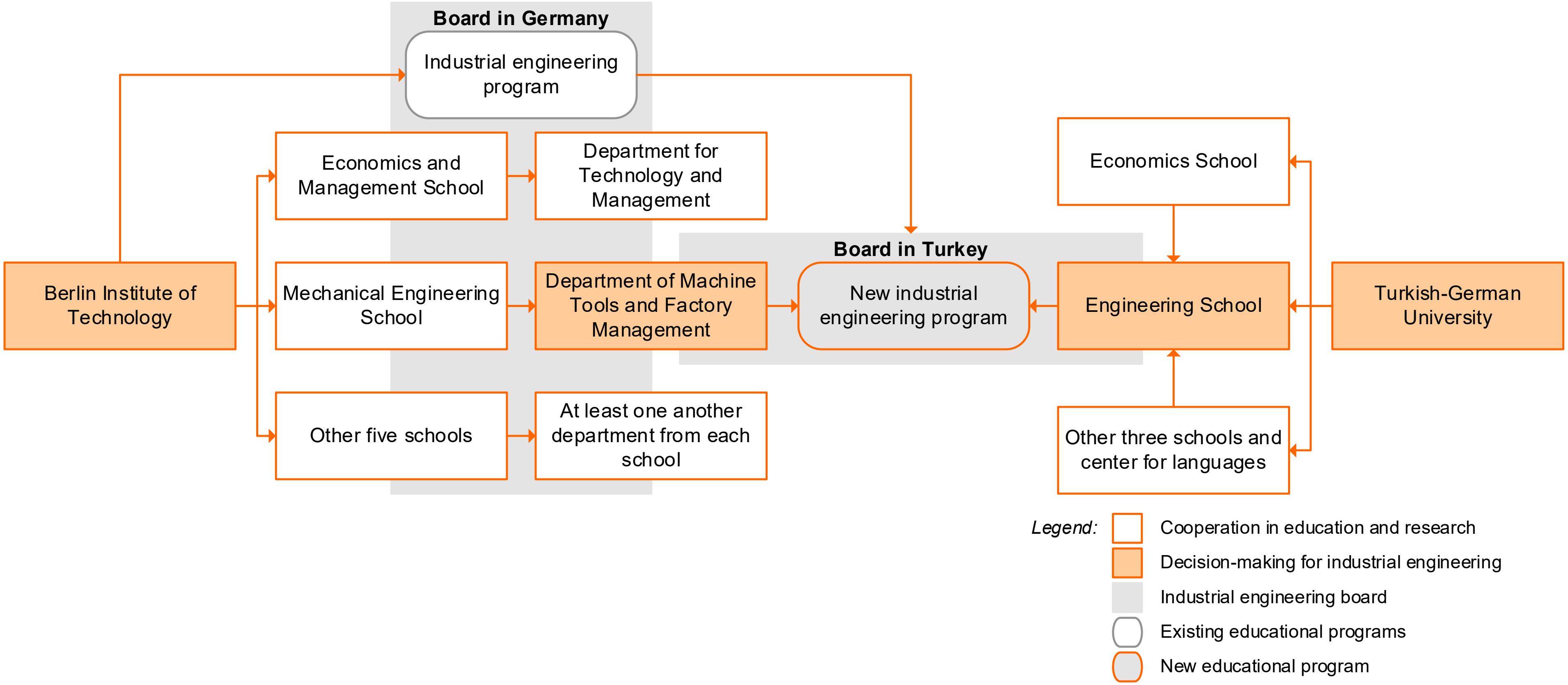


Figure 5-3: Stakeholders of the transformed industrial engineering program

After graduation, students receive a Turkish university degree, which provides opportunities for job assignments on the global labor market, on par with those from German higher education institutions. Focusing on high-tech engineering and sustainable development, the TDU seeks to train excellent academics and to provide ample professional qualification to Turkish lecturers, so they can compete on an international level. The young university provides an excellent platform between a developed and an emerging country to connect advanced technologies with unique approaches for the regional implementation of sustainable manufacturing. To establish a long-term cooperation in education and applied research, the identification of its stakeholders' requirements play a key role.

The TDU has five schools and a center for languages including their education and research activities at the TDU. Six Turkish deans and six German coordinators from the leading partners of the TDU work in close cooperation on behalf of the governmental stakeholders to decide and communicate the academic and administrative development of each school. They also provide scientific evidence to support strategy developments at a university and international level as well as for the long-term German-Turkish cooperation. As the Engineering School is coordinated by a German coordinator and with a Turkish dean, both of them are responsible for decision-making and operations regarding the school. The responsibilities and tasks of the coordinator and dean are summarized in Table 5-1.

The **TU Berlin** cooperates with research and higher education institutions in partner countries based on German standards. Coordination and management of the educational and scientific cooperation between the TU Berlin and higher education institutions in partner countries is handled mainly by the Department of Machine Tools and Factory Management (IWF, in German: Institut für Werkzeugmaschinen und Fabrikbetrieb). The IWF and other involved departments of the TU Berlin have acknowledged experience in the areas of manufacturing, electronic and environmental engineering, economics and mathematics. Interdisciplinary experiences are fruitfully integrated to prove the superiority of sustainable value creation against traditional paradigms following the principles of sustainable manufacturing and methodologies in technology and management. The IWF's international activities include the design and establishment of educational programs at the Vietnamese-German University (VGU) in Ho-Chi-Minh-City, Vietnam and the TDU. Since 2013, the TU Berlin has offered a master program on "Global Production Engineering and Management (GPEM)" at the VGU. Cooperative projects include the program design activities in Germany as well as job assignments in Turkey and Vietnam.

Table 5-1: Overview of the tasks for the Engineering School

Scope	Tasks	Samples
Boards of educational programs within the Engineering School	To design, establish and coordinate the congruence of the educational regulations	Congruence within the Engineering School as well as within the university,
	To link the educational programs on undergraduate, graduate and doctorate levels in the Engineering School,	Undergraduate industrial engineering program with the undergraduate program of mechatronics system engineering,
	To design and establish the engineering laboratories and testing fields in the Engineering School,	Building laboratories for automation technology,
	To mentor young instructors, lecturers and researchers at the TDU for confidence building in education and applied research,	Sustainable manufacturing courses for all undergraduate engineering programs,
	To mentor visiting scholars at graduate, doctorate, post-doctorate level,	Selection, application and enrollment in a graduate program relevant to the applied research profile of the TDU,
All schools within the University	To design and establish the cooperation among all schools and the center for languages,	Courses in economic science taught by the Economics School as a service for the Engineering School,
	To design and establish the infrastructure of the TDU,	Design and establish the infrastructure for the campus and student management systems,
Scientific community	To design and establish the exchange and dual degree programs with other regional and international engineering schools,	Student exchange programs, for example, Erasmus programs within the European Union,
	To design and establish the cooperation with other regional and international engineering schools for creating synergies in research,	Research projects in real-time cloud-based execution of virtualized machine control funded by national science foundations of multiple countries,
Industrial community	To design and establish the cooperation with regional and international companies in order to create opportunities for trainings and applied research,	Trainings in application of efficiency gains in a company, strategic workshops with industrial partners,
Govern-mental stakeholders	To communicate the goals and plans of the school with the German consortium and Turkish senate as well as to consult strategically the consortia,	Funding proposal for scholarships by the German government and use these to complete all listed tasks, to build the roadmap of the university with the governmental stakeholders to be implemented step-by-step,
All	To represent the school in consortia meetings and marketing,	Public relations in conferences and workshops.

Since 2010, the TU Berlin has been a leading partner of the TDU. Cooperation between the TDU and the TU Berlin to establish the Engineering School was agreed for two years in 2011 and then for five years in 2014 and will probably continue. The joint cooperative effort extends from design of the school's undergraduate, graduate and doctoral programs, as well as laboratories and scientific network to the assessment and recruitment of potential academic staff, students, senior administration staff and collaborative research, as listed in Table 5-1. Academic coordinators, deans of departments and flying faculty take positions in teaching, research and management activities of both institutions. Since 2014, the TU Berlin establishes an undergraduate program on “Mechatronics System Engineering” at the TDU.

Language of the undergraduate programs at the TDU is German to introduce students into the German-standard higher education. Language of graduate, doctoral and professional education programs is English. The English language opens the programs to students with a regional or international degree and enables to extend the cooperation between Germany and Turkey to the leading research universities such as in the USA.

The **industrial engineering board** at the TU Berlin has 28 members including all schools of the university, as demonstrated in Figure 5-3. From each school, at least one department, one full professor, one research engineer and one student are members of the board [TUB-12].

Each educational program at the TDU is coordinated with a German full professor on behalf of the German coordinator of each school. The industrial engineering board at the TDU has at least six members. Three of them are from the IWF in Germany, who are a full professor, a research engineer and an assistant professor. The other three are from the academic staff of the engineering school in Turkey. Turkish members of the board can be assistant, associate or full professors at the TDU. The dean of the Engineering School selects one of the three as the representative of the program. The program is mainly designed and coordinated by the board including all members, whose responsibilities and tasks are summarized in Table 5-2, and supported by the administrative staff.

Members of the board are also called designers or coordinators of the program as major stakeholders. They compare the requirements with the existing best practice from the German and USA universities and transform the program, if necessary. For the comparison, they organize some of the following events with a wide range of minor stakeholders: preliminary visits to universities, curriculum development workshops, follow-up visits to higher education and research institutions as well as to companies, meetings with the governmental community. The goal of these events for the board is fact-finding.

The board also meets the academic and industrial stakeholders in their local environment. For example, a board member and another instructor of the program meet an industrial expert to cooperate and design together a project-based course. Additional to the board member, the other two are then actively involved in the transformation of an educational program and optionally develop an applied research project. This allows a first-hand assessment of the current status of engineering programs and extraction of requirements. It also helps to identify specific topics for inclusion in the working sessions, which would be of future benefit to those attending. Board members are encouraged to continue work on the curricula following the workshop and to expedite the implementation of the new and revised curricula.

Table 5-2: Overview of the tasks for the Industrial Engineering Board

Scope	Tasks	Samples
Educational program	To develop and update the goals, focus, curriculum, course types within the program,	Focus on sustainable manufacturing to enhance advanced capabilities with project-based courses,
	To develop, design and transform the educational program,	Curriculum of the program at the TU Berlin is analyzed and adapted to the TDU,
	To develop and update the contents and prerequisites of courses,	Introduction of a project-based course for training local applications for principles of sustainable manufacturing,
	To design the course schedule and assign it to instructors and lecturers from Germany and Turkey,	Acquisition of instructors and lecturers as flying faculty to teach engineering courses in a certain fall or spring semester,
All schools within the University	To ensure the congruency of the program with other educational programs of the Engineering School and university as well as the German best practice,	Undergraduate industrial engineering program with the undergraduate program of mechatronics system engineering and economics
	To contribute to the design and establishment of engineering laboratories and testing fields,	Description of the use-based services of engineering laboratories for the program,
Scientific community	To select partner universities for exchange of students and academic staff,	Application to Erasmus programs to establish exchange programs with the TU Berlin and other leading partners of the TDU,
Industrial community	To select industrial partners, specify training programs for internships and organize excursions,	Training of students with conventional and new metal cutting processes in a technical internship and conducting motion-time-measurements on production lines,
All	To invite guest lecturers from the industrial, scientific or governmental community,	Presentation of different engineering applications by an expert in a course “Introduction to engineering”.

The first workshop, held at the TU Berlin in December 2013, was dedicated to the stakeholders who were interested in identifying the required capabilities and developing approaches to adapt new attributes of industrial engineering education for the TDU. Attendance at the workshop was encouraged for German and Turkish academics with teaching and curriculum responsibility, experts from research institutions and companies in manufacturing, mechanical engineering, mathematics, computer and environmental sciences as well as governmental authorities. Samples from the applied questionnaire are summarized in Appendix 8.1. The workshop addressed the question what are the opportunities and threats of adapting an existing industrial engineering program into a new university.

The **SWOT** of existing industrial engineering programs at different European and North American universities, for example, at the Georgia Tech and the TU Berlin, were reviewed, as presented in Subsection 2.2.2. Consideration was also given to the regional regulations to select the students, required graduate capabilities, teaching activities and assessment methodologies. The board analyzed the results of the questionnaires, which are presented in the next subsections, and summarized the results of the SWOT analysis. The board shared the results with all participants of the workshop in order to evaluate the current state of the existing programs and select the requirements of the industrial engineering education for the TDU.

The following aspects are identified as **strengths**. After the German-Turkish cooperation started with economic, military, cultural and social relations at the end of the 19th century, the educational and industrial cooperation followed after the first World War based on the practical experiences and field studies of German scientists in Western Europe and the USA. The Turkish government took advantage of the increasing number of refugees from Germany, especially educators and scientists, who significantly contributed to the development of Turkish universities and scientific establishments after 1933, in particular in engineering and natural sciences [Sha-01]. Since then, the German engineering education was seen in Turkey like in other parts of the world as a best practice with a focus on effective solution finding in engineering. German companies' reputation for quality in engineering, especially manufacturing engines and cars, remains as a big advantage worldwide [Car-08].

There is a shortage of engineers in western communities. For example, in Germany, there will be more open positions for engineers than there are individuals graduating from engineering programs over the next decade [VDI-14, p. 2 ff.]. Western countries need engineers which are produced in excess in Germany. In terms of a European comparison, Turkey, with a population of 76 million people, represents the second largest demographic and with an average age of 31 years the youngest community. The young Turkish population is more flexible and can easier adapt to rapidly changing conditions than the aging German population. Another advantage is that the instructors and lecturers in Turkey, as well as in China and South Korea, are respected more than in other, especially western OECD countries. The academic staff provides knowledge transfer, while they also counsel and guide their students, serving as role models for their students' future professionalism and private lives [Var-13, p. 13].

The university's location, quality of student intake and good facilities are less commonly cited strengths.

Weaknesses identified were (1) lack of training; (2) lack of cooperation between science, education and industry; (3) lack of self-organization; and (4) lack of holistic view.

Some of the observations are based on the Turkish education system. Both mandatory education and higher education provide mostly knowledge, and rarely skills. Students gain knowledge usually through teaching and learning, while they usually lack the opportunity to gain skills through application of methodologies or principles and discussion of theories or facts. The contribution of trainings to enhance skills and competence is hardly recognized by the Turkish education system [EC -15b, p. 75].

There is a big deficit between industrially necessary capabilities and the actual capabilities of junior engineers, who recently graduate from engineering departments of many universities. This deficit is mainly caused by the mismatch between the capabilities of academic staff and the required capabilities by the industry. The academic staff has mainly capabilities to teach in form of a lecture and one-sided presentations rather than to train students in order to apply knowledge in projects and internships by themselves under their instructions. However, industry requires engineers who can create creative, entrepreneurial and innovative solutions. As a result, the majority of graduates lack the capabilities to respond to practical challenges faced by the industrial companies and can only have very limited influence on the economy and society.

Many engineers and academic staff prefer to focus on ideal cases for education and research purposes instead of dealing with real applications. They enforce experiments under highly scientific control of conditions instead of running and managing applied projects with industrial partners and dealing with real issues including programming and developing machines, dealing with rust or maintaining any equipment. Competence to initiate projects, propose new technological and organizational solutions for industrial problems, test and verify new approaches under real conditions remains very limited. The majority of engineers follow conventional regulations and innovations in the second half of the innovation cycle as late majority and laggards, rather than exploring opportunities to discover technology-driven innovations in new business fields as innovators or early adopters [Rog-83, p. 205 ff.].

According to many industrial stakeholders, only the minority of engineers, who have graduated from Turkish universities, can meet the requirements of the labor market and are able to do any job without special training in companies. Many engineers and decision-makers do not distinguish creative tasks that solve new challenges from repetitive tasks of followers and copyists, who mainly complete known procedures. The majority of engineers accomplish clearly defined and limited practical tasks or scientific research, whereas only the minority take a risk to change a running system by their own initiative.

Many private and public stakeholders are aware of the necessity of sustainable development, at least for environmentally efficient production. However, initiatives for economic growth precede initiatives for sustainable development.

The main result of the workshop for overcoming the identified weaknesses was the **opportunity** that engineering education can be transformed adapting to modern educational programs in order to establish more technology transfer, more cooperation with industry, new research programs and more international cooperation.

Changing engineering education includes transformations necessary to strengthen the cooperation among higher education, research and industrial institutions, while creating sustainable value. The current Turkish higher education provides the required interdisciplinary, international and IT-based capabilities to a very limited extent.

Following the industrial strategy for 2015-2018 of the Turkish Ministry of Science, Industry and Technology, strengthening the role of universities is urgently necessary for research and innovation, in particular through cooperating with industry, especially with small and medium-sized enterprises (SME) [EC -15b, p. 75]. New strategies must be developed and implemented for entrepreneurship and public-industry-university cooperation in applied research [EC -15b, p. 53]. Engineering capabilities are applied in industry to create sustainable value. Creating sustainable value in manufacturing balances economic, environmental and social impacts, and leverages the sustainable development of the economy and society.

The main goal of the TDU is providing students with necessary capabilities to respond to industrial challenges through higher education and trainings. Application of knowledge in project-based courses and trainings can extend technology transfer. Professional education and trainings provide certificates to engineers for career development and involve customers and suppliers across the supply chain in the industry as well as on the academic staff in the industrial value creation. The professional education and career development of academic staff is beneficial if it improves the quality of engineering education. However, many scientists think that teaching a course is time-consuming and damages their career development. Promoting sustainable value creation in all levels of higher education must be integrated into the new programs.

Principles of academic freedom, free expression and freedom of association are articulated in, for example, the Universal Declaration of Human Rights, which was signed by Turkey in 1949, and the International Covenant on Civil and Political Rights, to which Turkey has been a signatory since 2000. The quality of higher education and research depend, among others, on these global principles [EC -15b].

The most common **threats** to transforming educational engineering programs were poor management, restrictive regulations, declining financial support with all its ramifications for staff and facilities, inflexibility of staff as well as unwillingness of academic staff, directors and governmental stakeholders to accept change.

The hierarchical structure of many institutions including higher education and research institutions as well as private manufacturing companies disable the communicative rationality. The stakeholders on a lower hierarchical level usually agree and operate without rethinking, questioning or discussing the decisions made by a higher hierarchical level. Taking responsibility or risks for one’s own actions on a lower hierarchical level is rare. Even if some stakeholders try to explore an innovative and new opportunity, they reject fulfilling the challenging tasks before completing the first round of trial, and step backward.

5.1.1.2 **Transforming Undergraduate Industrial Engineering Program**

The second workshop focused on the transformation of the program for the TDU. It was held at the TU Berlin in December 2014 to design the first draft of the new program based on the results of the SWOT analysis, as presented in this Subsection. Introduction of German standards requires a transformation of educational programs to enhance capabilities for the satisfaction of the German-Turkish as well as global labor market. The following capabilities required by higher education of industrial engineering through a new undergraduate industrial engineering program are in agreement with the transformative attributes, which are identified Subsection 4.3.1: (1) experience in the form of different internships in industrial companies, (2) capability to apply knowledge to any industrial setting to (3) create sustainable value, (4) capability to work with different IT tools and (5) in an international team as well as (6) ability to cope with time pressure. Transformative attributes were applied to the existing engineering programs. Preliminary information was sent to registered participants including the workshop program, goal setting, expected outcomes and proposed university participation.

Attendance at the workshop was encouraged for a selected group from the first workshop in 2013 including German and Turkish academics from industrial engineering boards with teaching and curriculum responsibility, selected experts from research institutions and companies in manufacturing and mechanical engineering as well as governmental authorities. The combination of ideas and recommendations from all participants was essential to achieve a synergy in the program transformation.

Each participant was encouraged to work intensively and actively during the workshop. Participants worked in small groups in four sessions based on their experience and interests in engineering, business administration, sustainable development and training on the first day. They reviewed the framework for a transformative industrial engineering, as presented in Section 4.3 to discuss and verify the transformative attributes. Administrative documentation, explanatory notes, affinity diagrams, curriculum planner and examples of related course and subject descriptions from a number of leading research universities in engineering, especially industrial engineering were analyzed in detail. Industrial engineering undergraduate programs at different European and North American universities, especially in Germany and Turkey, were questioned in detail, with regard to the proposal of the participants.

The participants proposed the changes which are necessary to transform the best practice industrial engineering programs to a new program for the TDU accordingly. Feedback was collected from a broader group of stakeholders, who attended the first workshop in 2013, to investigate the potential of the transformed industrial engineering program. The transformation provided a new, improved undergraduate program which applies the attributes of transformative principles to a higher extent than the best practice programs.

Building on these results, the second day was dedicated to the application of the transformative attributes within the new industrial engineering program and to the question if further changes are needed before implementation. The fulfillment of attributes by each iteration was analyzed based on the scientific, technical and professional fundament as well as structure of each course. The resulting outline of the new industrial engineering program was verified by the participants for implementation at the TDU.

The new industrial engineering program at the TDU is an undergraduate degree program to be completed in four years or eight semesters with 240 ECTS. ECTS represents the European Credit Transfer and Accumulation System and reads as credit points according to ECTS. The new program is based on the well-acknowledged four-year American and three-year German industrial engineering programs. All students take the same courses and a set of elective courses related to the selected specialization in sustainable manufacturing. Figure 5-4, resembling a house, demonstrates the framework of the program, which is in agreement with the framework proposed in Figure 4-6 in Subsection 4.3.2. It starts with the formal higher education, continues with trainings in the university, internships at companies, project-based courses and scientific thesis among higher education, research and industrial institutions, and should result in enhanced capabilities for the particular professional life of industrial engineers.

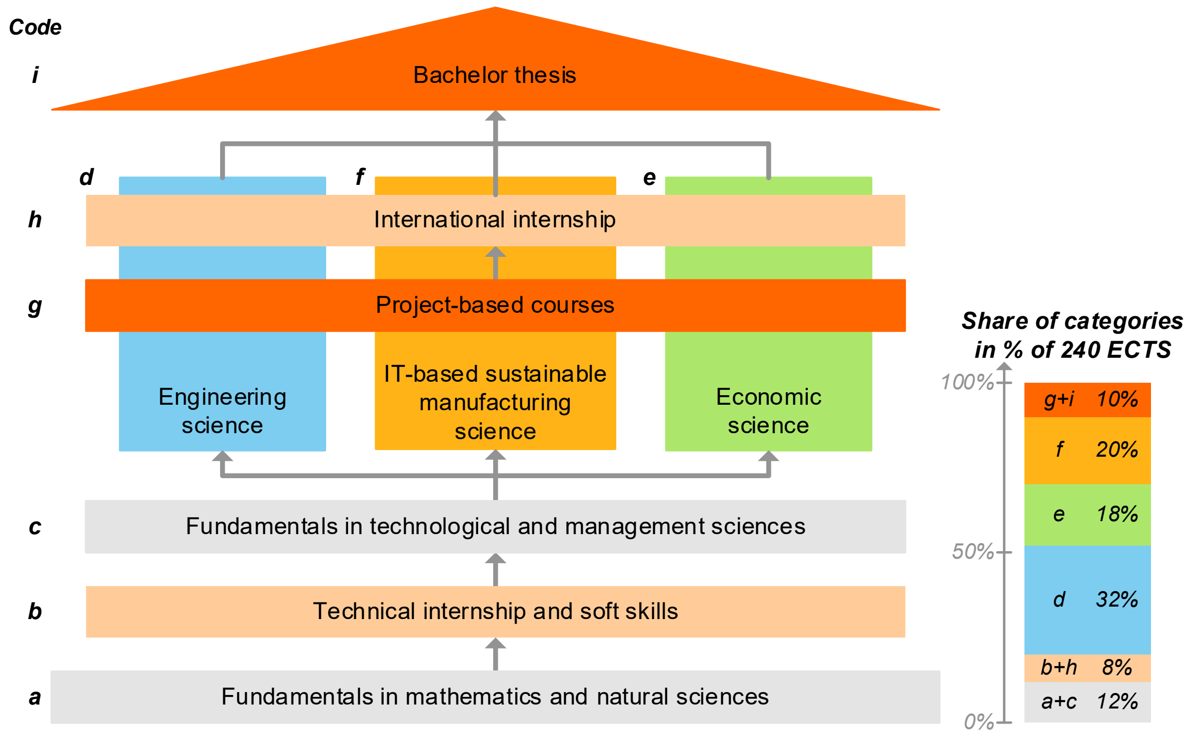


Figure 5-4: Framework of the transformed industrial engineering program for the TDU

Detailed information about the curriculum and courses are available in Appendix 8.3.1. Each course is assigned to a category. All courses in all categories together comprise 240 ECTS. Figure 5-4 summarizes the share of each category in percentages bottom-up, i.e. from the fundament of the house (a) to the roof (i) based on Figure 8-2, which presents all courses with their respective ECTS and SWS. Cumulative ECTS, SWS and the share of each category are listed in a curriculum planner worksheet in Table 8-5 in Appendix 8.3.1.

All students take a set of mandatory courses related to the specialization of industrial engineering in sustainable manufacturing. Mandatory degree requirements are listed in Table 5-3, which specify the requirement, the number (No.) of courses, academic discipline, sum of ECTS, share in 240 ECTS or total duration in detail. For example, it is mandatory to take at least four courses from mathematics and natural sciences with 24 ECTS, which equals 10% of the whole program. The implemented program at the TDU must be in congruence with these requirements.

Table 5-3: Degree requirements of an undergraduate industrial engineering program

No.	***Requirement***	***No. of courses***	***Discipline***	***Sum***	***Share in 240 ECTS***
1	minimum	4	mathematics and natural sciences	24 ECTS	10%
2	around	10	technological and engineering sciences	72 ECTS	30%
3	around	6	management and economic sciences	24 ECTS	10%
4	minimum	2	social science of law	6 ECTS	2.5%
5	minimum	2	computer science	12 ECTS	5%
6	minimum	2	sustainable manufacturing sciences	12 ECTS	5%
7	minimum	1	language course in English		
8	minimum	1	language course in German	6 ECTS	2.5%
9	minimum	1	language course in Turkish		
10	minimum	2	project in engineering	6 ECTS	2.5%
11	minimum	2	Internships	in total three months	
12	exactly	1	bachelor thesis*	in total three months	
13	* after completing at least 75% of the program with 90 ECTS				

Based on Table 5-3 and Figure 8-2 in Appendix 8.3.1, Figure 5-5 demonstrates the flow of the courses within the program per semester over a four years' timeline to present the relations among all courses and their categories.

The next subsections describe briefly how the new program applies the transformative attributes and confirms the contribution of transformative industrial engineering to sustainable manufacturing referencing Figure 5-4, Table 5-3, Figure 5-5, Table 8-5 and Figure 8-2.

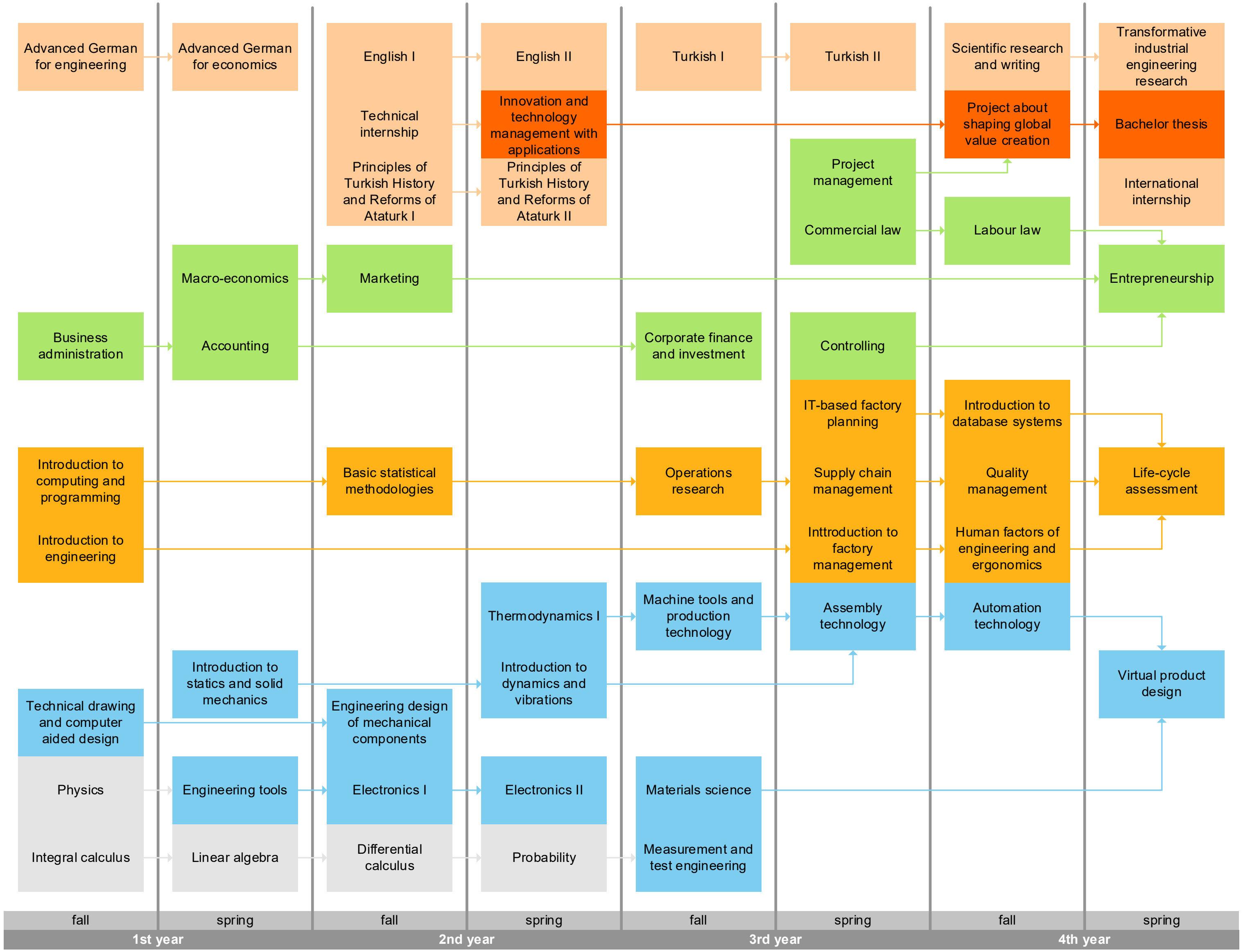


Figure 5-5: Curriculum as flow of the program at the TDU

The proposed program follows the **interdisciplinary** focus of best practice in industrial engineering and contains two main academic knowledge domains: technology and management. Courses in mathematics and natural sciences as well as in technological and management sciences comprise 12% of the whole program and build the fundament for the engineering sciences. 18% of the 240 ECTS for all courses are dedicated to economic sciences and 32% to engineering sciences.

Value creation factors, modules and production systems include tasks to plan, monitor, schedule, model, simulate, design and assess value creation. These tasks must comply with decision-making at operational and management levels by rapidly changing conditions and under time pressure. To deal with complex tasks in future practice for sustainable manufacturing, students are trained to use innovative IT tools during higher education. In many courses emphasis is placed on **digitalization** using computer hardware and software in information processing and on the interface of IT with management in helping to achieve the targets of a case study. All IT-based courses, for example, Introduction to Computing and Programming, Engineering Tools, Industrial Information Technology and Virtual Product Design, comprise around 20% of the total ECTS of the program. A sample list of IT-based courses and applied software is given in Table 8-6 in Appendix 8.3.1. Most of the IT-based courses are assigned to the category about sustainable manufacturing compared to the other categories. Thus, this category's name is changed to IT-based sustainable manufacturing science for the case study at the TDU.

Trainings are non-formal parts of higher education designed to impart skills through planned practical courses and real problems by applying knowledge during higher education. **Problem-solving** as an educational attribute builds the foundation for finding solutions to existing problems by industrial engineering. The goal, the background, the problem to solve, and usually the methodology on how to solve it is given by an instructor. Students train their capabilities by doing the problem-solving by themselves.

Building on this attribute, the new industrial engineering program consists of two categories with focus on **projects**: (1) the technical and international internship with around 3% and (2) project-based courses with around 5%. The German Federal Ministry of Education and Research (BMBF, in German: Bundesministerium für Bildung und Forschung) via the German Academic Exchange Service (DAAD, in German: Deutscher Akademischer Austauschdienst) additionally offers scholarships to attend two summer schools in Germany for the best third of the students from each intake.

Figure 5-6 illustrates the above listed practical elements of the program for an intake over a four years' timeline. Both summer schools are optional. All other practical elements are mandatory. Some practical elements require a preselection of the students according to their previous grades and interests. The schedule of elements distinguishes from Figure 5-5 and Figure 5-6. The latter one depicts the time within the four years' timeline, when the students experience the content of the element, whereas the first one depicts the time in the curriculum, when the completion of an element is approved by the TDU. A practical element is completed after the submission and approval of a final report and other kinds of documentation by a certain student. The following subsections introduce briefly all practical elements at the TDU, as presented in Figure 5-6.

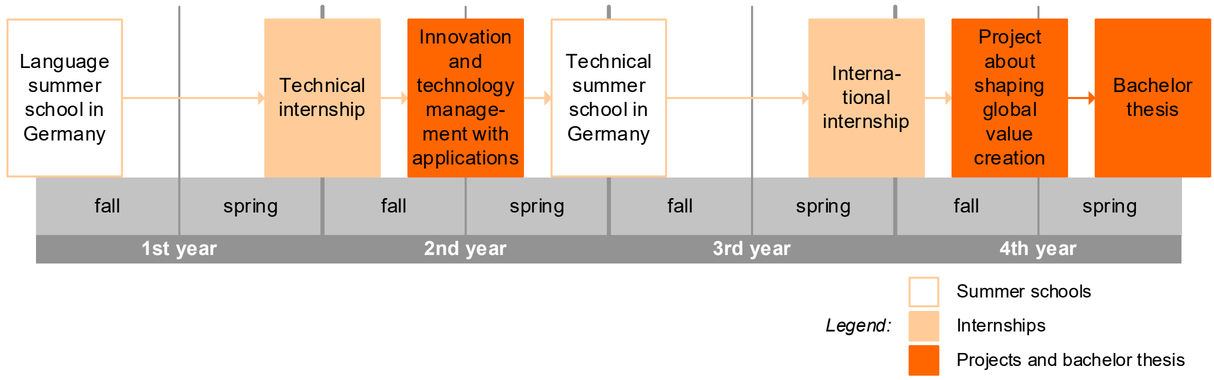


Figure 5-6: Framework for the practical elements

Due to the German program language, comprehensive and writing skills in German are mandatory for all students. The TDU requires a minimum of upper intermediate level of German according to the Common European Framework of Reference for Languages. The language requirement is waived for students who have received a high school degree from a school in any German-speaking country. Students starting with no knowledge of German take four to nine months of intensive instruction and acquire sufficient skills in all aspects of the language to enter the undergraduate program. They can also join a **language summer school** to intensify or expand their existing language skills in a German higher education institution. The summer school runs for four weeks before the first year fall semester.

A **technical internship** follows the first year of the program in order to apply basic knowledge in engineering in an industrial environment. The internship runs for six weeks within the summer holiday after the first-year spring semester. Students train, for example, how to use and combine materials for different value creation activities such as shearing, torqueing and deforming electrical appliances. The basic metal forming activities such as grinding, cutting, drilling, milling are also practiced during the internship. Students write a report on the work, prepare technical drawings and analyze errors in the processed materials. Both an industrial and academic supervisor approve the report and grade the students together, and asks for corrections, if necessary.

The course on **innovation and technology management with applications** takes place in the second-year spring semester. After gaining some methodological knowledge about innovation and technology management, intercultural property, team building and presentation tools, students have the opportunity to contribute to best practice examples of innovative companies, for example, in three-dimensional (3D) printing for components of electric cars. Their knowledge about these fields is applied to a real project to develop a prototype based on a given problem of an industry partner. This course trains the students for non-repetitive tasks in technical development and management departments with a focus on sustainability challenges.

The second summer school in a German research institution focuses on technical content to introduce the students to the advanced engineering applications; for example, programming of a robotic arm to pick and place small components or designing spare parts for 3D printing. The **technical summer school** runs for four weeks within the summer holiday after the second year spring semester. The goal of the second summer school is to introduce students to a research environment in order to train their skills for testing, demonstrating, drafting, calculating, assessing and presenting new ideas and their possible applications. Students attend lectures, visit innovative companies and work with German scientists within research projects.

The **international internship** represents a practical element as well as the transformative attribute regarding glocalization [Hes-11, p. 6]. This advanced internship provides students with the opportunity to experience the business world. The internship runs for two to three months between the third year spring and fourth year fall semesters.

The course forms a **project about shaping global value creation** during the fourth year fall semester. This course represents an intensive, semester-long, team-based engineering project, which should contribute to sustainable manufacturing.

A so-called client is involved in each project as the main stakeholder, who is represented by an academic or industrial instructor with an interest in the scientific or applied project outcomes. The client has an advisory role, discusses the results of each project stage with the project team and does not make any decisions or actions to run the project.

Academic instructors present multiple projects to senior students of an intake at the beginning of the semester. Students are responsible to apply for three projects according to their individual preferences. After the assignment by the instructors, three to five students comprise a project team, which is responsible for running the project.

While the background and goal of the project are clearly defined by the client, methodologies to achieve the goal are not necessarily specified. Students need to properly define and scope a problem, identify and analyze relevant factors, select and apply appropriate methodologies and IT tools, generate and evaluate potential solutions, while keeping the client informed about all progresses and intensions on a regular basis. For each meeting, the team prepares an agenda in written form, a progress report on the work done over the previous week, a list of unresolved issues, and the proposed next steps.

The projects have usually three major stages. Each stage culminates in an oral presentation and a written report, both of which are delivered to the client.

- **Project definition stage**: The problem, deliverables, strategy, methodology, project plan, and value to the client are defined. At the end of this stage, the project proposal presentation and report spell out the work the team plans to do and the value the client can expect to receive.
- **Interim stage**: Data are collected, analyzed, and verified, relevant factors are understood, and the strategy is finalized. At the end of this stage, the interim progress presentation and interim progress report describe the work product to date and the remaining plans for the semester.
- **Final stage**: The potential solutions are evaluated and their value demonstrated. At the end of this stage, the final presentation and final report provide a comprehensive and self-contained description of the work completed during the semester. The academic and industrial advisors grade the students together.

Project-based courses improve students' skills and competence in technical writing, public speaking, working within a team, as well as in project and time management.

The **bachelor thesis** follows the German standards in engineering education. It contains a research or industrial task similar to a one-to-one project between a student and an academic instructor. An industrial instructor can co-supervise a bachelor thesis, if necessary.

After having completed all other courses and internships, a senior student is responsible for running an independent research study in the fourth year spring semester near graduation. A bachelor thesis requires a very narrow scientific focus on a fixed subtopic of industrial engineering, especially in sustainable manufacturing science. For example, the uncertainty of a stationary test station for measuring wind energy rotors can be analyzed to measure the effective performance within a bachelor thesis.

The program promotes education, training, practice and research on **sustainable manufacturing** with the many educational courses and practical elements. Its uniqueness consists in a focus on: (1) balancing economic, environmental and social impacts, (2) providing solutions for sustainable value creation and demonstrating their impacts on the environment and society, (3) developing methodological and technological innovations and supporting their adoption by companies integrated into value creation networks and (4) leveraging the systemic reference breadth and production technology depth of the various projects in industrialized as well as emerging markets. Almost half of the courses are dedicated to sustainable manufacturing, which include courses about sustainable manufacturing with 10%, two project-based courses and the thesis with 10%, as presented in Table 8-7 in Appendix 8.3.1.

The cooperation between Germany and Turkey characterizes the **glocalization** focus of the TDU, which is a trilingual higher education institution. The undergraduate programs run in German and provide additional language courses in English and Turkish. All graduate, doctoral and training programs are in English and provide additional language courses in German and Turkish. The law school is in Turkish due to the local applicability of the law degree.

The glocalization focus of the industrial engineering program is highlighted by the global scope of sustainability issues. If each industrial engineer contributes to creating sustainable value regionally, people get closer to achieving a sustainable development on a global level. To enhance the required capabilities for sustainable manufacturing, it is essential for each student to gain some international experience during higher education in form of an international internship or exchange semester.

The international internship takes place in any country worldwide, even at a local company. It gives the opportunity to the companies to gain firsthand understanding of a talent and to the senior students to gain professional experience in research or practice. Students apply for a temporary position in a company in the professional field they are interested in. The gain of the student goes beyond the experience in the company and trains the student how to abstract any value creation activity in order to assess its contribution in creating sustainable value. The expected outcome of this advanced internship is that students train how to think globally and act locally.

The work done by the students can have a broad or narrow link to sustainable manufacturing. In both cases, students need to do some outreach activities in order to present the sustainable value created through their experience during the internship to a wide range of stakeholders, i.e. they provide an explanation of how the added value can influence different groups of stakeholders, for example, to raise awareness of or contribute to sustainable development. For example, a student can work in a team which develops a maintenance optimization model for a local production company to reduce inventories. The internship report contains the specific information about the development including the tasks of the students with goals, methodologies, requirements and attributes. In addition to the basic report, the outreach of this experience is described to discuss how these activities contribute to sustainable development and what opportunities for further improvement exist. For example, the maintenance optimization model can support the identification of potential suppliers to increase the quality of procuring spare parts from partner countries.

By understanding the interdisciplinary and global challenges of sustainability through the new, transformed industrial engineering program at the TDU, industrial engineers learn and train, while taking the responsibility of developing local solutions in multiple courses and trainings, as presented in Table 8-7 in Appendix 8.3.1. When junior engineers have already gained experience before graduation in synthesizing sustainable solutions, they are capable of exploring opportunities to practice and develop their career and talents in a sustainable manner.

5.1.2 **Graduate Dual Degree Program between Korea and Germany**

Analog to the first case study at the TDU, the second case study also analyzes a program designer or coordinator who was studied holistically by the architecture for sustainable manufacturing to design, execute and evaluate the transformation of an educational program between a developed and a partner country.

5.1.2.1 **Gap Analysis**

The goal of this case study is to test if transformative attributes can be applied in order to establish a graduate dual degree program between Germany and Korea. The deficits of existing engineering programs of both countries are analyzed to merge opportunities into a new graduate dual degree program. The identification of **stakeholders** and their requirements plays a key role to establish a long-term cooperation in education and applied research between both countries.

Since Korea has increased its investment in research and development as an upper-level developing country in the last two decades, the cooperation between Germany and Korea has also intensified. A scientific and technological cooperation agreement was concluded between the Federal Republic of Germany and the Republic of Korea in 1986 [Int-15]. Since then, numerous individual agreements have been signed between higher education and research institutions of both countries. Due to the high interest in cooperating with Germany, the BMBF and DAAD provide mobility funding for partner institutions from Germany and Korea [Jon-13, p. 44].

An international dual degree program between two leading research departments of a German and a Korean university is described to demonstrate the program development as well as participating students' potential contribution to sustainable manufacturing through enhanced capabilities. International dual degree programs are based on a formal agreement between two universities including at least one responsible department from each. Major stakeholders of a dual degree are two departments, which form a board to design and coordinate the program. Two universities and the board are briefly described in the next subsections, as presented in Figure 5-7 [KAI-12].

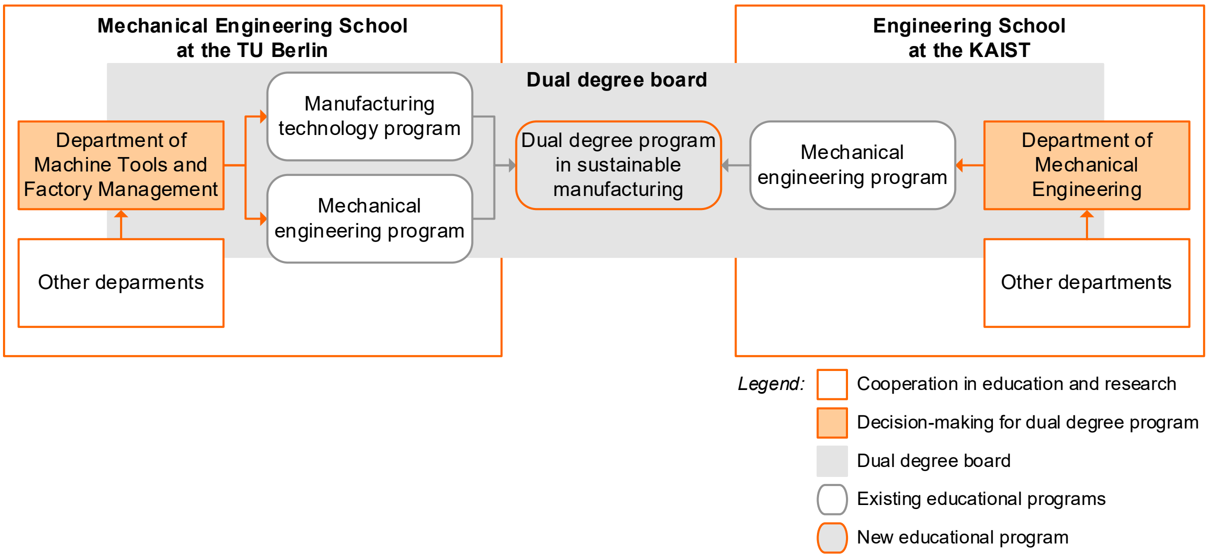


Figure 5-7: Stakeholders of the transformed sustainable manufacturing program

Along with the Georgia Tech, the **Korea Advanced Institute of Science and Technology** (KAIST) is recognized as a successful case of a research university in Korea, which has served a center of excellence since 1970s to nurture high caliber workforce in applied research and technological advancement [STE-15].

Recruitment of highly competent academic staff and enrollment of talented students was essential for the development of the KAIST with its exceling capacity in applied research for technological innovation. The rapid development was possible within a few decades due to exceptional incentives such as scholarships and free dormitories. The KAIST provided incentives such as high salary and free housing within the campus for academic staff and their family in order to induce Korean scientists and technologists residing abroad to return to Korea. Returnees had doctorate degrees. Their excellence contributed to attracting many talented students across the country.

In order to attract excellent students, the KAIST has offered additional services, for example, full-tuition scholarship, dormitory and preferential treatment for military service. In return, graduates have been obliged to serve in industry, higher education or research institutions for a certain period of time. The KAIST has also secured excellent students by providing various incentives to enable opportunities on the labor market by domestic production systems [STE-15]. Since 2007, the KAIST has adapted dual degree programs with leading world universities to offer its students diverse educational opportunities and strengthen academic exchanges.

The KAIST and the **TU Berlin** signed an agreement to transform some of their graduate engineering programs together in 2008. Both universities agreed to transform dual degree graduate engineering programs in 2009. The agreement included the transformation of two programs: (1) The first program was based on the electrical and computer engineering graduate program. (2) The second one was focused on sustainable manufacturing based on the graduate programs in mechanical engineering and in manufacturing technology. (3) A third dual degree graduate program in industrial engineering with focus on management rather than technology followed in 2010.

All three programs are offered at two campus locations: at the TU Berlin in Berlin, Germany and at the KAIST in Daejeon, Korea. The Department of Mechanical Engineering at the KAIST and the Department of Machine Tools and Factory Management at the TU Berlin take the responsibility to transform and apply the second program, which is described in detail.

Members of the **dual degree board** between both countries include a full professor and a researcher from the related departments from the KAIST and TU Berlin. A researcher can be a research assistant, assistant or associate professor. Four board members run the program operationally on behalf of the president of both universities and are also called the designers and coordinators of the program.

The joint board has the same responsibilities and tasks as the industrial engineering boards in the first case study, as presented in Table 5-2 in Subsection 5.1.1, to develop, design and continuously improve the educational program. The additional responsibilities and tasks are the following:

- The dual degree board selects and nominates students according to their academic, personal and linguistic qualifications. Any candidate must be enrolled in one of the three engineering graduate programs at the KAIST or the TU Berlin to be able to apply to the dual degree program.
- Students select their courses from the course pool of their educational program according to their individual interests and seasonal offerings in each university. The board also supervises the selection of the courses.
- The courses at both universities can overlap only slightly. An exception from the degree requirements can apply when the student submits a proposal with a content-based description and explanation to the dual degree board. The board examines the proposal and gives a recommendation to the KAIST and the TU Berlin. Both universities must confirm the exception to the regulation.
- The selection of semesters abroad, assignments to an internship or a project-based course must also be approved by the board.

The dual degree board conducted a **SWOT analysis** with stakeholders from both countries to evaluate the current state of the graduate engineering programs and select the requirements for the dual degree program in 2010 [Int-15]. Samples from the applied questionnaire are summarized in Appendix 8.1, which addressed three themes: preferences and existing solutions, needs and requirements as well as conditions. The goal of the analysis was to identify the opportunities for designing a dual degree program in congruence with both universities, which should focus on sustainable manufacturing, especially in the field of applied research.

The main **strength** was that both higher education institutions are well-acknowledged as a leading research university in their region. Aligning closely with Germany's applied research and industrial strategies following Industry 4.0, Korea aims to focus on translation of research outcomes into new products, the generation of science and technology related jobs in SMEs [Nol-14].

Both countries are regional innovators in developing attractive courses for international and exchange students. However, compared to the global average of internationalized educational programs, the internalization efforts in Korea remain limited [Jon-13, p. 30].

Korea is an advanced and a fast developing country in Asia. Despite the fact that the country has high investment rates in research and higher education, its performance still lags behind the developed countries. The higher education and accreditation were heavily criticized as the main **weakness** by the OECD for their lack of coherence, rigor and weak independence of the responsible institutions in 2009 [WEC-15a, p. 27].

The Korean mandatory and higher education rely heavily on rote learning and cramming for exams, leaving little room for creative thinking and entrepreneurial spirit. The size of academic staff mismatched the pace with rising enrollments and the share of part-time academic staff rose rapidly in the last years [BC -15]. The limited degree of internationalization in the higher education is reflected in the relatively low number of students from overseas [Jon-13, p. 30].

The most cited **opportunity** for the Korean higher education system was the shift of its focus from expansion in quantity of educational programs, students and facilities such as laboratories to increasing the quality of programs. Enhancing transparency among higher education institutions, reducing public funding to poorly-performing universities and internationalization were seen as further opportunities to strengthen competition and improve performance.

Governmental institutions require that universities conduct self-evaluation of their education and research, and publicly disclose the results. For higher transparency and additional responsibility for quality, external assessment and accreditation agencies have been introduced into the public recognition system since 2014 [Jon-13, p. 28 ff.].

Attracting international cooperation in higher education also supports upgrading its quality, in addition to providing workforce with highly enhanced capabilities for Korea. The governmental institutions, which fund the higher education and research, for example, Ministry of Education and Research, expand exchanges of students and academic staff, facilitating joint education and research among universities, and running joint and dual degree programs through some pioneering institutions [Jon-13, p. 30].

In case of an international dual degree program, two universities offer two degrees which run parallel in both institutions. The universities need to match their credit transfer regulations, curriculum cooperation strategies and degree structures, which lead to the lasting internationalization of both partner institutions and enable students to complete both degrees in less time than taking them separately.

The main **threat** to the transformation of an educational program was seen in the focus of Korean higher education institutions on improving regulations that enforce uniformity rather than quality through innovation [Jon-13, p. 29].

Another economic threat was identified. The Korean economy has suffered from trade preferences and monopoly rights for privileged companies. Inequalities among the private sector were caused by the preferential treatment of family-led corporate companies, which are called chaebol, with massive amounts of capital through subsidies and low-interest-rate loans in the late 20th century. Some chaebols have grown into massive business empires whose brands, which include Hyundai and Samsung, are now well-recognized and envied around the world. However, the ongoing dominance of chaebols poses challenges to regulators seeking to increase the competitiveness of the regional markets [Nol-14].

5.1.2.2 **Transforming Graduate Dual Degree Program in Sustainable Manufacturing**

The requirements at a new dual degree program were in agreement with the transformative attributes analyzed in Subsection 4.3.1 and applied for the TDU in Subsection 5.1.1. Two requirements were highlighted additionally: (1) capability to focus more on engineering than on economics by any industrial setting in order to create sustainable value and (2) capability to work with different IT tools to create and improve tangible products and processes rather than intangible services. Based on the results of the SWOT analysis in the previous subsection, the dual degree board reviewed the framework for a transformative industrial engineering, as presented in Section 4.3, for its applicability. The board agreed to apply the transformative attributes in order to transform the existing graduate programs and verify the attributes by the new dual degree program in 2010. The goals of the new program were specified:

- to model an adequate dual degree program, which fits the requirements of the stakeholders in both countries.
- to enable students receiving master degrees of both universities with a major in sustainable manufacturing.

- to enhance talented engineers with capabilities to support companies creating sustainable technological solutions.

The new, transformed program supports the exchange of graduate students between the Department of Mechanical Engineering at the KAIST and the Department of Machine Tools and Factory Management at the TU Berlin. The transformation provides a new graduate program in sustainable manufacturing, which applies the transformative attributes to some extent.

Application: Students, who are enrolled in the graduate program of mechanical engineering from both universities, and students who are enrolled in the graduate program of manufacturing technology from the TU Berlin, can apply for the program.

Tuition fees: Students participating in this dual degree program pay their normal tuition and registration fees at their home universities. During the term of the agreement the host universities waive all tuition fees for incoming students visiting under this agreement.

Travel and living expenses: Participants of the dual degree program are responsible for their own travel and living expenses during the exchange, if there is no third party funding. The dual degree board has provided a financial support through the DAAD since 2011.

Courses: Aligning with both universities, the dual degree graduate program is a four-semester in two-year and 120 ECTS degree program. Participating students need to take at least two semesters at the TU Berlin in Berlin, Germany and at least another two semesters at the KAIST in Daejeon, Korea. Students must take at least 60 ECTS from each university to get a dual degree in sustainable manufacturing.

Figure 5-8, resembling a house, is in agreement with the framework proposed in Figure 4-6 in Subsection 4.3.2. Detailed information about the courses are available in Table 8-9 in Appendix 8.3.2. Each course is assigned to a category. All categories together comprise 100% of the program, which equals 120 ECTS. Figure 5-8 summarizes the share of each category in percentage bottom-up, i.e. from the fundament of the house (c) to the roof (i) based on Figure 5-8, which presents all courses with their respective ECTS and SWS.

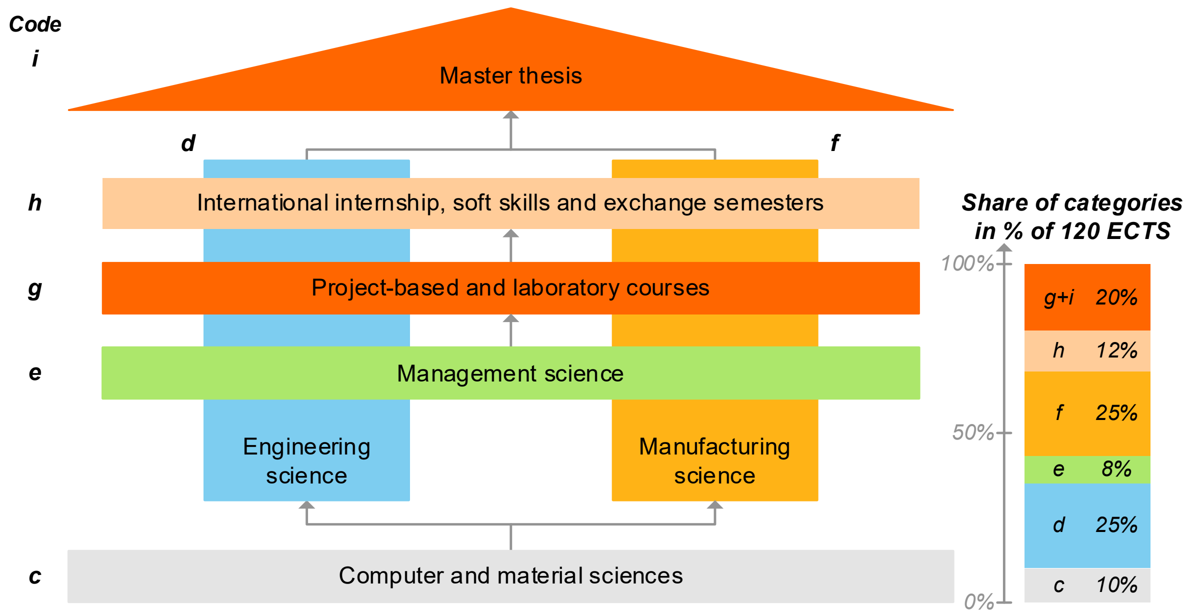


Figure 5-8: Framework of the dual degree program in sustainable manufacturing

Mandatory degree requirements are listed in Table 5-4, which specify the requirement, the number (No.) of courses, academic discipline, sum of ECTS, share in 120 ECTS or total duration in detail. For example, it is mandatory to take five elective courses from engineering science with 30 ECTS, which equals 25% of the whole program. The implemented dual degree program between the KAIST and the TU Berlin must be in congruence with these requirements.

Table 5-4: Degree requirements of a graduate sustainable manufacturing program

No.	***Requirement***	***No. of courses***	***Discipline***	***Sum***	***Share in 240 ECTS***
1	exactly	5	engineering science	30 ECTS	25%
2	exactly	1	material science	6 ECTS	5%
3	exactly	1	computer science	6 ECTS	5%
4	exactly	3	manufacturing science		
5	exactly	1	sustainable manufacturing	30 ECTS	25%
6	exactly	1	life-cycle assessment		
7	exactly	1	management science	6 ECTS	5%
8	exactly	1	project management	6 ECTS	5%
9	exactly	1	language course in English	6 ECTS	5%
10	exactly	1	language course in German	6 ECTS	5%
11	exactly	1	language course in Korean	6 ECTS	5%
12	exactly	1	project in engineering*	6 ECTS	5%
13	at least	1	KAIST laboratory for research*	in total three months	
14	minimum	1	international internship	in total three months	
15	exactly	1	master thesis**	in total three months	
16	* after completing at least 25% of the program with 30 ECTS				
17	** after completing at least 75% of the program with 90 ECTS				

The fundamentals of computer and material sciences provide a solid foundation in order to enhance the capabilities in engineering and manufacturing. Engineering and manufacturing sciences build the academic foundation. A project-based course, a participation in a selected KAIST laboratory for research and a master thesis provide the students with the appropriate capabilities to integrate economic, environmental and social aspects of manufacturing into their daily training and research in the university. The international internship enables the application of these capabilities in real industrial environments.

Cumulative ECTS and the share of each category are listed in a curriculum planner worksheet in Table 8-8 in Appendix 8.3.2. Based on Figure 8-3 in Appendix 8.3.2, Figure 5-9 demonstrates the flow of the courses within the program per semester over a two year's timeline, for example, from September 2015 until September 2017, to present the relations among all categories of courses.

The next subsections describe briefly how the new program applies the transformative attributes referencing Figure 5-8, Table 5-4, Figure 5-9, Table 8-8, Figure 8-3 and Table 8-9.

While undergraduate programs have a fixed curriculum, graduate programs include more elective courses. Multiple academic disciplines provide electives within the frame of defined categories. Students select their courses from a broader set of electives to tailor their graduate education around specific career goals and individual interests. Table 8-9 in Appendix 8.3.2 lists a sample of the electives for each discipline that are most commonly offered at both universities.

In contrast to the traditional mechanical engineering programs, the developed dual degree program follows an **interdisciplinary** focus and contains two main academic domains. 25% of the courses are dedicated to engineering science and 25% to manufacturing science. Computer and material sciences as well as management science support these two academic domains with 10% and 8%.

In order to have the capabilities to fulfill complex tasks by planning, monitoring, scheduling, modeling, simulation, designing and assessing value creation through engineering, students need to train applying, assessing and developing innovative IT tools during higher education. In many courses, emphasis is placed on **digitalization** focusing on the use of hardware and software in information processing and on the interface of IT with product and process design in helping to achieve the targets of a case study. At least 10%-15% of the program is comprised of IT-based courses also related to Industry 4.0, for example, IT solutions for digital factory, virtual product design technologies, and introduction to finite element method.

20% of the program is focused on **problem-solving** and project-based courses, which is analogously designed for the TDU.

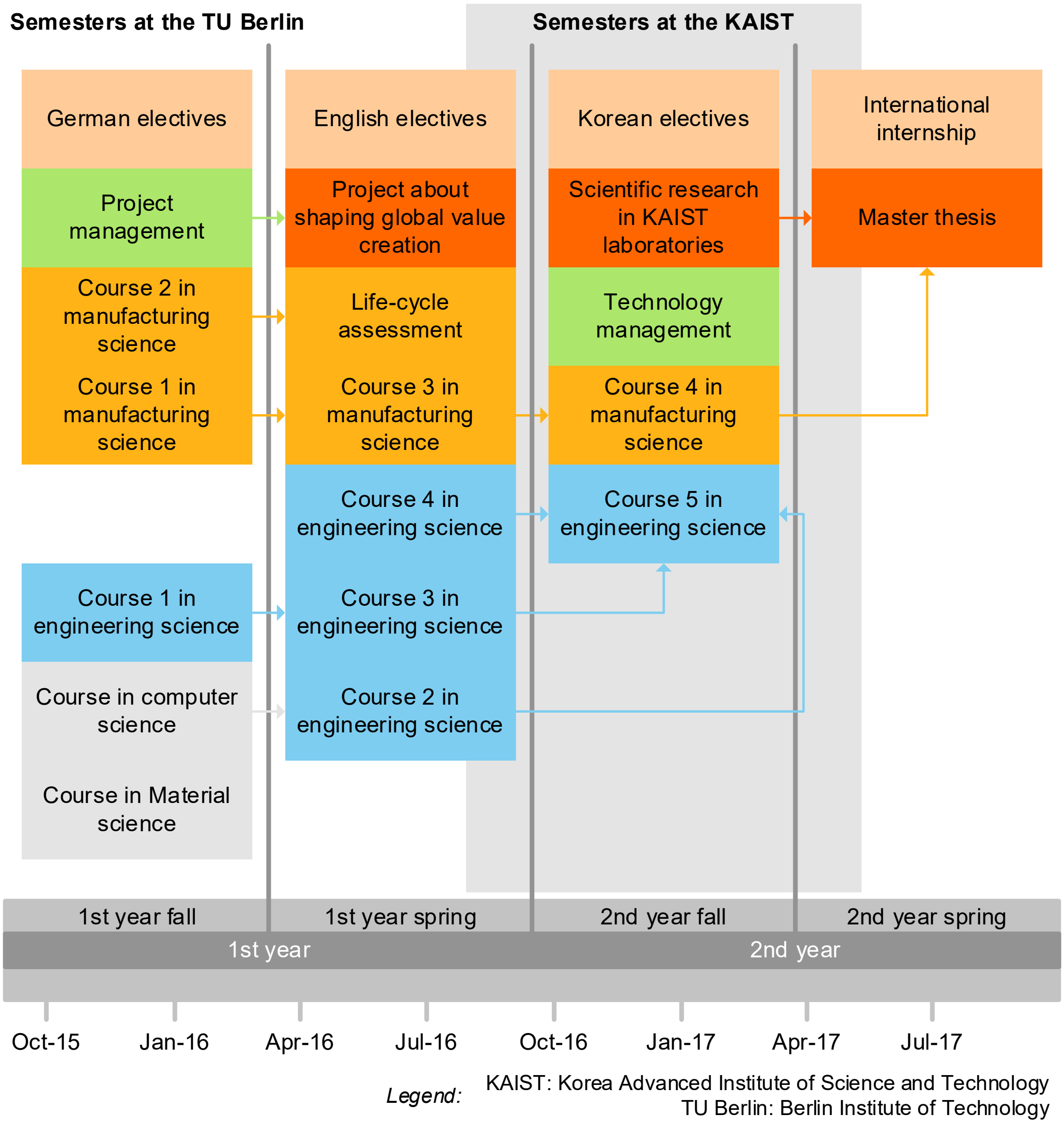


Figure 5-9: Curriculum as flow of the dual degree program in sustainable manufacturing

All students must select a **project** about shaping global value creation at the TU Berlin and a scientific research in KAIST laboratories after completing at least 25% of the program with 30 ECTS. In both courses, students work in teams with an academic instructor. Graduate students have two options to work on a project: (1) They select a project and a scientific topic for research, which are announced by the academic instructors each semester. (2) Students submit a project proposal by themselves and ask the dual degree board for approval. In both cases, they write a report and present their work to both departments from the KAIST and the TU Berlin.

A letter of intent for a research-based project between the KAIST and the TU Berlin frames the cooperation in project-based course. The letter outlines the expectations and understandings of both institutions as they begin to define a relationship for a joint research project, and further stages of cooperation, for example, related to the future transportation systems applying wireless power transfer technology. After the signature of the letter by both institutions or their authorized representatives, the KAIST and the TU Berlin are cooperation partners in the field of green transportation system and technology, including conducting joint research, exchanging research progress as well as researchers and students. Both institutions together aim to seek for potential research funding. This cooperation can last for five to ten years and can be extended with the mutual agreement. Any concerns about the contents should be resolved through mutual efforts.

The new, transformed program includes mandatory courses with focus on **sustainable manufacturing**. The goal of this focus is to demonstrate the economic, environmental and social impacts of manufacturing activities. Educational courses and project-based courses, each around 5% among all courses within the whole program, are dedicated to sustainable manufacturing.

The **glocalization** focus of the industrial engineering program is highlighted by the global scope of sustainability issues. If each engineer contributes to sustainable manufacturing regionally, all together can cooperatively for the sake of a greater competitive advantage than the sum of individual solutions. Such synergies can be used to leverage the sustainable development on a global level. To enhance the required enhanced capabilities for sustainable manufacturing, it is essential for each student to gain some international experience during higher education in form of an international internship and exchange semesters abroad. All students must do an international internship between their first and second year, which is analog to the international internship for the TDU. The international internship is part of the KAIST’s commitment to identify capable students with a penchant for research and innovation. Students immerse themselves in another culture and experience a different way of education and life that could broaden their perspective through the exchange semesters.

An ideal case is if students leverage the project-based course, the scientific research in laboratory and their international internship with the master thesis. To select a subject for the master thesis, a conceptual formulation in English must be sent and approved by the dual degree board. Joint master thesis, supervised both by German and Korean academic staff, are preferred.

Students can take courses in English and Korean at the KAIST as well as in English and German at the TU Berlin. As a pioneer within the KAIST, the Department of Mechanical Engineering has increased the ratio of lectures taught in English in the last decade. From 2009, many graduate courses have been taught in English to eliminate any difficulties for foreign and exchange students. However, not all courses are offered in English. All courses, which are offered at both universities may change slightly in each semester. Dual degree students need to take at least one course in three languages German, English and Korean additionally. Almost 8% among the courses fall into the linguistics without any mandatory engineering and manufacturing specialization. A current list is provided by the dual degree board to the students, as presented in Table 8-9 in Appendix 8.3.2 for the fall semester 2015 and spring semester 2016.

By understanding the interdisciplinary and global challenges of sustainability through the new, transformed dual degree program in sustainable manufacturing between the KAIST and the TU Berlin, engineers learn and train taking the responsibility of developing local solutions in multiple courses and trainings, as presented in Table 8-9 in Appendix 8.3.2. Thus, the junior engineers should have enhanced capabilities after graduation to explore opportunities on the global labor market to practice and develop their career and talents.

5.1.3 **Future Work regarding Transformative Engineering**

Case studies demonstrate transformation of two educational programs in this section. Two best practice and two new programs are compared to evaluate the extent to which each attribute is followed by each program and the extent to which the identified deficit can be closed through education and training. The undergraduate and graduate industrial engineering programs, which are offered at the Georgia Tech in the USA since 1946 and at the TU Berlin in Germany since 1927, are selected as best practice programs in Section 2.2.2. Transformation of two educational programs is demonstrated and the attributes are verified between a set of countries: (1) The transformed undergraduate industrial engineering program, which has been offered at the TDU in Turkey since 2014, in Subsection 5.1.1. (2) The dual degree graduate program in sustainable manufacturing between the KAIST and the TU Berlin, which has been offered since 2010, in Subsection 5.1.2.

Board members, decision-makers in companies, non-profit and governmental institutions together compare the application of six attributes in educational programs. Table 5-5 presents the comparison of attributes’ fulfillment among the existing best practice and transformed programs including a completely fulfilled ideal case.

Both new educational programs apply transformative attributes to a higher extent than the established best practice in developed countries regarding the following aspects:

- Application of project-based elements, which are essential to enhance the role of teamwork and streamlined set of decisions and actions,
- Expansion of cooperation by strengthening the integrated innovation, in part by promoting sustainable value creation,

- Promotion of glocalization by facilitating training and experience with foreign institutions to enhance benchmark and competition, and
- Seek of accreditation from the engineering accreditation commission of the ABET to demonstrate that they satisfy all of the general criteria [ABE-15, p. 24].

Table 5-5: Comparison of attributes' fulfillment

Educational programs	Existing		Transformed		Ideal
Universities / **Attributes**	**Georgia Tech**	**TU Berlin**	**KAIST**	**TDU**	
Interdisciplinarity	●	●	●	●	●
Digitalization	●	◑	●	◑	●
Problem-solving	◑	◑	●	●	●
Projects	○	○	◑	●	●
Sustainability	○	◑	◑	●	●
Glocalization	○	○	◑	◑	●

Legend: ○ not directly applied, ◑ partly applied, ● completely applied

The comparison indicates that the existing best practice programs from the Georgia Tech and the TU Berlin fulfill the current attributes having similar scores in total. IT tools are integrated into educational programs at the Georgia Tech more than at the TU Berlin, while the TU Berlin highlights sustainability more than the Georgia Tech. Both programs remain limited, when the fulfillment of transformative attributes is considered.

The graduate dual degree engineering program between the KAIST and the TU Berlin performs better than the American and German best practice programs in glocalized, project- and sustainability-based attributes. The undergraduate program for the TDU transcends the fulfillment of the program between the KAIST and the TU Berlin in project- and sustainability-based attributes. The program for the TDU systematically integrates problem-solving and project-based elements into the whole educational program. It promotes sustainable value creation between Germany and Turkey in trainings, summer schools and internships. It is likely to enhance capabilities of industrial engineering to narrow the gap between these countries more than in any other analyzed educational program.

The framework for transformative industrial engineering can be used as a reference for transforming educational programs in and between many countries. Feedback from the transformed programs at the KAIST and the TDU can be investigated to improve educational programs and individual courses at the Georgia Tech, the TU Berlin and many other higher education institutions. The SWOT analyzes the different conditions, stakeholders and requirements according to political and socioeconomic context of each country separately. In other words, the framework is modular to apply to “what-if” questions for any set of countries and enable formulating any other possible solutions or elements for change. When searching for elements for a successful program, program boards should share both successful and failed examples. Successful examples may be best practices, however, failed examples can also provide various opportunities and help finding new solutions for partner countries [STE-15].

Implementing educational transformation is challenging, given its central role in every country and the magnitude of what is at stake. In Korea and Turkey, the high importance accorded to education makes transformation even more challenging. First, it is important to actively engage stakeholders, including students, parents, instructors, lecturers and managers of higher education institutions, in formulating and implementing responses. In particular, instructors and lecturers need reassurance that they will receive the necessary tools to be successful in further scientific career development. Second, it is necessary to clearly explain the underlying transformative attributes and goals of the transformation. Third, transformation should be based on clear evidence. Given the complexity of any higher education system, there are no simple action plans that can deliver major changes. Moreover, even with good policies, improved educational results usually take a long time to achieve, and clear evidence of the improvements even longer. Hence, all stakeholders ought to have realistic expectations about the possibility of achieving better results through education.

Transforming and implementing new educational programs is a long-term approach for sustainable manufacturing. Both case studies presented that the development of an educational program between a set of countries can provide an alternative path to the one followed by most countries. Thus, instead of providing plug-in solutions for a partner country, a new program is developed together in teamwork which should have sufficient leverage to connect advanced methodologies in technology and management with unique approaches for the regional implementation of sustainable manufacturing. In this way, the transformation supports to narrow the gap between these countries aiming at an equal distribution of social benefits and environmental burden in order to shift the focus on sustainable value creation.

Nevertheless, upgrading the education system is crucial, as even small improvements can have multiplier effects and significant positive impacts on sustainable value creation in practice. If transformative attributes are applied by new educational programs, it is likely to enhance the required capabilities by future engineers to create sustainable value. The more engineers understand the challenge of sustainable development, the more they find technological and organizational solutions. Further research should evaluate in detail whether the transformed programs with an interdisciplinary, IT-, problem-solving, sustainability-, and project-based glocalized focus demonstrate a new best practice, which is to be implemented throughout developed countries, for example, Germany and the USA.

With the focus on engineering profession in practice and research, the presented transformation may not include tools such as learnstruments to enhance an institution’s intellectual capital through new capabilities and cooperation. Learnstruments is a portmanteau, a made-up word coined from a combination of “learn” and “instrument”, describing tangible and intangible products or equipment, which automatically demonstrate their functionality to the user such as an operator in a factory, and provide adequate learning goals towards repetition and fulfilment of creation [Mus-15, p. 71]. Recent research investigates how learnstruments can demonstrate their functionality for users with various capabilities.

The framework for transformative industrial engineering must be further applied to other transformed engineering programs, and developed beyond the focus on practice and research in order to provide innovative tools how to enhance which individual engineering capabilities with which forms of education and training. Furthermore, the results in terms of the success of the programs should be monitored over multiple intakes of students and with multiple departments in research and higher education institutions. The verification should assign transformative attributes to learnstruments, education forms, identified capabilities of researchers, instructors and students. The results can be used to determine what is taught and learned to adjust forms of courses, educational programs and trainings as well as tasks for the school and program boards. Due to the fact that these questions are out of the scope of this research, the next section focuses on the practice. To what extent the practice of transformative industrial engineering through the enhanced capabilities meets the stakeholder requirements is verified by three project-based implementations in Section 5.2.

5.2 Verification of Value Creation in Manufacturing

The hypothesis from Chapter 4 proposes that the application of transformative attributes in educational programs can enhance engineering capabilities for sustainable value creation. These capabilities enable engineers to apply principles of sustainable manufacturing, when engineers implement the architecture for sustainable manufacturing in practice and research. Engineers who understand the economic, environmental and social impacts of value creation within the frame of local and global conditions, are capable of collecting data, analyzing, and designing value creation at every stage of development. This section investigates the hypothesis that transformative industrial engineers can implement methodologies in technology and management to create sustainable solutions and tests if they are capable of meeting the requirements better than the existing solutions. The architecture is applied to verify its universal applicability. Figure 5-10, which is an excerpt from Figure 4-1 in Section 4.1, presents how to verify the value creation through the architecture. Three industrial case studies demonstrate the multiplier effects resulting from the implementation of the approach for analysis and closed-loop synthesis, as proposed in Sections 4.2 and 4.4.

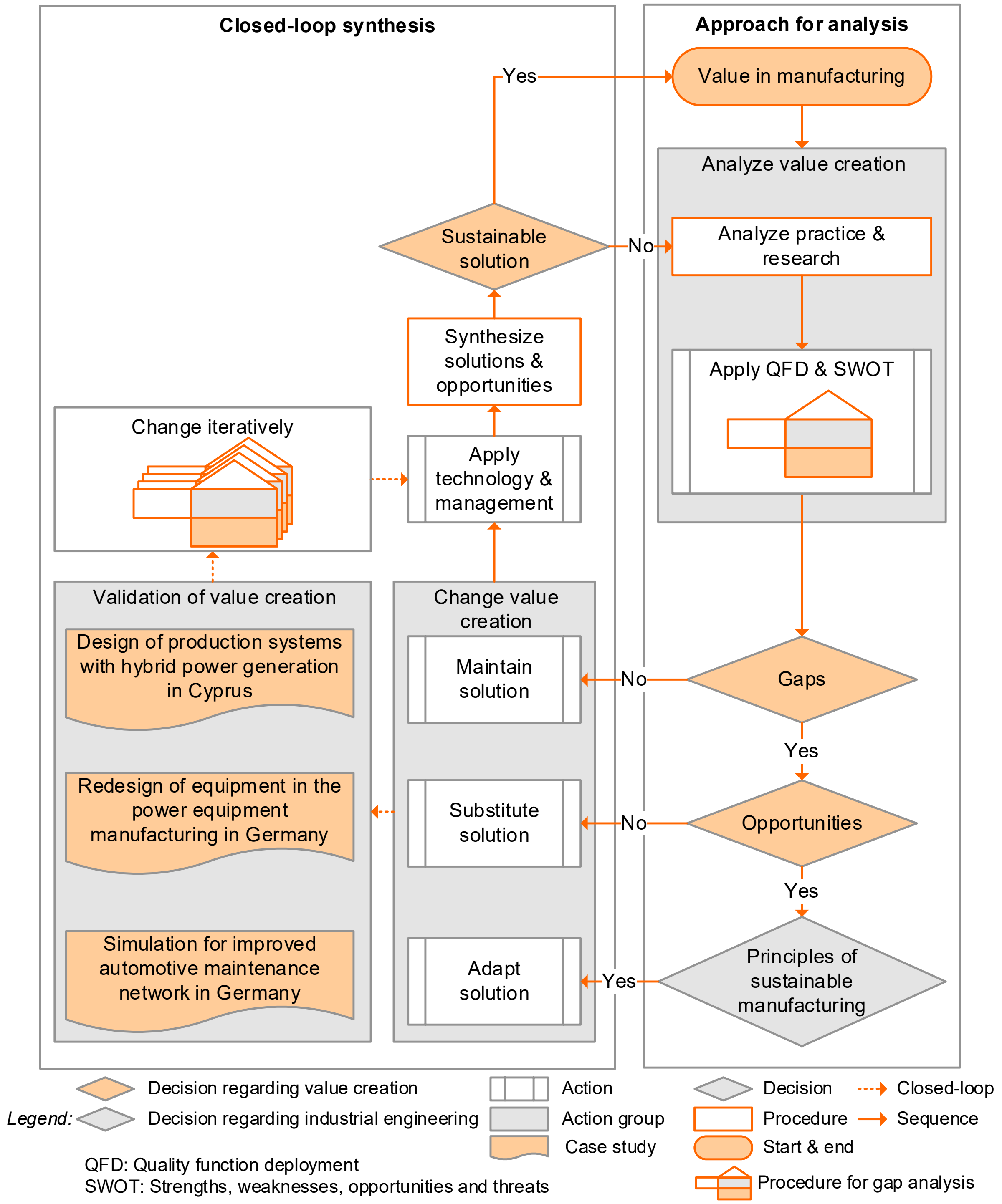


Figure 5-10: Verification of value creation through the architecture

For example, changeable and ergonomic solutions increase the functionality, productivity and resource efficiency of a certain value creation, and saves resources, time and capacities. Savings can have successive and magnified effects on a company in different ways. First, the initial injection of savings provides monetary benefits for the company. Second, the company can spend these savings to improve working standards of the workforce and provide professional trainings for the workforce how to balance economic, environmental and social impacts by any change. Third, the workforce in turn can explore other opportunities to create new solutions, while balancing impacts within the company as well as in the supply chain. Such decisions and actions spur successive rounds of changes and a multiple of the original savings. Generally, multiplier effects describe this cumulative sum of successive rounds how much one or more variables change in response to a change in other specific variables [Kha-95, p. 65].

The value creation in the case studies are analyzed based on the seven steps of the procedure for gap analysis. Sample goals and questions, which are used to identify and justify gaps and opportunities within a house of quality, are summarized below. Instructions on how to build a house of quality including all seven steps for a case study are given in Table 8-4 Appendix 8.2 and followed in Section 5.2 by verifying value creation in manufacturing. The analysis relies on the assumption that industrial engineers are aware of and committed to sustainable manufacturing. The framework of transformative industrial engineering is tested by applying different methodologies for the case studies in order to change and verify the value creation towards sustainability.

Sample questions are identifying **stakeholders in Step 1** are: *What capabilities does the project team need to create new solutions, which can cope with case-specific conditions, while sustainably improving value creation? Who are the main stakeholders?*

Each case study demonstrates an applied research project, which applies the transformative attributes to change value creation, while contributing to sustainable development. The researchers also instruct students within a project-based course, which supports the research project. Academic staff, students and other stakeholders work in close cooperation to achieve the predefined project goals. Researchers and students comprise the project team. The teamwork creates an overall better result than if each person within the group works toward the same goal individually.

The team also identifies case-specific stakeholders classified in three groups for data collection and verification. Compared to individual decisions and actions taken separately, unpredicted decisions and actions of the team together with stakeholders create an emergent synthesis, which is also known as synergy with a higher value than the sum of separate parts.

A sample question for identifying **requirements in Step 2** is: *What are the requirements of stakeholders? What is the importance of individual requirements or categories for stakeholders?*

The project team identifies the regional, sociopolitical and economic conditions and analyzes stakeholder requirements for creating value, for example, through a SWOT analysis. Requirements gathered from secondary data for recent research in sustainable manufacturing is verified with primary data gathered from the stakeholders in the three case studies. Primary data is collected through the following events: visits to institutions and companies as well as interviews, panel discussions, technical and committee meetings. Additionally, a questionnaire is sent to stakeholders. Sample questions are presented in Appendix 8.1.2. The importance of individual requirements or categories, cumulatively for all requirements within the category, are also justified. Around 30 requirements r_i, represented by the number n, have been confirmed and assigned to six categories c_k, where $k \in [1, \dots, 6]$, through the analysis of primary and secondary data for three case studies. Requirements are also assigned to some value creation factors based on their most relevant impact on the (1) economy, (2) environment, or (3) society for each case study, as presented in Appendix 8.1.2.

A sample question for synthesizing **solutions in Step 3** is: *What solutions do exist currently and could potentially be examined?*

Existing and potential solutions for value creation in manufacturing are listed.

A sample question for justifying **fulfillment in Step 4** is: *To what extent do the solutions fulfill each requirement?*

The SWOT analysis identifies relations among all solutions and requirements in order to justify the extent of the requirements' fulfillment by each solution.

A sample question for calculating **scores and targets in Step 5** is: *To what extent do the solutions fulfill all requirements and what is the target for the fulfillment?*

A further goal of the SWOT analysis is to determine the score and targets for each solution as well as reveal ideal cases.

A sample question for calculating **gaps in Step 6** is: *What are the differences between targets and scores for each solution? What gaps can be identified?*

The comparison of scores and targets identify the respective gaps. If no gaps are identified, the project team recommends stakeholders to maintain the existing solutions.

A sample question for identifying **opportunities in Step 7** is: *What are opportunities in order to fulfill the requirements at a higher level through change of value creation?*

If some gaps, but no opportunities are identified, the project team researches new potential solutions, which can substitute completely or partly the existing value creation. If opportunities are identified, the project team explores them in order to adapt within the frame of transformative industrial engineering.

The following three case studies follow this procedure to propose changes for value creation iteratively. In order to evaluate the impacts of the change and synthesize opportunities for new solutions, new concepts, models, simulations and prototypes are developed and tested by applying different methodologies in technology and management. Table 5-6 presents an overview of which methodologies are used in which context for verifying the value creation in these case studies. The scope of change moves from supporting strategic decision-making to supporting tactical and then operational decision-making with the first to third case studies.

The third case study demonstrates an adaptation of a value creation factor, the second one a substitution of a value creation module, and the first one combines both change approaches for a production system.

- To address the sustainability challenge through the identification of regional conditions, the initial state of an agricultural production is modeled and a new production system is designed conceptually in one of the least competitive European countries in Subsection 5.2.1. This case study exemplifies manufacturing as the second product life-cycle stage for agricultural production within the process industry. A hybrid and adaptable product-service system is created for value creation modules such as power and water generation to substitute existing solutions. Innovative design approaches of most competitive western countries such as Germany and the USA are used to assembly a mobile and modular factory which can operate efficiently and effectively by changing conditions.

The adapted methodology is verified through two further case studies that demonstrate how to redesign equipment and value creation networks in Germany. Both case studies address tangible and intangible products in use as the third product life-cycle stage.

- Computer-aided design (CAD) tools are used to redesign the handling equipment for transportation and protection of components of high-value products in the power equipment manufacturing in Subsection 5.2.2. The redesigned equipment should be modular and ergonomic substituting the existing solutions. This case study exemplifies how a tool can be designed to ensure safe remanufacturing processes of high-value components in post-use at the last life-cycle stage. The analysis of remanufacturing of components as a value creation module shifts the focus to equipment as a value creation factor aiming at an ergonomic and flexible handling equipment. Resources such as machine, equipment, and components are planned with compatible and modular interfaces to increase the scalability and efficiency of men and machine interaction. Potential solutions are evaluated analytically and tested experimentally.

Figure 5-11 gives an overview of the variables applied to analyze gaps of current solutions and evaluate potential of new solutions.

Table 5-6: Overview of the case studies for verifying the value creation

Case study title	***Hybrid Production System***	***Power Equipment Manufacturing***	***Automotive Maintenance Network***
Subsection	5.2.1	5.2.2	5.2.3
Change of value creation	Adaptation and substitution	Substitution	Adaptation
Scope of change	Strategic	Tactical	Operational
Time scope	Year	Month	Day
Change approach	Conceptual	Analytical and experimental	Heuristic
Scope of case study	Production system	Value creation module	Value creation factor
Characteristics	Hybrid and adaptable product-service system	Ergonomic and flexible handling equipment	Reconfigurable scheduling
Focus of change	Value creation module	Value creation factor	Feature
Sample	Water and energy generation	Transportation, storage, protection	MRO planning and scheduling
Scope of product	Product-service	Tangible equipment	Service
Product life-cycle stage	Manufacturing	Use	Manufacturing
Process life-cycle stage	Design	Redesign	Simulation
Methodology	Conceptual design	Redesign with CAD tools	Material flow simulation with IT tools
Equipment life-cycle stage	Operation	Design	Maintenance
Scope of process	Processing	Manufacturing	Delivery of service
Sector	Primary and secondary	Secondary and tertiary	Tertiary
Sample	Agricultural production	Remanufacturing of turbine blades	Automotive maintenance
Scope of equipment	Factory	Tool	Station
Scope of organization	Production system design	Manufacturing resource planning	Production planning and control
Characteristics	Mobile and modular	Compatible and modular	Effective and efficient
Scope of people	Farmer, investor, entrepreneur	Operator and engineer	Operator, driver, engineer
Impacts	Economic, environmental and social	Economic, environmental and social	Economic
Scope of efficiency increase	Energy and resource efficiency	Resource efficiency	Resource efficiency

						Category $c_1(o_j)$	
						Solution	
						AS-IS	TO-BE
Category	*Importance*	***Requirement***	*Importance*	***Indicators***	*Importance*	o_1	o_2
$c_1(r_i)$		r_1	$p(r_1)$			$s(r_1,o_1)$	$s(r_1,o_2)$
				w_1	$p(w_1)$	$s(w_1,o_1)$	$s(w_1,o_2)$
						$b(w_1,o_1)$	$b(w_1,o_2)$
	$p(c_1)$					$s(c_1(r_i),o_1)$	$s(c_1(r_i),o_2)$
					$S(o_j)$	$S(o_1)$	$S(o_2)$
					$t_{min}(o_j)$	$t_{min}(o_1)$	$t_{min}(o_2)$
					$t_{max}(o_j)$	$t_{max}(o_1)$	$t_{max}(o_2)$

Legend:

$b(w_z,o_j)$	Value of the *zth* evaluation criteria for the *jth* solution
$c_h(o_j)$	*hth* category of the *jth* solution
$c_k(r_i)$	*kth* category of the *ith* requirement
o_j	*jth* solution
$p(c_k)$	importance of the *kth* category
$p(r_i)$	importance of the *ith* requirement
$p(w_z)$	importance of the *zth* evaluation criteria
r_i	*ith* requirement
$s(c_k(r_i),o_j)$	Significance which describes the fulfillment of the *kth* category by the *jth* solution
$s(r_i,o_j)$	Significance which describes the fulfillment of the *ith* requirement by the *jth* solution
$s(w_z,o_j)$	Significance which describes the fulfillment of the *zth* evaluation criteria by the *jth* solution
$S(o_j)$	Score of the *jth* solution
$t_{max}(o_j)$	Maximum target of the *jth* solution
$t_{min}(o_j)$	Minimum target of the *jth* solution
w_z	*zth* evaluation criteria

Figure 5-11: Analysis scheme for the case studies

- IT tools are applied to simulate the material flow in an automotive maintenance network of the urban service sector for delivery of services such as cleaning and waste management in Subsection 5.2.3. This case study exemplifies how change of production planning and control can influence the efficiency and effectiveness of a maintenance network through reconfigurable scheduling of orders for maintenance as third life-cycle stage of equipment during the provision of services. Heuristics are used to determine solutions for a combinatorial problem such as the vehicle routing problem [Mak-14a, p. 764]. Inputs of the simulation are heuristic, which specify the features such as operating and failure time as well as number of vehicles per workshop. A simulator integrates these data into a model of the network, including the rules as to how the features interact with each other. After the initial state is identified, the simulator follows the operation of the model over time, tracking events such as overload and bottlenecks. The output provides a set of statistical data about the performance of the network and supports the verification of potential solutions. In Subsection 5.2.4, concluding observations are based on the scores to verify the extent of methodologies to which each case study contributes to sustainable value creation, the extent each case study applies the transformative attributes through engineering capabilities, and what further work is needed in the future.

5.2.1 **Design of Hybrid Production Systems in Cyprus**

The design and operation of production systems affects the production performance and should support achieving competitive advantages, while creating sustainable value [Suh-98, p. 228 f.]. Implementation and research of sustainable manufacturing requires the combination of engineering capabilities from different disciplines. CRCs are long-term university-based research projects, established for up to 12 years mainly in developed countries. Interdisciplinary researchers work together within a research field in the frame of a CRC. A CRC can also include national, regional and international cooperation with industrial, research and higher education institutions [DFG-16].

The CRC 1026 combines 19 individual research projects from engineering disciplines including manufacturing technologies, product development, sustainability engineering, mathematics, education, and economy to investigate solutions for sustainable manufacturing. The overall goal of the project, which is named “integration shop” within the CRC 1026, was to develop a methodology for description, assessment and configuration of resource-efficient solutions. The project also aims to actively empower local people through gain of enhanced capabilities and intense training to help themselves following the approach help for self-help [CRC-16].

This case study presents an international subproject which is part of this research project within the CRC 1026. The architecture for sustainable manufacturing is tested to verify that the architecture creates a sustainable solution for a production system in a crisis-ridden region of southern Europe. The overall goal of this subproject is to provide technological solutions for sustainable value creation through transformative industrial engineering. Compared to a random solution, which focuses on economic impacts of value creation, the proposed solutions should balance economic, environmental and social impacts and increase local added value more effectively, which also contributes to sustainable value creation.

Cyprus was selected as the implementation area due to extreme conditions by international trade barriers and major effects of climate change. Global challenges and the island's local conditions were analyzed according to Geddes' concept [Agu-11, p. 2299]. The analysis of Cypriot value creation shifted the focus to agricultural production. Preferences for planted harvest goods and availability of renewable resources for regional production were analyzed in order to determine conditions and the current position of Cypriot agriculture in global markets. After the analysis of gaps and opportunities, a new production system was designed and verified by iterative changes.

5.2.1.1 **Step 1: Multinational Stakeholders**

The Middle East Technical University (METU) in North Cyprus has been involved with the CRC 1026 network since 2012, which is presented in Subsection 2.1.1. The METU has served as a forum for international research on sustainable manufacturing since then.

The team for the subproject, hereafter called the project team, was made up of international students: six from Germany, four from Cypriot, two from Turkey, one from Spain, and one from India; seven international researchers. The team involved fourteen graduate students from the departments of Manufacturing Technology, Industrial Engineering, Mechanical Engineering, Sustainable Environment, Renewable Energy Studies, Computer Engineering for Data Collection and Analysis.

The goals of the project regarding the enhancement of engineering capabilities were to

- train students in critical thinking through combining technological solutions by addressing principles of sustainable manufacturing,
- create empathy in order to increase the ability for recognizing and responding to the needs and requirements of stakeholders within the frame of regional conditions,
- raise awareness for synergies and trade-offs within the ecosystem in order to improve the value created in Cypriot production systems,
- promote innovation and entrepreneurship to engage stakeholders, and
- demonstrate developed applications and their competitive advantages.

The following groups were identified among around 20 stakeholders: (1) farmers, who harvest olives, nuts, and pomegranates; (2) mill owners or operators of juice presses, who process the harvest; (3) public officers from governmental institutions, who organize trade regulations in ministries for agriculture, natural resources, economy, energy; (4) directors from research institutes and laboratories, pump and generators, and non-governmental organizations, for example, wind energy system providers and chiefs of agricultural producers' unions, who provide services, analyze and support agricultural production.

Public data from both states on the island, the Turkish Republic of North Cyprus (TRNC) and the Republic of Cyprus, as well as from international institutions and different investigators, had significant variations, for example, about gas discoveries in the northern and eastern basin of the Mediterranean Sea. Limited data was provided by the Ministry of Agriculture and Natural Resources Statistics in the TRNC, from the Planning Division of the Department of Meteorology in the Republic of Cyprus [CY -16] and from the European Climate Change, Hydro-conflicts and Human Security Report [Bru-12b, p. 5]. The lack of standardization in environmental data management and the poor resolution of measured data made it necessary to carry out detailed questionnaires with stakeholders [Eme-15, p. 1823].

5.2.1.2 **Step 2: Cypriot Conditions and Requirements**

The regional conditions in Cyprus describe the political, social, economic and environmental limitations on the island before the determination of requirements.

In political context, Cyprus has been governed by the Republic of Cyprus since the independence from the United Kingdom was proclaimed in 1960. The British government imposed power-sharing between Greek and Turkish Cypriots as a condition for island's independence [Güs-14]. Greece, Turkey, the United Kingdom and the United Nations have offered governmental and economic subsidies since the Cypriot independency. The sociopolitical situation has been exacerbated by the political and ethnical division into Greek and Turkish sectors since the outbreak of civil war between Greek and Turkish Cypriots soon after the independency. Cypriot ethnic violence reached a crisis on several occasions between 1960 and 1974. After the invasion of Cyprus by the Republic of Turkey in 1974, a buffer zone of United Nations has separated two sectors on the island. The Greek sector in the south part has remained to be governed by the Republic of Cyprus, whereas the Turkish sector has been governed by the Republic of Northern Cyprus since 1983. Hereafter, Cyprus is used to describe the complete island, and North Cyprus to describe the Turkish sector in the northern part.

In social context, the period of Cypriot civil war has caused a generation with deep mutual hostility and mental diseases [The-16]. This generation has focused on private well-being rather than on a sustainable development of the society. Ethical values have been based on the well-being of individual families, and disregarded entrepreneurial and creative spirit.

In economic context, while the Greek sector is an internationally recognized member of the European Union since 2004, the Turkish sector is recognized by no country worldwide except Turkey. It is diplomatically, politically and economically isolated from the world by international trade sanctions and travel embargoes. Lack of international recognition and trade barriers have depressed economic performance in North Cyprus. For example, the leading sector of the North Cypriot economy is higher education with students from more than 100 countries. However, the Cypriot higher education institutions are blocked from participation in programs based on intergovernmental agreements, for example, the Bologna Process and the Erasmus Program [Güs-14]. To reverse this distressed situation, renewed efforts for a negotiated settlement started in 2014. A joint declaration can reopen the Cypriot market to free trade and capital flows worldwide promoting the entrepreneurial activities [WEC-15a, p. 16].

In environmental context, the impact of climate change on agricultural production and the decreasing availability of energy and fresh water are no longer an issue confined to underprivileged and rural areas. “For example, in many countries in southern Europe the increasing frequency of natural disasters heavily impacts agricultural production through damage to property and infrastructure, which leads to lost productivity” [Eme-15, p. 1817]. The awareness of sand forecasts for future limitations triggered by changed dynamics of the ecosystem requires a paradigm shift in traditional food industries [WWA-14, p. 80].

Since the last four decades, Cyprus has suffered from a chronic shortage of water. The average annual precipitation from 1970 to 2015 in Cyprus was 470 mm, as compared to 543 mm from 1901 to 1969 [CY -16]. As presented in Figure 5-12, very dry periods rarely occurred.

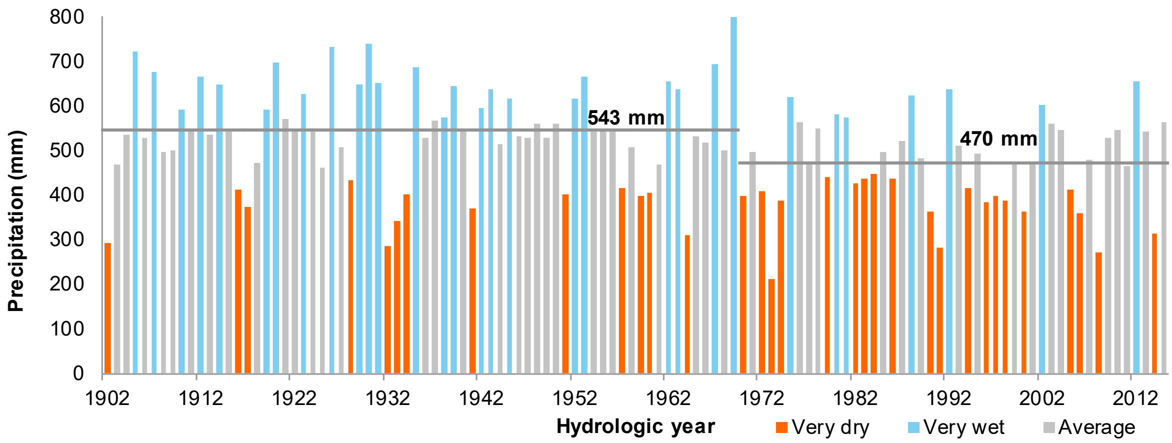


Figure 5-12: Annual precipitation over Cyprus from 1902 to 2015

Over the past quarter century, the average annual precipitation decreased to 466 mm. While the average annual precipitation over the century is almost stable, the yearly rain period has been shrinking from 4-5 months to 2-3 months. This brings regional floods more often and causes an insufficient regeneration of the ground water level [Bru-12b, p. 5 ff.].

The sinking ground water level from a depth of 40 m to a depth of 100 m and increased salinity during summer time are two of the main effects of climate change over the past quarter century. Since 1960, over 80 dams with water capacity of more than 300 million m^3 have been built in Cyprus. Since dams are partly recharged with ground water, they also affect the sinking ground water levels in North Cyprus. This causes a progressive deterioration of the water situation in North Cyprus, which now has a capacity for less than 20 million m^3 annually.

The production of agricultural goods in North Cyprus has been mainly hampered by scarce water resources and rising energy prices. Climate changes trigger regulatory and economic counteractions, for example, rising electricity prices, fuel costs for pumping ground water for irrigation and investment in new, deeper wells, including new filter technologies. Electricity prices for industry and annual consumer prices for fuel in North Cyprus have increased over 200% in the last decade [Eme-15, p. 1817]. As prices increase, diesel generators are used to operate water pump systems for irrigating plants over a five-month dry period in summer from May to September annually by farmers.

These conditions have increased the local agricultural production costs and decreased the competitiveness of Cypriot goods on global markets [Eme-15, p. 1817]. Further results are higher CO_2 emissions per product, lower local added value, and increased unemployment. Requirements are specified to overcome these conditions by changing the agricultural production. All requirements related to these conditions are assigned to some value creation factors based on their most relevant impact on the (1) economy, (2) environment, or (3) society in Table 8-10 in Appendix 8.4.1. Requirements within each category are described in the following subsections following the assignment to the categories of requirements.

Easy access to production facilities, for example, olive presses, is essential for farmers to gain a competitive advantage. “The shorter the time between harvest and pressing, the higher the quality of olive oil” [Eme-15, p. 1823]. Easy transportation of production facilities to different harvest regions can enable a high mobility of the production system and indicate a superior flexibility of the solution. Mobile, modular and scalable production facilities are required for a **changeable** production system.

Both harvest quantity and the duration of individual processes determine the demand of each farmer. In Cyprus, both efficiency and effectiveness can be increased through an innovative design of production facilities to process agricultural goods with high **productivity**. Less resources, higher speed and less waste save money, time and resources. The new production system should be affordable with low investment and life-cycle costs, little space utilization and increased degree of capacity utilization in terms of time. The challenge is to model precisely the real demand of harvest goods as well as accessibility to renewable resources with variable seasonal availability.

Functionality can be increased by fulfilling farmers' needs to a higher level within the frame of Cypriot conditions. IT-based services support generation, analysis and distribution of information, and can increase the efficient use of resources following the 6R approach.

Use of regional, low priced and renewable resources for energy generation and water supply substitute non-renewable and expensive resources. This approach enables the access to clean water over dry seasons, protects ground water level as well as applies technologies to reuse the waste. Environmental impacts, for example, CO_2 emissions, are measured to evaluate the increase of **resource efficiency**.

Despite the current high unemployment rates, the Cypriot workforce, including farmers, has a high level of education. Since the beginning of the 20th century, Cypriot youth completed higher education mostly in Commonwealth countries founded by the British Empire as well as in British, Greek, Turkish, other European and North American universities. The entrepreneurial spirit has not been supported and, after graduation, most youths became public officers on the island.

Farmers can learn easily how to use and share production facilities and generated renewable energy by increasing awareness for sustainable value creation. Application-based software can train farmers through simple use of IT tools how to improve the capacity utilization and knowledge share to create synergies.

The degree of **stakeholder engagement** can be estimated by the existence and extension of win-win-situations; increased freedom of action for farmers; social well-being and direct contact to customers worldwide. Raising awareness about how agricultural production can contribute to sustainable value creation by a wide range of stakeholders can stimulate further innovations, for example, for the development of sustainable solutions for the higher education or tourism sectors on the island.

5.2.1.3 **Step 3: Existing and Potential Solutions for Agricultural Production**

Based on the current position of the Cypriot agricultural goods in global markets, existing production systems are analyzed to identify which processes add more value to the harvest. For example, making jam and pressing juice out of fruits are compared processes.

Potential harvest goods, which have a huge potential for more local added value through production, are olives, almonds, pomegranate, and citrus fruits. The annual average harvest in North Cyprus between 2006 and 2010 was about 4000 tons of olives, 600 tons of nuts, 800 tons of pomegranates and 150,000 year of citrus fruits [TRN-11]. The water demand of olive or almond trees is ten times less than that of citrus fruits [Eme-15, p. 1818].

The biological harvest can be processed into different value-added agricultural products. The pomegranate fruit sold in north Europe in 2015 for around 2 EUR/kg, the peeled pomegranate seeds are sold for 4 EUR/kg, and its juice sells for 6 EUR/kg. Pomegranate syrup sells for 50 EUR/kg and pomegranate oil for 200 EUR/kg. The more value is added through processing, the higher the market price is. Furthermore, certificate of CO_2 neutral production as well as fair-trade and organic certificate increase the market prices [Eme-15, p. 1819]

The project team analyzed an annual production period of six months; each month contains thirty days, each day contains two shifts, and each shift covers seven working hours. There is no processing of agricultural goods in the other six months, while energy and water is still needed for irrigation. In Cyprus, electricity can be provided from non-renewable and renewable resources. Water can also be generated from air. The modeling and simulation results show that on an hourly basis, 200 kg of olives are processed into 50 kg of olive oil, which are sold at a retail price of 2.50 EUR/kg by a 100% sales success. For a production capacity of 3 tons of olives per day, the simulation shows maximum energy consumptions of 12.3 kW including 3.9 kW for water generation, 4.6 kW for the processing of harvest and 3.8 kW for the recycling of produced organic waste and wastewater [Eme-15, p. 1823].

The subtropical Mediterranean climate on Cyprus provides a huge potential for solar energy with a substantial 326 days of sunlight. In summer, the daily solar irradiance is about 7 kWh/m^2, which is as high as locations near the equator. In the winter, the daily solar irradiance lies at 3 kWh/m^2, which is as much as the daily average solar irradiance for Germany over an entire year. Wind energy is not directly accessible on the island, although mountain or coastal areas have potential for wind energy [Eme-15, p. 1818]. Lack of comprehensive measurements hindered wind potential analysis in detail for this research. The average wind speed in Cyprus is 3.3 m/s and lower compared to Hamburg, Germany with, for example, 4.35 m/s. The wind speed variation for the coastal region over a day is on average 2.5-6.3 m/s [TRN-11].

A decision tree, as illustrated in Figure 5-13, is applied to list existing solutions and identify potential solutions for each value creation module through interactive discussions with relevant stakeholders. Each node of the decision tree addresses at least one requirement regarding at least one value creation module. Existing and possible solutions present branches for each module, which can be combined to different configurations for the agricultural production system (APS) in order to verify synergies. Input materials, for example, available solar radiation, are slightly changed to develop multiple APS configurations. To simplify the simulation through justification of solutions and their consequences, one input material is changed, while all other inputs are fixed so that they do not affect the output.

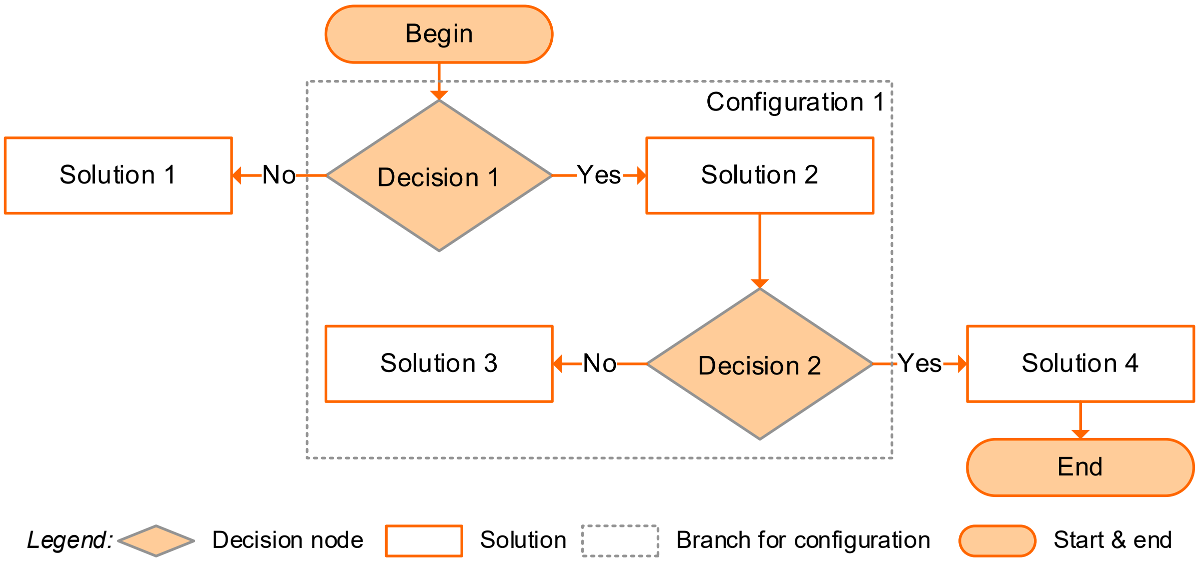


Figure 5-13: Sample decision tree

Following the value creation architecture, as presented in Subsection 2.1.1, the Cypriot APS consists of five value creation modules: production, business, recycling, water and energy. Each value creation module provides a service for the APS, as presented by $VCF_1 = product$, to enable processing of local goods, for example, olive oil. The titles of value creation modules define the technological processes of water and energy generation, crops processing, recycling and the organizational process of business administration, as presented by $VCF_2 = process$. The modules, including the equipment and production facilities, enable processing of harvest goods and resources, as presented by $VCF_3 = equipment$. The whole APS can be scheduled and booked as a production facility, if necessarily indicated by a product-service system, as presented by $VCF_4 = organization$. Due to its intermodal functionality, the organization, hereafter referred to as business module, integrates all other modules into an APS. Main stakeholders are farmers, operators and entrepreneurs, as well as engineers, as presented by $VCF_5 = people$.

5.2.1.4 **Step 4: Fulfillment Levels**

The analysis of Cypriot conditions and requirements indicates the inextricable link between the water and energy demands of regional production systems [Eme-15, p. 1819]. As many others semi-closed ecosystems in southern Europe, the island is significantly affected by climate change. Restrictions imposed by trade barriers indicate that the entrepreneurial freedom of action in Cyprus is extremely limited. By comparing the relations between requirements and solutions, oil production from crops is proposed by the local stakeholders as the process with the highest local added value. However, the competitiveness of the Cypriot agricultural oil production in international markets are endangered by the existing solutions. The fulfillment of the identified requirements by existing solutions is very limited in comparison to the new solutions, as compared in detail in the next subsection.

Despite the sociopolitical conditions and economic limitations, the existing Cypriot value creation must change to overcome effects of climate change on the island. The seasonal availability of renewable resources and geo-political limitations are to overcome with new technological solutions, which must be developed, assessed, implemented and continuously improved to adapt to changing conditions [Eme-15, p. 1817]. According to the analysis, scalability and modularity combined with an efficient and effective APS can provide better agricultural goods and increase the local competitiveness of farmers.

Based on the simulation results, the output, for example, generated electrical energy, water and olive oil, is analyzed and economic, environmental and social impacts of the configurations on the ecosystem are justified. Evaluation of the solutions for verifying the value creation modules are processed sequentially, as presented in Figure 5-14 briefly and extended into a decision tree in Figure 8-4 in Appendix 8.4.1.

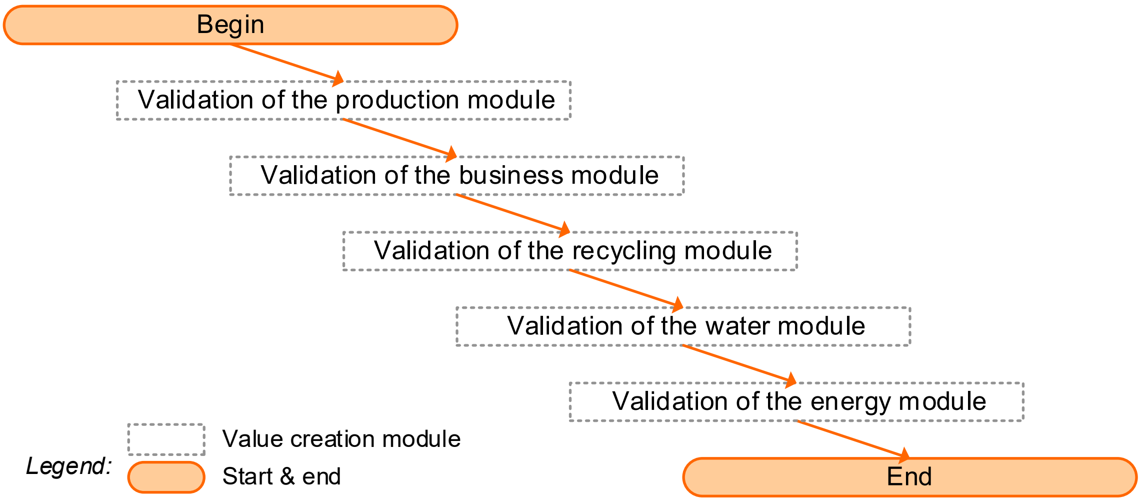


Figure 5-14: Sequential verification of the value creation in the APS

The development and evaluation of existing and potential solutions for each module are repeated, one step at a time, until there remains an acceptable solution, for which the evaluation results indicate a sustainable solution. The six following questions, each represented by a node in the decision tree in Figure 8-4 in Appendix 8.4.1, test a requirement's fulfillment by each solution, as presented by Table 5-7.

Table 5-7: Questions to justify solutions for value creation modules

Value creation module	*Related question*	*Evaluation in Table*
Production	Is easy access to production asset possible?	Table 5-10
Business	Is a product-service system provided?	Table 5-11
	Is the product-service system supported by an IT-tool?	Table 5-12
Recycling	Is a closed-loop system provided?	Table 5-13
Water	Is a sustainable water generation provided?	Table 5-14
Energy	Is a sustainable energy generation provided?	Table 5-15

Since there are varying degrees of fulfillment, a three-level scale is used to identify the significance of a fulfillment, as presented in Equation (4) in Subsection 4.2.1. For the production, business, and recycling module, a fulfillment of a requirement is marked with ☒. A nonfulfillment is marked as ☐. The score of the category depends on the fulfillment of the requirements belonging to a specific category, whereas the number of related requirements varies. Table 5-8 presents the indication of the category's value to fulfillment levels. The assignment of fulfillment are interchangeable among the requirements r_i.

Table 5-8: Indication of values to fulfillment levels for a category ($i \leq 3$)

Value of the requirement	***Notation***		
	$s(r_1, o_j)$	$s(r_2, o_j)$	$s(r_3, o_j)$
$s(c_k(r_i), o_j) = 0$	☐	☐	☐
$s(c_k(r_i), o_j) = 1$	☐	☐	☒
$s(c_k(r_i), o_j) = 3$	☐	☒	☒
$s(c_k(r_i), o_j) = 9$	☒	☒	☒

Further details for justifying and scoring solutions is given in Appendix 8.4.1.

5.2.1.5 **Step 5: Scores and Targets of the New Production System**

Scores and targets of existing and potential solutions for each value creation module are calculated according to each question and described in the next subsections. Table 5-9 presents the most relevant factor specifications for each module for the whole APS.

The set of proposed solutions for all value creation modules synthesizes a new APS, which presents the selected path over all nodes in Figure 8-4 in Appendix 8.4.1 compared to another solution. Technological solutions for five value creation modules within the APS are described to demonstrate how to increase the local added value by fulfilling the local conditions and stakeholder requirements.

The demonstration starts with the **verification of the production module**, which is the central asset of the system. Energy and water are created as needed in the production module by the respective modules. Following traditional methods, olives are pressed, centrifuged, and filtered in olive mills for the extraction of their oil [Eme-15, p. 1820].

A production module is classified according to the geographic distribution of facilities into a (1) centralized or (2) decentralized container, for example, to press olive or nut oil as well as orange or pomegranate juice.

Table 5-9: Specification of Cypriot value creation for agricultural production

Value Creation Module	***Value Creation Factor***				
	$VCF_1 = product$	$VCF_2 = process$	$VCF_3 = equipment$	$VCF_4 = organization$	$VCF_5 = people$
Production	Olive oil or pomegranate juice	Cleaning, separation, press and packaging	Mill, malaxer, decanter and separator	Seasonal production planning depending on harvest	Farmer and production planner
Business	Booking, scheduling and engagement	Operation of the APS	Conventional control units or extended software applications	Listing or optimizing the capacity utilization	Farmer or operator
Recycling	Solid waste in pellets, water and fertilizer	Drying, pressing, centrifuging and ultrafiltration	Belt dryer, pelleting press, separator, and nano-filtration	Seasonal production planning synchronized with production	Operator
Water	Water	Condensation	Cooling compressor, heat exchanger, humidity condenser, fan and water tank	Daily production planning and distribution depending on demand	Operator and farmer
Energy	Electrical energy and heat	Photoelectric effect, electromagnetic induction, combustion and storing	Solar panels, wind turbine, generator, battery and combustion chamber	Daily production planning, configuration of energy mix, distribution and storage depending on demand	Operator and distributor

The existing facilities are centralized and located in multiple towns in Cyprus. To guarantee a high quality for the olive oil it is necessary to process the harvested goods within 24 hours, which is an advantage of the approach “local for local”. Following the comparison of both solutions, the decentralized production indicates a modular and mobile design for the APS. A scalable production capacity for small and big amounts of harvest and well-coordinated schedule are also crucial. Modular and mobile APS is a well-fitting solution to attain the Cypriot requirements.

Thus, the production system is divided into four independent value creation modules in separate containers following the approach of mini-factories with scalable capacities. All value creation modules of the APS have the standard design of shipping containers of 6-16 m, as established by the International Organization for Standardization according to the ISO Norm 668 [ISO-13]. Each container can be defined as a mini-factory, as all equipment required for a certain product is included in the container. Decentralized production saves time and transportation costs with local production planning and operation close to the harvest area. The modular design of the APS increases the changeability in order to adapt the value creation to the changing conditions, as presented in Table 5-10, which illustrates all notations and variables in detail.

Table 5-10: Evaluation of the changeability for the production module

House of quality for the production module			***Category***	
			$c_1(o_1) = AS\text{-}IS$	$c_2(o_2) = TO\text{-}BE$
			Solution for production facilities	
Category	***Importance***	***Requirement***	$o_1 = centralized$	$o_2 = decentralized$
$c_1(r_i) = Changeability$		$r_1 = High\ modularity$	$s(r_1, o_1) = "-"$	$s(r_1, o_2) = "+"$
		$r_2 = High\ mobility$	$s(r_2, o_1) = "-"$	$s(r_2, o_2) = "+"$
		$r_3 = High\ scalability$	$s(r_3, o_1) = "-"$	$s(r_3, o_2) = "+"$
	$p(c_1) = 9$	$s(c_1(r_i), o_j)$	$s(c_1(r_i), o_1) = 0$	$s(c_1(r_i), o_2) = 9$
		$S(o_j)$	$S(o_1) = 0$	$S(o_2) = 81$
		$t_{min}(o_j)$	$t_{min}(o_1) = 20$	$t_{min}(o_2) = 40$
		$t_{max}(o_j)$	$t_{max}^{AS-IS}(o_1) = 40$	$t_{max}^{TO-BE}(o_2) = 81$

The proposed mobile APS including material and energy flows with a decentralized production module is presented in Figure 5-15. "The bio-waste is dispatched to the recycling module, and converted into pellets for later use, for example, in the energy module. The wastewater produced from cleaning the olives and from the secondary centrifugation of olive oil is redirected back to the water recycling module for purification" [Eme-15, p. 1820].

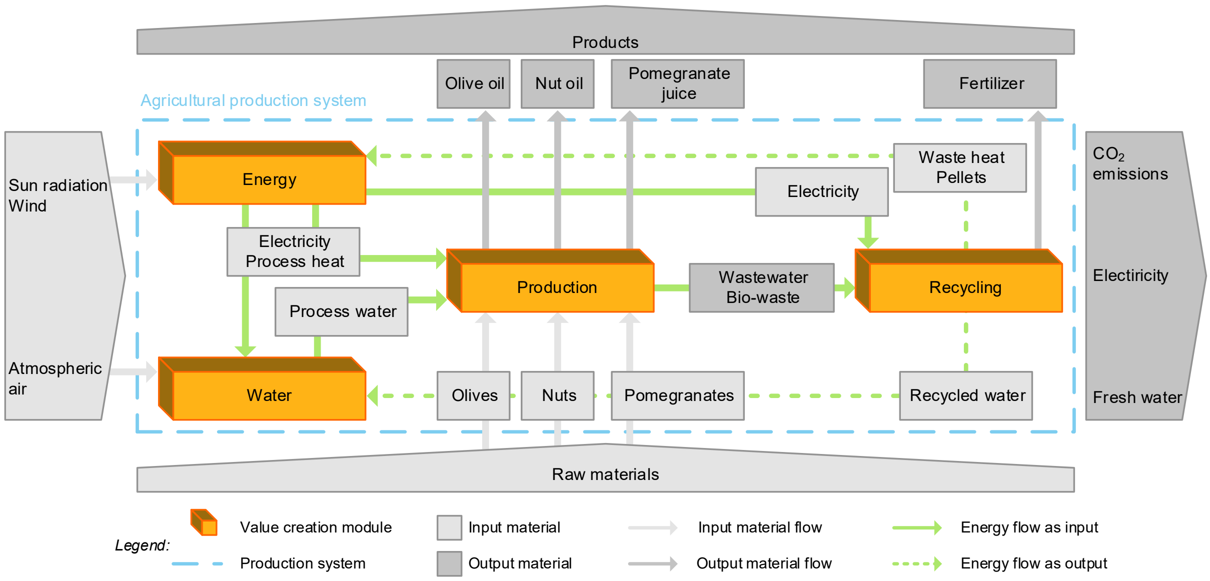


Figure 5-15: Agricultural production system including material and energy flows

To implement the proposed solution with containers in Cyprus, a business module integrating multiple stakeholders into the value creation is needed. The **verification of the business module** is based on Cypriot requirements. The project team has analyzed how to operate the APS and how to control the operations of the APS.

The APS can operate as a stand-alone or as a shared unit. Both solutions are evaluated in Table 5-11 with simplified notations, as presented in Table 5-8: (1) A stand-alone unit as a product provides four value creation modules in containers, which can be sold to operator or farmers completely. Thus, the APS is available for an individual farmer at a time and in sequence for multiple farmers. (2) Provision of the functionality instead of the product as a stand-alone unit presents a PSS, which is called APS sharing as a solution [Mei-10, p. 607 ff.]. A PSS can offer services to generate energy and water, to process goods, and to recycle emissions separately. Thus, the production module of the APS is available for an individual farmer, while all other modules and services can be provided to multiple farmers at the same time.

Table 5-11: Evaluation of product-service system approach for the business module

House of quality for business module regarding the product-service system approach			***Category***	
			$c_3(o_3) = AS\text{-}IS$	$c_4(o_4) = TO\text{-}BE$
			Solution for operating facilities	
Category	***Importance***	***Requirement***	$o_3 =$ $stand\text{-}alone\ unit$	$o_4 =$ $APS\ sharing$
$c_1(r_i) = Changeability$		$r_4 = High\ modularity$	$-$	$+$
	$p(c_1) = 9$	$s(c_1(r_i), o_j)$	0	1
$c_2(r_i) = Productivity$		$r_5 = High\ capacity\ utilization$	$-$	$+$
		$r_6 = Low\ investment\ costs$	$+$	$-$
	$p(c_2) = 9$	$s(c_2(r_i), o_j)$	1	1
$c_3(r_i) = Functionality$		$r_7 = High\ satisfaction$	$+$	$+$
		$r_8 = High\ added\ value$	$-$	$+$
	$p(c_3) = 3$	$s(c_3(r_i), o_j)$	1	3
$c_6(r_i) =$ $Stakeholder\ engagement$		$r_{29} = Upgrading\ know\text{-}how$	$-$	$+$
		$r_{30} = Creating\ win\text{-}win\ situations$	$-$	$+$
	$p(c_6) = 3$	$s(c_6(r_i), o_j)$	0	3
		$S(o_j)$	12	36
		$t_{min}(o_j)$	15	31
		$t_{max}(o_j)$	31	63

The sharing of the APS by multiple users as a mini-factory composes four containers at a preselected location with all value creation modules, and ensures the agricultural production when, where, and however much is needed. The mobile APS can be accessed by every farmer easily and is flexible to adapt to various harvest amounts and farmers' needs.

Compared to a stand-alone unit, a PSS supports the creation of more added value through sharing the production facilities as well as provision of additional services. While a farmer processes the harvest, others can supply water for irrigation in a closed-loop through energy generation and the recycling of waste [Eme-15, p. 1825]. In particular, APS sharing increases satisfaction of farmers' needs through multiple service opportunities by higher capacity utilization, while farmers only need to pay for the used functionality of the APS instead of purchasing a stand-alone unit.

While the entrepreneurial freedom for the APS owner increases through the gained experience and created win-win-situations among farmers and the owner, the investment costs must be covered by the owner or funded by governmental institutions. What is more, interactions between farmers and APS owners open space for further improvements.

Beyond conventional control units, new services can be provided through IT support with extended software applications (app), which are easily accessible through cloud-based services and online interfaces for all stakeholders. Both solutions for controlling the APS are compared in Table 5-12. Combined with user interfaces, apps enable visibility and networking, as well as continuously reviewing the APS by generating win-win situations among farmers. Farmers can profit from the APS by using its modules actively or other services passively.

Table 5-12: Evaluation of IT support for the business module

House of quality for business module regarding the IT support			***Category***	
			$c_5(o_5) = AS\text{-}IS$	$c_6(o_6) = TO\text{-}BE$
			Solution for IT support	
Category	***Importance***	***Requirement***	$o_5 =$ $conventional\ control\ unit$	$o_6 =$ $extended\ applications$
$c_3(r_i) = Functionality$		$r_{11} = Technical\ support$	$-$	$+$
	$p(c_3) = 3$	$s(c_3(r_i), o_j)$	0	1
$c_6(r_i) =$ $Stakeholder\ engagement$		$r_{29} = Upgrading\ know\text{-}how$	$+$	$+$
		$r_{30} = Creating\ win\text{-}win\ situations$	$-$	$+$
	$p(c_6) = 3$	$s(c_6(r_i), o_j)$	1	3
		$S(o_j)$	3	12
		$t_{min}(o_j)$	3	6
		$t_{max}(o_j)$	6	12

Apps including IT support for the APS sharing are essential to engage multiple stakeholders through an online platform. The cloud enables easy access to services via mobile devices such as smartphones and tablets, thus reducing hardware costs. Following services are possible through apps [Eme-15, p. 1819 ff.]: harvest organization, gathering help, communication, tutorials, profile creation for each farmer, and customer relations.

Developed apps can support stakeholders who are using PSS in improving their economic impact by saving energy, water and processing costs for stakeholders; their environmental impact by decreasing CO_2 emissions, and their social benefit through diverse cooperation between farmers, owners, and customers. The presented technological solution allows sustainable production and enables cooperation between competing stakeholders by sharing the APS, while extending the limits of social compatibility.

The **verification of the recycling module** follows. The goal of the recycling module is to contribute that the APS generated ideally zero waste and emissions through the 6R approach.

Currently, after processing olives in a malaxer, the wastewater is recycled to use in the decanter to some extent. After the decanter separates olives, cores and the pressed oil, the residual pomace of processed olives and fruits is dried in a belt dryer, burned to heat up the paste in the malaxer to gain heat and electrical energy as well as used as fertilizer in the following season.

The recycling module is designed to add more value through the recycling of organic waste and wastewater in order to reuse byproducts, for example, solid and liquid residues. Two sample byproducts are compared in Table 5-13 [Eme-15, p. 1820 f.].

Table 5-13: Evaluation of closed-loop approach for the recycling module

House of quality for recycling module			***Category***	
			$c_7(o_7) = TO\text{-}BE$	$c_8(o_8) = TO\text{-}BE$
			Solution for operating facilities	
Category	***Importance***	***Requirement***	$o_7 = Pellet\ from\ bio\text{-}waste$	$o_8 = Water\ treatment$
$c_2(r_i) = Productivity$		$r_6 = Low\ investment\ costs$	$+$	$-$
		$r_{12} = Low\ area\ and\ space$	$+$	$-$
	$p(c_2) = 9$	$s(c_2(r_i), o_j)$	0	0
$c_4(r_i) = Resource\ efficiency$		$r_{23} = Application\ of\ 6R$	$+$	$+$
	$p(c_4) = 9$	$s(c_4(r_i), o_j)$	1	1
$c_6(r_i) = Stakeholder\ engagement$		$r_{30} = Upgrading\ know\text{-}how$	$+$	$-$
	$p(c_6) = 3$	$s(c_6(r_i), o_j)$	1	0
		$S(o_j)$	39	9
		$t_{min}(o_j)$	19	19
		$t_{max}(o_j)$	39	39

The attached recycling module increases resource efficiency by generating, for example, thermal energy from biomass, in a closed-loop. The technology for pellets adds more value than the water treatment methods, as presented in Table 5-13.

The **verification of the water module** is described as next. The water module must provide an uninterrupted supply of water to the production module, while seasonal water scarcity presents a major environmental limitation in Cyprus. Pumped ground water exceeds the natural regeneration of water reservoirs, which has a negative impact on the ecosystem. The project team examined different technologies, as evaluated in Table 5-14, to meet the water demand, such as condensation, filtration, and the conveyance of water from its source to the point of usage in the production facilities. Table 5-14 presents the simplified values.

Table 5-14: Evaluation of solutions for the water module

House of quality for water module			***Category***		
			$c_9(o_j) = AS\text{-}IS$	$c_{10}(o_j) = TO\text{-}BE$	
			Solution		
Category	***Requirement***	***Importance***	$o_{10} = Filtration$	$o_{11} = Conveyance$	$o_{12} = Condensation$
$c_1(r_i) = Changeability$	$r_2 = High\ mobility$	$p(r_2) = 9$	1	1	3
$c_2(r_i) = Productivity$	$r_6 = Low\ investment\ costs$	$p(r_6) = 3$	9	9	0
$c_4(r_i) = Resource\ efficiency$	$r_{19} = Protection\ of\ ground\ water$	$p(r_{19}) = 9$	9	0	9
	$r_{24} = Low\ power\ demand$	$p(r_{24}) = 1$	1	9	9
		$S(o_j)$	118	45	117
		$t_{min}(o_j)$	49	99	99
		$t_{max}(o_j)$	99	198	198

For using filtration and osmosis within the APS, the whole system should be located close to the coast, which contradicts the requirement of mobility. Facilities for filtration and conveyance are fixed on a location, and not mobile. Investment and running costs for these facilities are also very high [Eme-15, p. 1821].

Atmospheric air is another input for water generation independent of ground water. Condensation using atmospheric water generators is a flexibly applicable solution for changing demand and matches the Cypriot requirements better than other solutions. It fulfills the requirements such as mobile access, lowest possible energy consumption, and availability [Eme-15, p. 1822].

The last demonstration is the **verification of the energy module**. The goal of the energy module is to generate electrical energy by ensuring continuous availability of electricity by exploiting seasonally and climatically available renewables with less operating costs.

The use of biomass, solar, wind, or mixed energy sources are examined to generate electricity for the power grid as potential solutions. Following local requirements are presented in Table 5-15: availability of energy resources, little space, and affordable life-cycle costs, independence of location as well as creating fewer CO_2 emissions, in contrast to currently used solutions. For example, a solution is rated positively if little or no CO_2 is emitted. The return on investment for the implementation of a new energy module in Cyprus is between four and six years depending on configuration and capacity [Eme-15, p. 1822].

Table 5-15: Evaluation of solutions for the energy module

House of quality for energy module			**Category** $c_9(o_j) = AS\text{-}IS$		$c_{10}(o_j) = TO\text{-}BE$		
			Solution				
Category	**Requirement**	**Importance**	$o_{13} = Diesel\ generator$	$o_{14} = Biomass\ generator$	$o_{15} = PV\ solar\ panel$	$o_{16} = Wind\ turbine$	$o_{17} = Hybrid\ generator$
$c_2(r_i) = Productivity$	$r_5 = Low\ area\ and\ space$	$p(r_5) = 1$	3	1	0	0	1
	$r_7 = Low\ life\text{-}cycle\ costs$	$p(r_7) = 3$	0	0	9	1	1
$c_4(r_i) = Resource\ efficiency$	$r_{21} = Temporal\ distribution\ of\ resources$	$p(r_{21}) = 9$	9	3	1	3	9
	$r_{22} = Low\ CO_2\ emission$	$p(r_{22}) = 9$	0	0	3	9	1
	$r_{24} = High\ potential\ of\ resources$	$p(r_{24}) = 3$	0	3	9	1	9
		$S(o_j)$	84	37	90	114	121
		$t_{min}(o_j)$	56	56	112	112	112
		$t_{max}(o_j)$	112	112	225	225	225

A hybrid energy generator, which combines more than one resource to increase the availability of energy supply, is the best fitting and most adaptable solution. It also decreases the energy expenses for the whole system with less operating costs. The hybrid generator consists of two components: clean energy and backup. The clean energy component continuously generates the required energy from renewable resources and organic waste, for example, solar radiation, wind and biomass. The backup component is complemented with a diesel generator and storage batteries [Eme-15, p. 1821].

The hybrid generator encompasses available renewable resources in different combinations that are aligned with the energy demands of the three other value creation modules in Figure 5-15 including production, atmospheric water generation, as well as water and biomass recycling.

Due to the seasonal availability of solid waste and solar radiation, the energy module also needs wind energy. The energy generated by solar radiation, wind and solid waste delivers the energy mix. For improvements of environmental impacts, the cumulative energy demand of the APS should be monitored and optimized when the prototype of the energy module is implemented [Eme-15, p. 1827].

5.2.1.6 **Step 6: Financial and Entrepreneurial Gaps**

The focus on resource efficiency shows that energy and water modules cause zero emissions and byproducts due to the use of renewable and unlimited resources. After the physical transformation of materials, some byproducts can be processed through the 6R approach [Eme-15, p. 1827].

A detailed feasibility study and business plan are required, which should be presented to potential financial and governmental stakeholders to raise funding. However, funding opportunities for Cyprus are very limited. Additional to the trade barriers in North Cyprus, the financial crisis and the unresolved situation have caused a weak economy and high unemployment rates in Cyprus in European comparison in the last decade. Multiple bailouts to prop up government finances and the financial sector have increased the country's relative debt load to one of the highest in Europe [The-16]. Lack of transparency continue to flourish in Cyprus and pose inherent risks for entrepreneurs and investors, who could support and fund the realization of a prototype for the APS. To overcome the distressed situation, conversion of these limitations, into economic and social opportunities for Cypriot entrepreneurs is needed, while protecting the environmentally hampered of the island.

5.2.1.7 **Step 7: Further Opportunities**

The implementation of the selected configuration for the APS should be elaborated in a follow-up project. The architecture for sustainable manufacturing can be applied iteratively in order to improve the quality of results, for example, for increasing effectiveness of the production and recycling modules.

Including multiple stakeholders' preferences creates a disorder which increases both the entropy for the agricultural production and the number of directions to change the proposed APS. Farmers can discuss advantages, as well as disadvantages, of the changes online using the apps. Different perspectives on the same issue can widen the space for either effective or efficient solutions. An innovative consensus can be achieved, even if, in the short-term, it is not the first preference of each stakeholder. When single or multiple stakeholders identify opportunities, these can be exploited.

The Cyprus Water Supply Project provides another opportunity to overcome the water scarcity [Gie-13]. Some areas are selected by Cyprus and Turkey to install special pipelines for irrigation and started the supply in 2015. It has still not published how many and which Cypriot farmers draw benefits from this project [Hac-15].

5.2.2 Redesign for Power Equipment Manufacturing in Germany

Following Figure 2-4 in Subsection 2.1.2, remanufacturing as one methodology of the 6R approach involves the re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many components as possible without loss of functionality [Jaw-06, p. 4]. The technological and organizational processes for remanufacturing are essential to ensure at least the level of performance equal to the original specification including the material and functional value of used products. Tires, motors and power engines, and vehicle parts have the most significantly remanufactured components in the USA. The main goal of remanufacturing is reducing environmental impacts and cost savings up to 50% in comparison to new component production [Ort-14, p. 1044].

Although the reverse logistics of remanufactured components might vary according to components' characteristics, in general, the reverse logistics includes the following processes: collection of the used component after a certain life-cycle, disassembly, sorting, visual inspection, testing, or scanning, cleaning, processing, repair, reassembly and visual, hardness, penetration inspection, packaging and transportation, and reuse [Wil-14]. Recognized remanufacturing challenges include the procurement of used components, processing and remanufacturing of components, assembly and quality of remanufactured components. Size, location, and number of facilities as well as the internal logistics influence the unit cost of remanufactured components [Ort-14, p. 1045].

The architecture for sustainable manufacturing is exemplified in a case study, which addresses remanufacturing of components in the power equipment manufacturing sector in Germany. This sector manufactures gas turbines for power plants with a heavy machine design. Since gas turbines operate with high precision and performance within ever increasing temperature ranges, many of their components are subjected to extreme stress during operation and must be replaced after a certain life-cycle to ensure the gas turbine's performance.

For example, each gas turbine includes about 2,400 blades as components. Gas at a temperature of 1,400 °C impinges on the blades at a speed of 100 m/s. This forces the blades to rotate with a velocity of 50 or 60 revolutions per second, while the blades stay cold through innovative air-cooling methodologies. Air distribution is achieved through laser technology to drill up to 0.4 mm small cylindrical holes into curved blade surfaces. Up to four different metallic and ceramic coatings shield the blades from thermal stress and from high temperature corrosion, while all of these layers as well as the base material have different physical characteristics [Bec-11]. High temperatures induce hot corrosions, cracks, creep, and dimensional deviations which cause vulnerable damages on the thermal barrier coating of the turbine blades. For example, coating with a mix of ceramics and metallic materials is used to preserve the blades against corrosion, oxidation and high temperatures during the working period of the engines.

For the remanufacturing, the blades are disassembled from the power engines and sorted according to individual specifications. Incoming blade surfaces deviate in thickness and size. After a visual inspection and test, they are chemically and mechanically cleaned to remove surface deposits and coatings. The blades are then visually inspected for cracks, gross damage and wear [Mal-89, p. 20 f.]. Welding, grinding, drilling, computerized numerical control (CNC) milling and coating are the primary processes used to restore shape and functionality of damaged blades [Piy-11] [Wil-14].

5.2.2.1 **Step 1: Multidisciplinary Stakeholders**

Manual, semi- or automated remanufacturing processes for turbine blades have been a practically and scientifically explored area over the last two decades [Mal-89] [Piy-11]. Teams of international researchers has identified relevant stakeholders in the power equipment manufacturing sector within the remanufacturing network in 2011. International partners of these stakeholders across the supply chain mainly from Brazil, eastern Asia, western European countries and the USA have been added to the stakeholders in 2012. Manufacturing and remanufacturing companies such as raw material suppliers, original equipment manufacturers, retailers, service providers, and costumers as well as research and higher education institutions from various disciplines were involved among around 70 stakeholders.

5.2.2.2 **Step 2: Requirements for Analysis**

To identify relevant requirements of the stakeholders, a questionnaire was applied during the ReMaTec Exhibition in Amsterdam, Netherlands and sent to remaining stakeholders in 2013 [BRA-13]. The project team analyzed all responses and selected some requirements to use for different case studies.

The goal of this case study was to indicate requirements for the development and implementation of an upgraded equipment. Besides the technological processes, the case study focused on the organizational issues faced by remanufacturing of turbine blades as components. The internal logistics of a power equipment manufacturer was examined with the proposed architecture for sustainable manufacturing in order to evaluate existing solutions as well as identify their gaps. Following design and test of potential solutions should increase the effectiveness of remanufacturing by providing a sustainable solution for the selected value creation module.

The power equipment remanufacturing company has around 200 employees including managers, engineers, and operators. The project team analyzed a period of two months in 2014; each month contains twenty working days, each day contains two shifts for operators, and each shift covers eight working hours.

Each blade must be remanufactured after a life-cycle of 25,000 working hours of the gas turbine. Remanufacturing accounts for 30% of the cost of a new component. Based on the assumption that the lifetime and performance of the remanufactured blade are the same as a new blade, remanufactured components have a 100% guarantee for the next 25,000 hours. After coating and repair, the components are re-assembled in the engines for the next life cycle. After three life-cycles, only 10% of the raw material can be reused.

A motion-time-system based on methods-time-measurement (MTM) is used to analyze the internal logistics for different component types based on the time in which a worker completes a process. The logistics and organizational challenges caused by transporting the blades between different institutions and moving them between different processing equipment highlighted potential savings and synergies possible with a new handling equipment. Redesign is selected as a methodology of 6R approach to implement for creating a sustainable solution for the handling equipment.

Redesign of the handling equipment demonstrates a value creation module. A brief introduction into its value creation factors (VCF) follows: Turbine blades are high-value internal combustion engine components, as presented by $VCF_1 = product$. The weights of blades vary between 50 and 800 kg as well as sizes between 10 and 150 cm. A life-cycle of a component is completed after about 25,000 working hours of the engine. After each life-cycle, components are disassembled for remanufacturing, which involves technological processes such as welding, grinding, coating and repairing, as presented by $VCF_2 = process$. The handling equipment, while serving as a tangible object as presented by $VCF_3 = equipment$, provides use-based services such as transportation, storage and protection during the internal supply of the components over all ten processes of the reverse logistics. The organizational processes following each life-cycle such as sorting, packaging, and transportation are presented by $VCF_4 = organization$. For each component, necessary processes are selected by respective engineers and operators, as presented by $VCF_5 = people$, depending on the function, engine and component type [Bil-16a, p. 3].

All requirements are assigned to some value creation factors based on their most relevant impact on the (1) economy, (2) environment or (3) society in Table 8-14 in Appendix 8.4.2. Requirements within each category are described in the following subsections following the assignment to the categories of requirements.

Regarding **changeability**, streamlining remanufacturing processes to improve quality of internal logistics and cut costs imposes tremendous pressure on the availability and reliability of handling equipment. Handling equipment must be (1) scalable to different blade types and sizes, as well as (2) compatible with existing manual, semi- and automated equipment, machine tools and warehouse. Both enable a flexible equipment to be easily adapted to changing conditions and blade characteristics, for example, by fluctuation in demand.

Regarding **productivity**, easy load and unload of components increase the velocity and time efficiency of all processes. Additional requirements for the new handling equipment are demands of low area and space, low investment costs, low maintenance costs and efforts.

Regarding **functionality**, Handling equipment must reduce or avoid dust contamination and low fragmentation of coating, and damages during logistics through collision, crash, scratch, bounce and touch inside and outside the remanufacturing facilities.

Regarding **resource efficiency**, handling equipment must be resistant against acid and heat. Additionally, equipment should be assembled by using renewable resources and applying the 6R approach.

Regarding **ergonomics**, handling equipment must enable ergonomic load and upload of components. Information about a certain product, its state, pre-processes and further workflow should be easily visible, readable and accessible to the operators to complete the orders effectively. Redesign should also enable the ergonomic handling of the equipment by different operators independently from age, gender, height and weight [IEA-16]. In addition, information about how to use and setup the handling equipment should be provided in form of manuals and guidelines. All information should be available and easily visible on the equipment to demonstrate how to handle the equipment and blades for comprehensive understanding of the workforce.

Regarding **stakeholder engagement**, to be able to respond to changing requirements according to the state of the used components after a life-cycle or capacity utilization of the machinery for coating and repair adequately, repeated interactions among engineers and operators are needed.

5.2.2.3 **Step 3: From Present to Next Generation of Equipment**

A decision tree is applied to list existing and potential solutions. While existing solutions indicate the present generation, potential solutions aim to lead to the next generation of handling equipment. All solutions are analyzed and justified through interactive discussions with relevant stakeholders.

From an engineering perspective, a common understanding of the principles of sustainable manufacturing and changing requirements is needed to upgrade the existing solutions by integrating a redesigned equipment into the current remanufacturing environment. The workforce has the capabilities to apply interdisciplinary problem-solving. However, the awareness and motivation for searching sustainable solutions remain limited. Principles of sustainable manufacturing can be mediated to the workforce within a training program. The integration of such training programs into the industrial companies provides a potential contribution to career development for academic and non-academic workforce. The goals of the project regarding the enhancement of capabilities through the training were to

- increase the awareness for sustainable development,
- integrate environmental and social impacts into decision making and actions, while ensuring competitive advantage,
- encourage the workforce in order to apply methodologies in technology and management, while contributing to sustainable development,
- interrogate the current value creation in a project, while investigating opportunities to change it sustainably, and
- stimulate synthesis of sustainable solutions among opportunities following the architecture for sustainable manufacturing.

5.2.2.4 Step 4: Fulfillment Levels

The existing and potential solutions are evaluated following Figure 5-16.

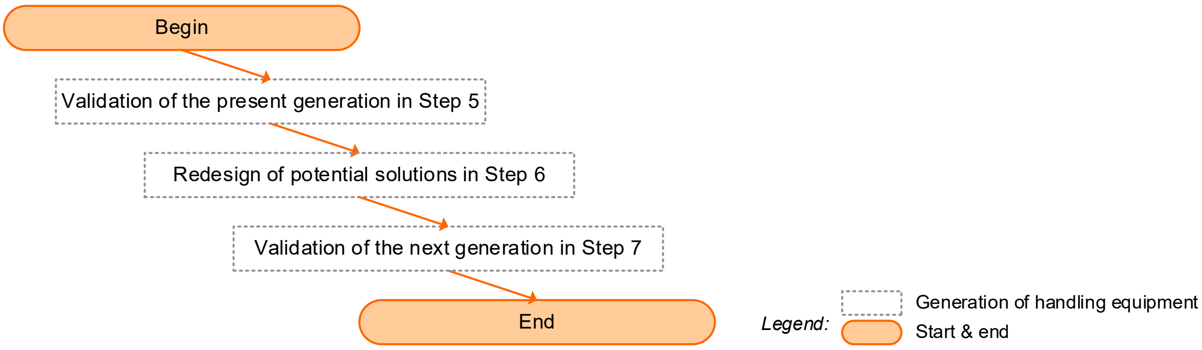


Figure 5-16: Verification of solutions for handling equipment

Sample questions, each represented by a node in the decision tree in Figure 8-5 in Appendix 8.4.2, test a requirement's fulfillment by each solution, as presented by Table 5-16. Each node of the decision tree addresses at least one requirement.

The development and evaluation of existing and potential solutions for handling equipment is repeated through iterative changes. Since there are varying degrees of fulfillment, a three-level scale is used to identify the significance of a fulfillment, as presented in Equation (4) in Subsection 4.2.1. The fulfillment of individual requirements and categories is indicated following Table 5-8 in Subsection 5.2.1. The verification of existing solutions in Subsection 5.2.2.5 results in gaps of the present generation. In order to narrow these gaps by the redesign of the equipment, while fulfilling more requirements, potential solutions are constructed and simulated using CAD tools. The evaluation of potential solutions results in the proposal of next generation of handling equipment in Subsection 5.2.2.6. The next-generation equipment is verified by exploring further opportunities in Subsection 5.2.2.7.

Table 5-16: Questions to justify solutions for handling equipment

Related question	***Validation of***
Is a certain solution compatible with other equipment?	Present generation
Does a certain solution include scalable boxes for multiple sizes of turbine blades?	
Is a certain solution designed mobile on wheels?	
Does a certain solution include modular box type jigs for guiding multiple sizes of turbine blades?	Next generation
Does a certain solution guide turbine blades on conveyors?	
Does a certain solution include a docking station to any work places?	
Does a certain solution include a modular cover for protecting the turbine blades?	

The development and evaluation of existing and potential solutions for handling equipment is repeated through iterative changes. Since there are varying degrees of fulfillment, a three-level scale is used to identify the significance of a fulfillment, as presented in Equation (4) in Subsection 4.2.1. The fulfillment of individual requirements and categories is indicated following Table 5-8 in Subsection 5.2.1. The verification of existing solutions in Subsection 5.2.2.5 results in gaps of the present generation. In order to narrow these gaps by the redesign of the equipment, while fulfilling more requirements, potential solutions are constructed and simulated using CAD tools. The evaluation of potential solutions results in the proposal of next generation of handling equipment in Subsection 5.2.2.6. The next-generation equipment is verified by exploring further opportunities in Subsection 5.2.2.7.

5.2.2.5 **Step 5: Scores and Targets of Present Generation**

Scores and targets of existing solutions for present generation of handling equipment are calculated according to collected data by operators, customers and experts through interviews, questionnaires, meetings, facility visits and external resources.

For example, operators who are responsible for individual processes and engineering students who are interns and research assistants worked together by applying FMEA. Times of manual handling processes such as loading and unloading the blades were determined using the MTM methodology. Operators and students identified together potential failure modes based on experience and common physics of failure logic with similar products and processes over two months. Some of the failure modes for back disorders of operators included bad body mechanics such as (1) continued bending over at the waist; (2) continued lifting from below the knuckles or above the shoulders; and (3) twisting at the waist, especially while lifting.

Four existing solutions are identified as present generation equipment and evaluated. A summary of the scores and targets is presented in Table 8-15 and Table 8-16 in Appendix 8.4.2

for each category of individual requirements. Results highlight main gaps as lack of universality, lack of protection, lack of ergonomic handling, waste of time and resources.

5.2.2.6 Step 6: Redesign of Equipment according to Gaps of Present Generation

The gaps impose better fulfillment of the following requirements: Flexibility and compatibility of equipment made by the use of renewables; less resources and avoiding waste for transportation, storage and protection; and improving ergonomics and working standards. A modular design might be helpful to meet these requirements [Bil-16a, p. 458].

Following Figure 2-4 in Subsection 2.1.2, redesign as a methodology of the 6R approach was selected to demonstrate the contribution of the implemented architecture to creating sustainable value by remanufacturing of turbine blades. Redesign involves actions for redesigning the equipment, which use components, residual materials and resources recovered from the previous life-cycle [Jaw-06, p. 4].

The project team provided trainings and assisted operators and engineers by handling turbine blades to move physically ergonomic and prevent disorders. Resulting from the FMEA methodology, effects analysis by studying the consequences of these failures highlighted the urgent need for an ergonomic equipment design. To increase the individual well-being of operators by handling and avoid component damages by handling and transportation, the focus of the redesign was shifted to ergonomics. Also developing training materials and documentation were required to ensure the high quality of handling and remanufacturing.

The workforce with enhanced capabilities discovered new opportunities for redesigning the equipment among the identified gaps. For example, to carry diverse components and to standardize solutions for equipment, a modular design is drafted providing a mobile and compatible equipment. EUR pallets are elevated on wheels in different ways to justify their impacts. As sufficient space is necessary between a set of blades from the same or different sizes, different types of jigs are tested. All identified opportunities are synthesized to shape potential solutions in iterative cycles, and examined. The scores and targets of six potential solutions are summarized in Table 8-15 and Table 8-16 related to the categories of requirements and presented in detail related to individual requirements. These solutions are drawn and tested as potential solutions with 3D-modeling and blueprints [Bil-16a, p. 458].

5.2.2.7 Step 7: Opportunities for Next Generation

The scores of existing and potential solutions are ranked and discussed with relevant stakeholders to nominate a redesigned solution as the next-generation equipment. The selected path over all nodes is presented in Figure 8-5 in Appendix 8.4.2 in comparison to other existing and potential solutions.

The first ranked solution with the highest score is selected to transport, store and protect the components, and then integrated into the internal logistics for remanufacturing for a test phase of one month. After collecting the feedback of operators and engineers, the next-generation equipment is adapted to verify its applicability. Three further next-generation solutions are developed, assembled and tested in a second test phase of another month to confirm the applicability of the next-generation equipment for ergonomic, resource-efficient, safe and high-quality remanufacturing processes. For example, a laminated paperboard is tested for use instead of plastics to assemble modular shelves for diverse components. Detachable safety guards are built for outdoor protection. Assembly costs for a unit of the next-generation equipment including shelves are kept below 1,500 EUR. The scores and targets of three next-generation solutions are presented in Table 8-15 and Table 8-16 in Appendix 8.4.2 related to individual requirements and categories [Bil-16a, p. 458].

This case study demonstrates how enhanced capabilities of the workforce by professional education contributes to finding a sustainable solution by redesigning and assessing handling equipment. Such a solution is likely to advance similar production systems.

5.2.3 **Simulation of Automotive Maintenance Network in Germany**

While design and operation of equipment have been widely explored in research, contribution of maintenance, repair and overhaul (MRO) as the next life-cycle stage to prevent and balance negative impacts on the whole value creation module have been poorly investigated [Tak-04, p. 643 ff.]. In order to encourage initiatives from industrial and research institutions in this research field, research clusters are established with governmental support mostly in developed countries. Clusters describe geographic concentrations of interconnected industrial, research and higher education institutions, which compete but also cooperate, in a particular field [Por-98].

In general, MRO combines all technological, administrative and managerial processes during the life-cycle of a product intended to retain or restore it to a state in which it can perform its required function [EFN-16]. When maintenance presents a value creation module interacting with other value creation modules in a MRO network, such as procurement of spare parts, it can be characterized by the determination of five value creation factors (VCF): Delivery of MRO as a service during the life-cycle of a product presents $VCF_1 = product$. All technological, administrative and managerial MRO activities present $VCF_2 = process$. Processes determine, assess and change the product to the predefined state. Various tools and machines can be applied as $VCF_3 = equipment$ to complete these processes. Planning, scheduling, logistics and performance measurement regarding all processes using IT tools form $VCF_4 = organization$. Workforce including operators, service providers, designers and managers represent $VCF_5 = people$ [Bil-15, p. 295 f.].

The innovation cluster MRO has established multiple research projects to investigate this research field with a particular focus on (1) repair and overhaul technologies, (2) cleaning methodologies, (3) condition monitoring and diagnosis, as well as (4) MRO planning and diagnosis. Based on production planning and control, MRO planning and scheduling describes organizational processes including decision-making and operation which are applied on a regular basis in a certain production system. This particular research field of MRO deals with the allocation of resources to tasks and orders over given time periods in order to optimize one or more targets [Fra-11].

5.2.3.1 **Step 1: Regional Stakeholders**

The majority of countries provide municipal services to collect and recycle solid waste, clean and sweep streets, and if necessary a special winter service. The material flow of a service provider for waste collection and cleaning in Berlin has been selected to analyze the organization of MRO within an automotive maintenance network. The goal of the project was to reduce the utilization of the maintenance network through balancing the volume of maintenance orders for vehicles as equipment with the capacity of MRO facilities, while contributing to sustainable manufacturing. Vehicles of a service provider create value for the company through their operating time, which is generally recorded as the cumulative working time of the product since its last overhaul.

The municipal governmental and community in Berlin, suppliers, and sponsors are main external stakeholders, while the workforce including managers, engineers, drivers of vehicles, operators and managers in workshops and administrative staff represent the internal stakeholders. This case study focuses on internal rather than external stakeholders. Similar to the previous case study, the awareness and motivation of stakeholders for searching sustainable solutions remain limited. Principles of sustainable manufacturing can be mediated to them within a training program. The integration of such training programs into the industrial companies provides a potential contribution to career development for academic and non-academic workforce. The goals of the project regarding the enhancement of capabilities through the training were to

- increase the awareness for sustainable development,
- integrate environmental and social impacts into decision making and actions, while ensuring competitive advantage, and

- stimulate synthesis of sustainable solutions among opportunities following the architecture for sustainable manufacturing.

5.2.3.2 **Step 2: Requirements for Data Mining**

The goal of MRO for the service provider is to increase the maintenance network's performance through sequencing and scheduling the right maintenance type at the right equipment, time and place. The main function of MRO planning and scheduling is to reduce both scheduled and unscheduled downtimes of equipment in order to achieve high availability and reliability of the network. The selection of an appropriate MRO methodology whether periodic, condition-based or corrective for each downtime is crucial.

The goal of this case study is to balance the volume of maintenance orders by utilizing the network's capacity to decrease the throughput time of orders. Maintenance orders are created by the service provider and received by the maintenance network to deliver MRO services. Within this case study, the current sequencing and scheduling strategy of the maintenance network has been modeled and simulated to identify the uncertainties and opportunities for potential improvements. Statistical distributions, for example, the Weibull distribution for mechanical system elements, are used to describe the stochastic failure behavior of the vehicles. This kind of distribution uses the remaining life of the vehicle to calculate the maintenance intervals for a certain type of vehicles [Bil-14, p. 12].

All requirements to achieve this goal are identified and assigned to value creation factors based on their most relevant impact on the economy in Table 8-17 in Appendix 8.4.3. Requirements are assigned mainly to the category of productivity. For example, the number and frequency of failures influence the performance of the maintenance network. Failures cause costs in terms of time, capacity and spare parts [Raj-06, p. 812 f.]. To improve the performance of the maintenance network high capacity utilization by low throughput times for MRO and inventories are required. To guarantee on-time delivery and short throughput times, despite of the capacitive, logistical and order specifications, a reasonable sequencing in the context of maintenance planning and control is needed.

5.2.3.3 **Step 3: Existing Solutions for Maintenance Planning and Control**

The service provider company has around 5,100 employees who decide about and operate the delivery of services for cleaning and waste collection with a fleet over 2,000 vehicles in two shifts adhere to fixed schedules. There are about 35 vehicle types which include litter pickers, waste collection vehicles, cleaning boats, vacuum vehicles, rinsing vehicles, sweepers for main roads, inner roads, walkway streets [Bil-14, p. 14]. Each vehicle of the fleet is assigned to a location in the network according to its operation area. An operating vehicle starts its daily tour from a specific station und returns to the same location and parks when the shift ends.

The municipal maintenance network, which has been developed in Berlin since 1951, have consisted of three levels. Each level was identified to model a subsystem with the simulation software: (1) MRO network level, (2) workshop level and (3) repair station levels. At MRO network level, twelve small workshops (W) and two main workshops (MW) were modeled which are distributed across the city of Berlin, as presented in Figure 5-17.

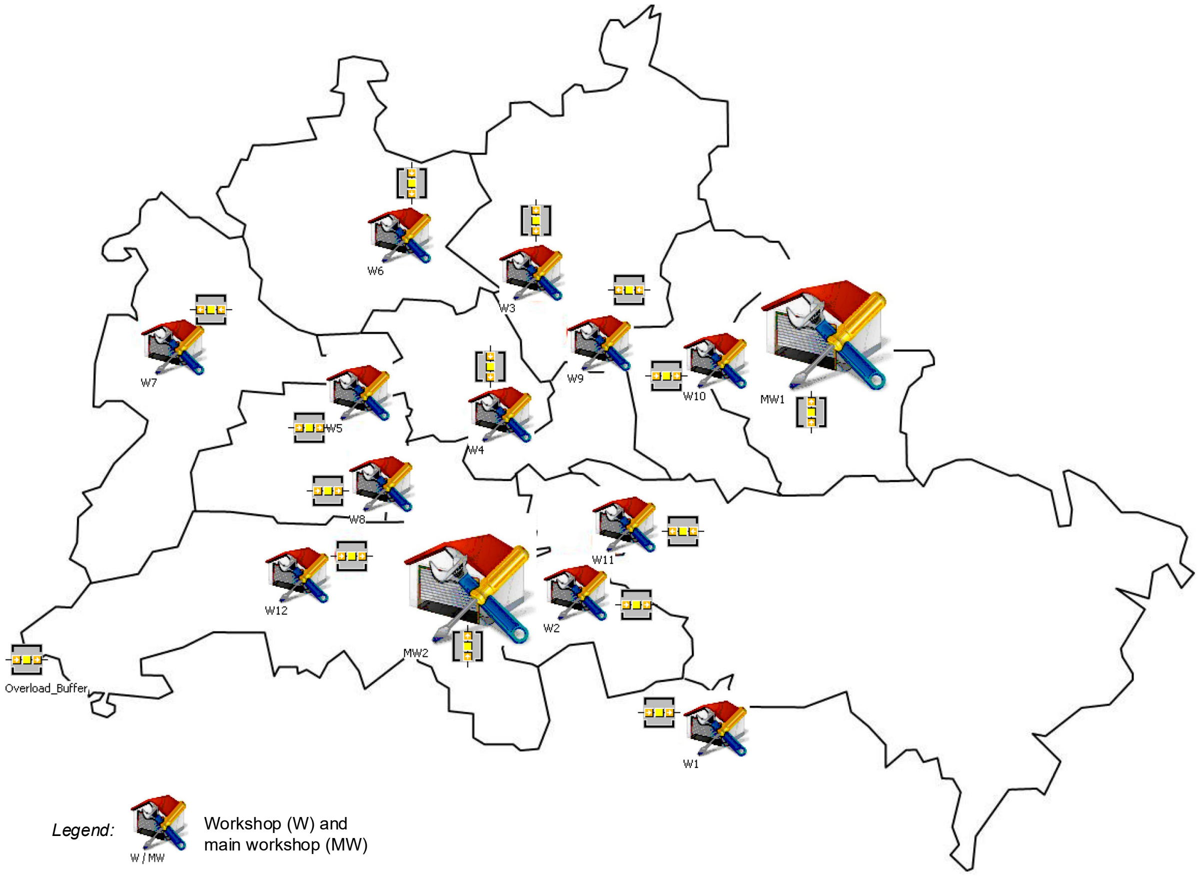


Figure 5-17: Map of maintenance network

High availability and reliability of vehicles ensures the performance of required function of the service provider under given conditions for a given time interval. The vehicle's state is affected by several characteristics such as type, amount, age and arrangement of components in the vehicle. The weather and road conditions and operations including operators, working habits and safety measures also impact the wear [VDI-00, p. 13 ff.]. If the maintenance is effective, failures on critical components and thus their consequences can be reduced.

Data mining provided the input for modeling and simulation of the material flow in the maintenance network. An excerpt from for data mining is inserted in Table 8-18 in Appendix 8.4.3. Different types of maintenance orders and operations set for those order types were analyzed according to their throughput time. Bottlenecks of the maintenance network have been identified. Especially, long waiting and buffer times as well as low speed for spare part delivery lead to imbalances. The processes in running MRO depend on the state of the vehicle varying in type, duration, required workforce and necessary equipment. Three types of orders are distinguished in the analysis:

- Some small breakdowns such as a flat tire lead to temporary interruptions of the daily tour. These breakdowns are promptly repaired either by the driver or by a mobile workshop without the need of creating a maintenance order. This type is disregarded for further investigations due to small capacity utilization and time issues.

- Bigger damages or breakdowns of the vehicle reported by the driver and operator, or found during the daily check-up, lead to a corrective maintenance order. In this case, the vehicle is moved from the parking area to a MRO facility, hereafter referred to as workshop. 24 operating and parking areas are assigned to 14 workshops, where vehicles with maintenance and repair requirements are initially received. Unplanned corrective maintenance orders were created by random generators based on the mean time between failures (MTBF), which were calculated for each vehicle type. One random generator was modeled for each vehicle type. 38 generators created the corrective maintenance order independently randomly. All together accounted for around 39,000 orders in 2009 [Abd-11, p. 5]. Figure 5-18 presents how MTBF for each vehicle type is calculated following Equations (25), (26) and (27) in Appendix 8.4.3.

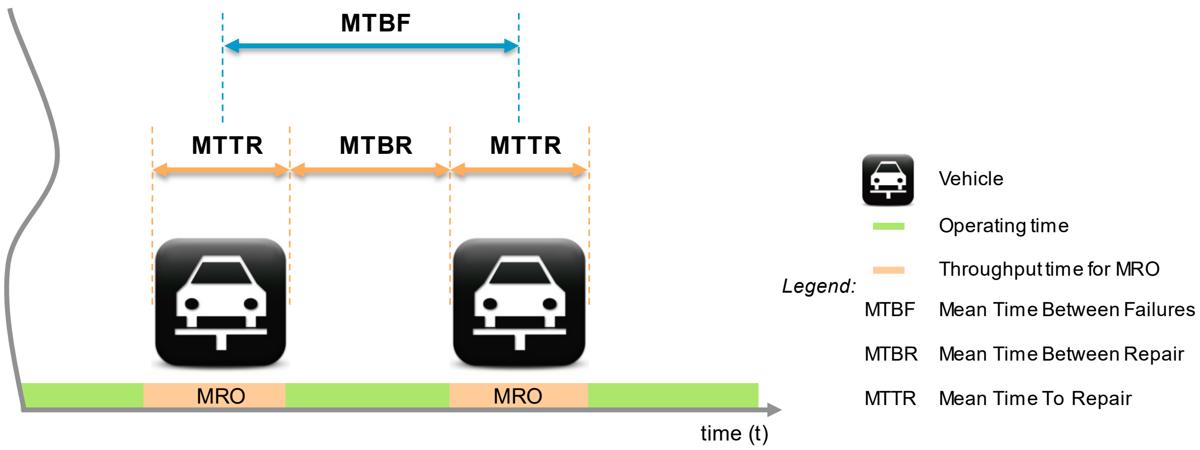


Figure 5-18: Mean times for each vehicle type

- Preventive maintenance orders were generated based on the scheduled preventive maintenance from the year 2009. Each order was created at the specific date by a generator. This order was then sent to a planned workshop buffer and waited until a repair station was available. To prevent unexpected large failures, some processes for inspection are collected preventively in scheduled and run regularly on the vehicles. For each scheduled maintenance check, a new preventive maintenance order is placed after the daily tour. In this case, the vehicle is checked for further damages that can be repaired during the MRO without interrupting the daily assignment. The activities are performed in workshops with different repair stations. Thus, sequencing issues are also related to pre-assignment of vehicles to repair stations.

The small workshops are able to handle simple repairs for certain types of vehicles. The main workshops differ from small workshops by offering a large spectrum of scheduled preventive maintenance services and voluntary corrective repair services. If preventive maintenance or more serious corrective maintenance is required, the vehicles are moved from a small workshop to one of the main workshops. After the maintenance and repair activities are completed, these vehicles are returned to their parking area. Information and material flow are used to instruct the modeling, as presented in Figure 5-19:

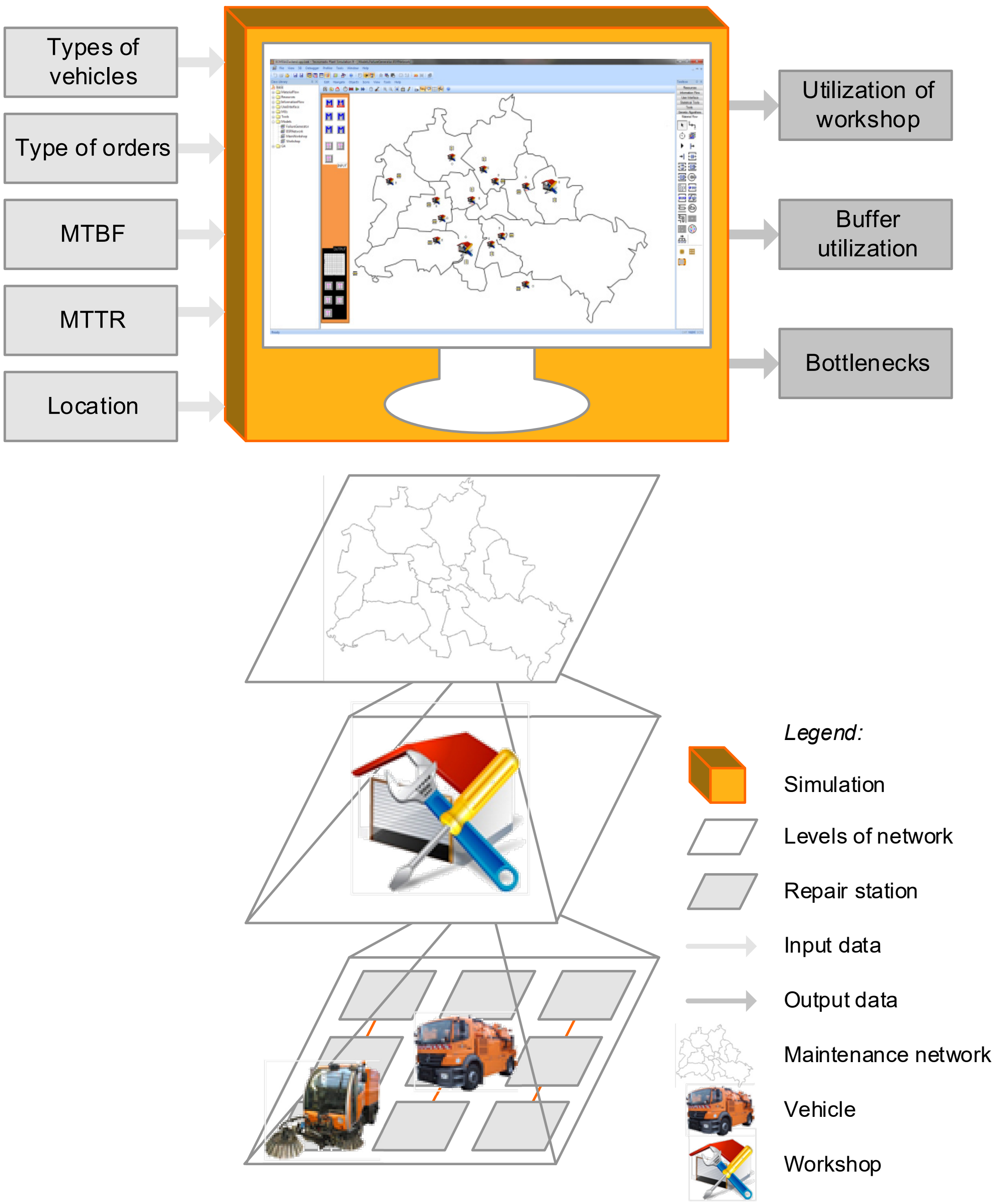


Figure 5-19: Simulation of three levels including information flow

- A certain maintenance order is generated.

- The maintenance order is assigned to a certain workshop.
- The type of the order and the mean time to repair (MTTR) is assigned to the order.
- The capacity utilization of the workshop is examined. If necessary, the maintenance order is transferred to another workshop.

5.2.3.4 **Step 4: Fulfillment Level of AS-IS State**

In order to solve sequencing issues in networks, modeling and simulation tools were applied for the verification of a suitable material flow. A discrete event simulation methodology based on the material flow simulation software from Siemens, Tecnomatix Plant Simulation, was applied to understand the maintenance network, analyze the possible failure modes for imbalances and to test new solutions for the network by developing different planning and scheduling scenarios.

A top-down approach was applied for modeling the maintenance network. A top-down approach breaks down a system, which is presented by the maintenance network in this case study, to gain insight into its compositional subsystems, which are presented by workshops and repair stations. This approach formulates an overview of the system, specifying but not detailing any subsystem. Each subsystem is then refined in yet greater detail until the entire specification is reduced to its basic components.

Waiting to be maintained or repaired in any parking area results in an overall increase in non-operating time for one of these vehicles. Such waiting times should be decreased to improve performance of the service provider, while saving resources. While the current network works without any predefined priorities, operators and managers in workshops justify the importance of orders based on the repair portfolio of other workshops and on their personal relations with colleagues from other workshops to prioritize some orders with time pressure.

A workshop is full when all of its repair stations are occupied and their operators work on vehicles, i.e., the next incoming vehicle must be moved from the parking area to wait in a designated buffer. The capacity of these buffers is also limited; if they are also full, the vehicles must wait in the parking area. A buffer is placed in front of each workshop in the modeling, as presented by Figure 5-20, to represent a parking place for vehicles waiting to be maintained or repaired in the workshop. If a small workshop is occupied including its repair stations, parking place and buffer zone, then the vehicles can be transferred from small to main workshops to reduce the waiting time. This assignment depends on distance between a set of workshops and the capacity of main workshop.

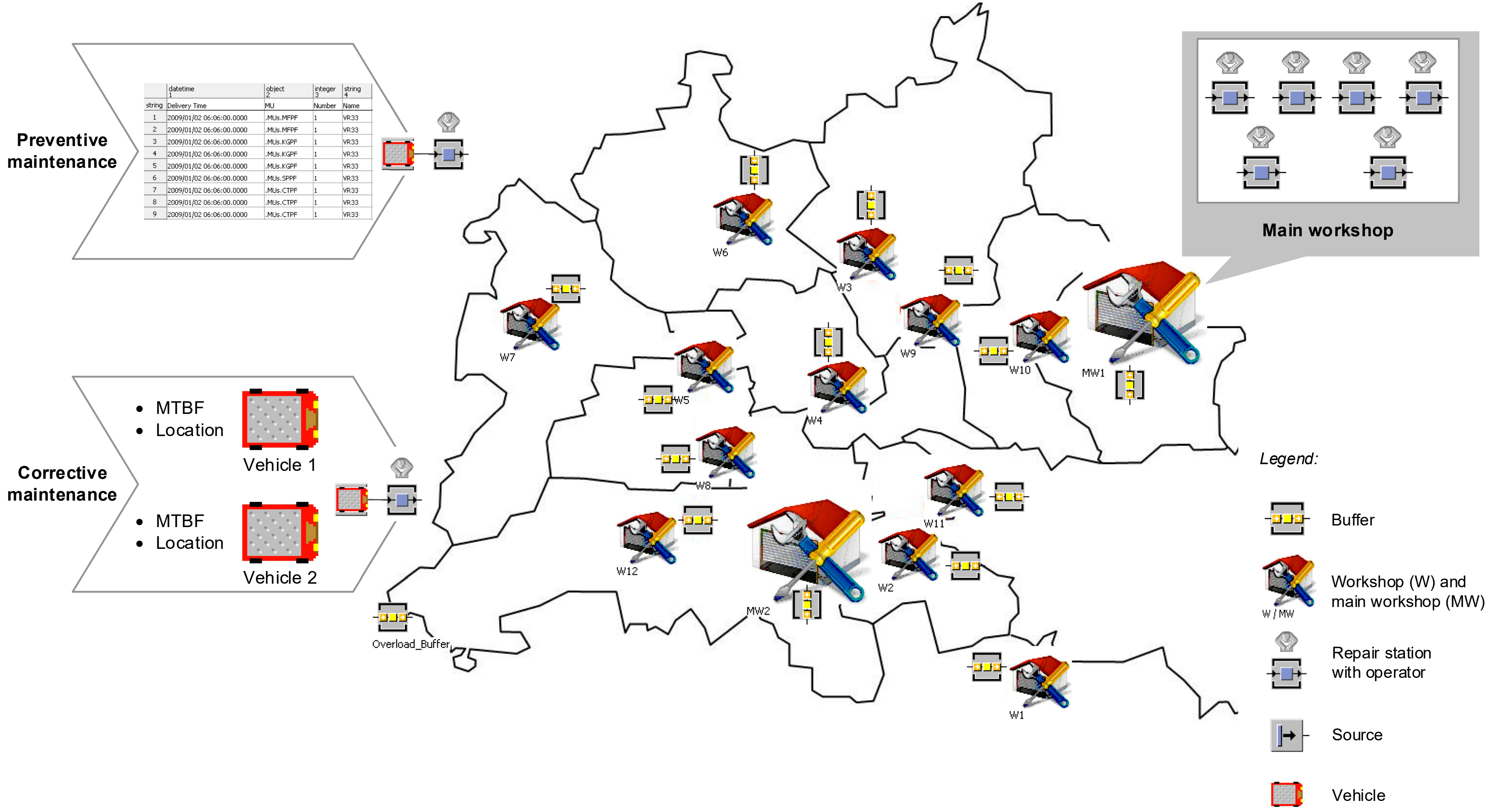


Figure 5-20: Model of the maintenance network

In the model, entities represented two types of orders for MRO either for preventive or for corrective maintenance. For the sake of modeling, the first-in-first-out (FIFO) principle was applied to the buffer so that the first vehicle entering the buffer is the first one sent to the next available repair station. As the capacity of these buffers is fixed and varied depending on workshop size, overload of maintenance orders in buffers is possible. To overcome this issue, a dummy overall buffer was modeled.

The workshops are then refined at the workshops level where repair stations and operators for each workshop were modeled. In the next level, each repair station is refined according to the capacity and specification of the repair station, its resources and its productivity.

5.2.3.5 **Step 5: Scores and Targets of Modeling**

Modeling results indicate that preventive maintenance orders are placed mostly in a main workshop twice annually for each vehicle, while unplanned corrective maintenance orders are placed between five and ten times annually for each vehicle. The majority of unplanned orders are operated in small workshops.

Due to large differences between the throughput times for an individual vehicle, it is not suitable to use the mean of throughput times to model the considered orders. Thus, to get a realistic output from the modeling, throughput times for each vehicle type are separated into corrective and preventive maintenance orders, and analyzed to provide occurrence probabilities. Five time classes are defined according to MTTR for each vehicle type. Afterwards, the number of observations in each time class is counted and set in relation to the total amount of observations for each vehicle type to obtain their relative share. This relative share, which is considered as the occurrence probability of the average for each time class, is an appropriate dimension to obtain a realistic output from the modeling.

In modeling for a simulation, the level of abstraction always comes into question. A high level of abstraction leads the model to approximate the real system, and a low level of abstraction is not sufficient to adequately represent the real system. In many cases, data availability and the duration of the study determine the abstraction level. Some assumptions were made and implemented in the model for this case study:

- Every repair station is able to receive every type of vehicle, which describes resource independency.
- Every operator is able to perform all types of MRO processes, which describes capability independency.
- Each maintenance order needs only one operator at a particular time to complete the order, which describes capacity independency.

- There are no parallel activities in one maintenance order.
- Seasonal effects are not considered, and no priority is applied for seasonal vehicles.

The model is drafted for one year precisely. The outcomes such as utilization of workshops, utilization of workshops' buffer and throughput time for maintenance orders are recorded.

5.2.3.6 **Step 6: Simulation of Scenarios according to Gaps of Modeling**

The classes from the model of the AS-IS state are used in developing and simulating potential scenarios for the maintenance network. In simulation, each order is assigned to a class with its throughput time randomly based on the occurrence probability of their classes.

In simulating the unplanned maintenance orders, specific rules are applied and presented in Figure 5-21.

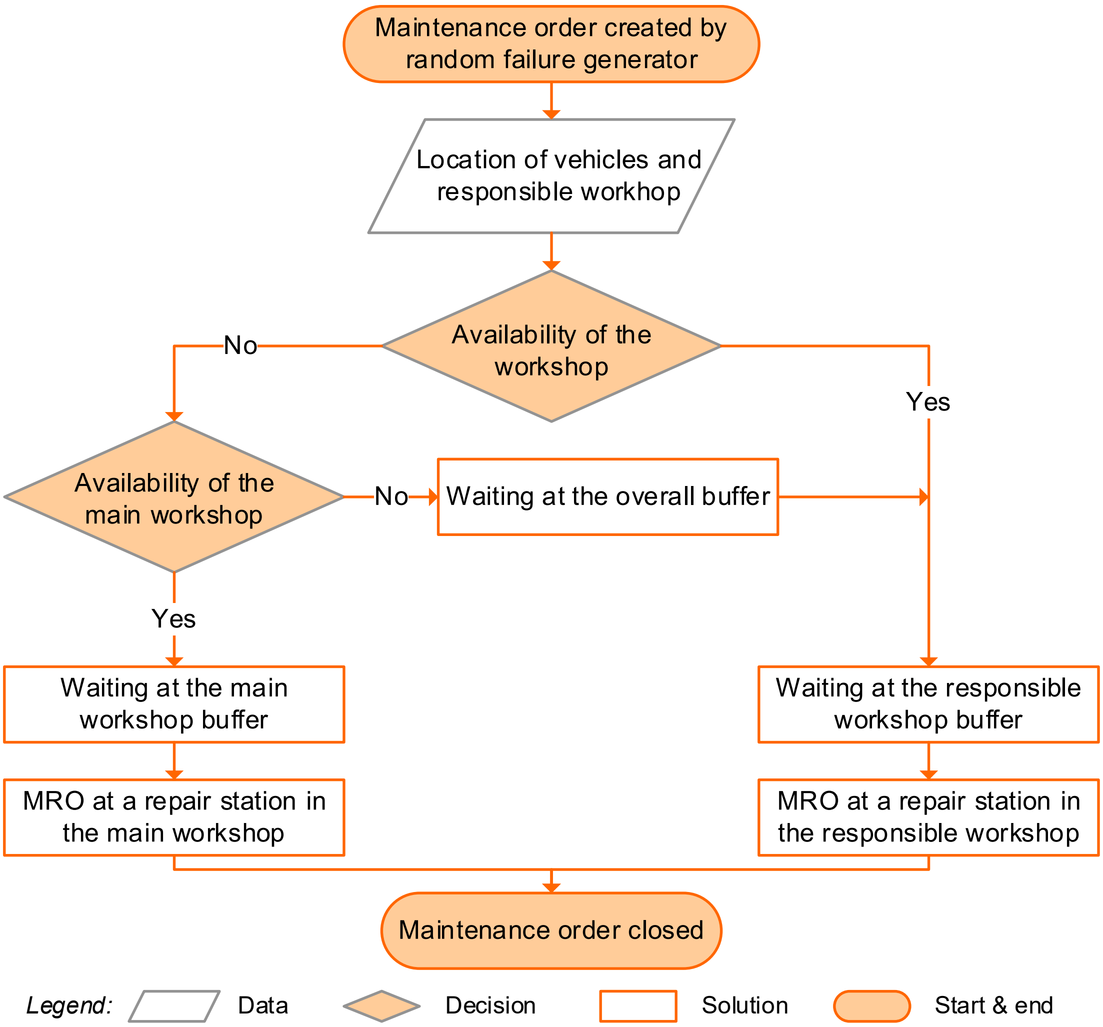


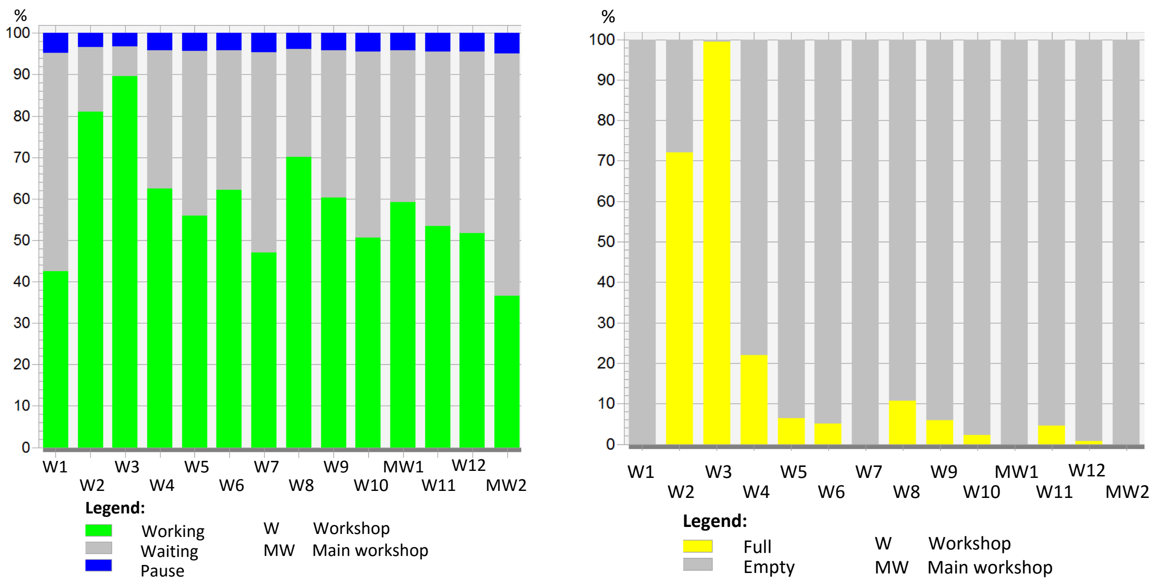
Figure 5-21: Rules for scheduling maintenance orders

For example, when a corrective maintenance order is created, the location of the vehicle and the responsible workshop are identified. Availability of the responsible workshop is then checked. If the workshop is able to receive the maintenance order, and if there are available repair stations or places at the buffer, the workshop accepts the order. The vehicle is then sent to the buffer before reaching the repair station for MRO. The maintenance order is completed later in this workshop.

If the responsible workshop cannot accept the maintenance order, the availability of main workshops is checked. A main workshop accepts the order if it has enough capacity to complete the required MRO. In case both main workshops cannot accept the order, it is sent to the overall buffer, where the maintenance order waits until the buffer of the responsible workshop can receive it.

Three potential solutions of the MRO network with different maintenance strategies were developed and simulated accordingly [Abd-11, p. 10 ff.]. The outcomes from these solutions have been compared technically, logistically and economically with the AS-IS state. The best solution has been proposed to the service provider for improvement of the whole network through better planning and scheduling of MRO. The best case also provides measures for dealing with unforeseeable repairs. Scores of all scenarios are presented in Table 8-19 in Appendix 8.4.3.

The simulation was run several times, and the average outcomes were recorded. Figure 5-22a shows the utilization of workshops in the maintenance network. The value in the graph represents the mean utilization of all repair stations at the workshop based on working, waiting and pausing percentages. Working means the repair station has a vehicle to be maintained and an operator to maintain it. The repair station is empty in the waiting mode, and the pausing mode demonstrates breaks in the working shift.



(a) Utilization of workshop (b) Utilization of workshop buffer

Figure 5-22: Capacity utilization at (a) workshops and (b) buffers

The operators and managers involved in MRO must be trained to adapt to new rules. By repeating the MRO planning and scheduling over and over again, they can improve the value creation step by step.

5.2.3.7 **Step 7: Opportunities for Experiments**

From the graph in Figure 5-22a, three workshops with high utilization are identified. Workshop 3 (W3), workshop 2 (W2) and workshop 8 (W8) have an average utilization of more than 70% annually. With an average utilization of between 50-60%, imbalance in utilization occurs in the remaining workshops due to two main reasons: (1) The first reason is a high ratio in preventive maintenance orders in available repair stations at certain workshops. Preventive maintenance orders created through a scheduled list according to the real orders in 2009 is completed at the planned workshop and could not be transferred. Huge numbers of preventive maintenance orders are scheduled for a particular workshop without considering the fact that its capacity would lead to high utilization of the workshop. (2) The second factor in the imbalance comes from the corrective maintenance order rules and arrangement. For corrective maintenance, the operation area of the vehicle determines the responsible workshop. Some vehicle types appear to be high in corrective maintenance, with a higher maintenance throughput time than others.

A relevant element of the maintenance throughput time is waiting time. Most of the waiting time for a maintenance order occurs at the workshop's buffer. To investigate workshop influence in throughput time, the utilization of the workshop's buffer is recorded through their ratio of full and empty capacity during the simulation year. In other words, a workshop buffer can be seen as a bottleneck of the maintenance network. The recorded outcome is shown in Figure 5-22b. Compared with the workshop utilization, a similar trend can be found. W3 and W2 are two workshops with high buffer utilization. Both workshops' buffers are almost full during the whole simulated year. This situation leads to longer waiting times for the scheduled maintenance orders that are assigned to these workshops.

The next outcome from the simulation is throughput times of the orders for each vehicle type. Figure 5-23 presents the simulated annual number of orders and average maintenance throughput times according to sample vehicle types. The times are recorded from the opening of an order until its completion. With different order classes, randomly created orders and uncertain waiting times, the maintenance throughput time for every vehicle type varies. There are four to six vehicle types with longer throughput times. In order to decrease the throughput time of the maintenance network, these types of vehicles need to be invigilated during scheduling and arrangement of responsible workshops.

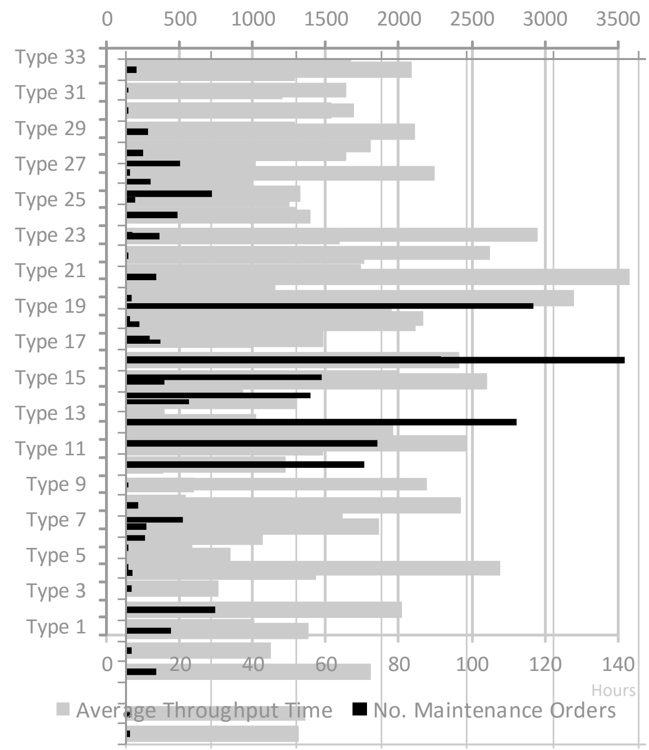


Figure 5-23: Maintenance throughput time and orders according to vehicle types

As a result, a reconfigurable scheduling of maintenance orders is ensured. Reconfigurability addresses the operative ability of the maintenance network to switch with minimal effort and delay to a particular vehicle type through the addition or removal of components at repair stations in multiple workshops [EIM-14, p. 159 ff.]. This enables effective assignment of orders to workshops and increases the efficiency of the network due to increased capacity utilization and decreased throughput time.

During the life-cycle stage use of a product, not only continuous and scheduled MRO but also unpredictable repairs are necessary. MRO can not only restore the product to its original state but also incorporate improvements that bring it up to date with the latest technological developments. MRO processes thereby make a significant contribution to resource protection and energy efficiency, while at the same time providing economic benefit.

5.2.4 **Future Work regarding Value Creation**

The production sector with globally significant stakeholders in many fields of practice and research has the chance to shape the next-generation technologies and to play a great role in shifting the global economy towards sustainable value creation. This role enables the increase of competitive advantages for all stakeholders, while increasing working and living standards worldwide and decreasing environmental burden. The interplay of multiple disciplines such as engineering, computer science and economics combines the depth of sample implementation of production technologies and the breadth of systematic analysis and synthesis of their economic, environmental and social impacts.

Applied research projects, which address the need for action in order to realize potential solutions for sustainable value creation, are introduced as case studies in this section. Case studies demonstrated research results how to change a certain value creation to provide satisfactory solutions aligned to positive impacts on the triple bottom line of sustainability, as listed in Table 5-6. By building these samples, applying the architecture for sustainable manufacturing could support decision-making by promoting globally thinking and locally acting which enables integrating resource-efficient solutions into existing production systems. A brief summary of results from each case study follows:

- The more holistic the scope of the case study, the more sustainable the solution: The conceptual design of the hybrid production system has a huge potential to balance impacts towards sustainability with five value creation modules, namely production, business, recycling, water and energy, and various mobile and modular equipment for each module. Before its realization, a detailed feasibility study and business plan are required, which should be presented to potential financial and governmental stakeholders to raise funding.
- The narrower the scope of time and a case study, the easier its experimental testing, verification and final implementation: The analysis and experiments to redesign an ergonomic handling equipment for remanufacturing of high-value components results in positive impacts economically, environmentally and socially. The case study confirms that the architecture can be universally applied on the level of individual value creation modules to determine a sustainable solution based on experience of stakeholders, CAD simulations and mathematical analysis.
- The more detailed the input data, indicating cause-effect relations, and the less the selected requirements, the more realistic the simulation results: Capacity utilization affects efficiency directly, when supported by an effective MRO planning and reconfigurable scheduling. Saving time and spare parts influence environmental impacts indirectly. Based on the modeling of the initial state and setup of different scenarios with heuristics, maintenance orders as discrete events are simulated to compare the capacity utilization of workshops. Results approximate a higher utilization, but cannot guarantee offering an optimum solution. Further analysis and simulation of scenarios is needed to fulfill further requirements with most relevant impacts on the environment and society.

These results are verified with the stakeholders to analyze whether the recommended solutions comply with the conditions and requirements. Results gathered by the verification of value creation through the case studies confirmed the increasing relevance of an architecture for sustainable value creation. The discussed case studies resulting in flexible, adaptable and ergonomic solutions increase awareness, understanding and motivation of a wide range of stakeholders and later of the society. If the project work and resulting solutions can activate mind of a wide range of stakeholders, gaps that might lead to incompatibility with compounded impacts on sustainable value creation can be reduced during the project work effectively. The impacts of value creation stimulate verification of results through iterative changes. Stimulation describes how the case-specific requirements within the frame of conditions provoke new solutions by the stakeholders in the attempt to cope with sustainability challenges. Thus, stimulation guides their intentions in action to promote multiplier effects through the iterative implementation of the architecture for sustainable manufacturing.

In order to demonstrate the relevance of the transformative attributes to the engineering profession in practice, the application of attributes for completing the case studies are compared in Table 5-17. The next subsections briefly describe how and to what extent the project teams applied the transformative attributes. The discussion that follows is illustrative to present opportunities stakeholders have to apply attributes and leverage creation of sustainable solutions to balance economic, environmental and social impacts.

Table 5-17: Comparison of attributes' fulfillment

Scope of change	Strategic	Tactical	Operational	
Case studies / **Attributes**	**Hybrid Production System**	**Power Equipment Manufacturing**	**Automotive Maintenance Network**	**Ideal**
Interdisciplinarity	◑	●	●	●
Digitalization	◑	◑	◑	●
Problem-solving	●	●	●	●
Projects	◑	●	●	●
Sustainability	●	●	◑	●
Glocalization	●	◑	◑	●

Legend: ○ not directly applied
◑ partly applied
● completely applied

The comparison indicates that the wider the range of stakeholders, the more disciplines must be involved in the **interdisciplinary project team**. Operators and engineers were relevant stakeholders for the redesign of a handling equipment for remanufacturing of high-value components as users and designers in the second case study. Drivers as users of the vehicles, operators as maintenance staff and workshop managers as decision-makers were involved as relevant stakeholders to collect data in the third case study who monitor and estimate the initial state of vehicles and workshops continuously. With a scattered group of stakeholders, the first case study involved farmers from agricultural, entrepreneurs and investors from economic, and engineers from technological disciplines. However, there was no agricultural researcher with a focus on biology or biotechnology to prevent biosafety that may affect human health and the ecosystem on the island.

Two aspects of **digitalization** are (1) provision of data and information as input for the change and (2) support of decision-making based on real-time data. While the first case study totally lacks in the first aspect, it satisfies the second one through the apps for mobile devices. Apps provide all stakeholders online information and enable interactive communication. The other two case studies only provide detailed data and information for the change. After the redesign and simulation is completed, iterative changes can be only initiated by another project which needs to restart the analysis.

All case studies score well in **problem-solving**, as they combine logical thinking with analysis and synthesis by applying methodologies in technology and management such as (1) design with IT-based apps to use product-service system as a business module, (2) redesign with an assessment methodology, and (3) simulation with a time and cost focus in the third case study.

Projects incorporate problem-solving, interdisciplinary teamwork and project management. Due to the lack of agricultural science capabilities, project-based focus is applied only to a limited extent in the first case study. The other two case studies applied the attribute completely and score well.

The superiority of the proposed solutions developed within the case studies regarding **sustainability** is defined by how far these solutions leverage effects on the economy, environment and society. All case studies delivered a positive impact on at least one of these three aspects through the application and combination of methodologies in modeling, design, redesign, simulation and assessment. Results excluded any major negative impacts on either of the other two aspects. The case studies aimed at positively influencing a certain sector along with resource efficiency for the ecosystem through the development of a mobile and modular production system, compatible and modular equipment, and effective and efficient MRO planning. The first case study additionally focused on energy efficiency through the hybrid energy and water generation modules. While the first and second case studies systematically balanced economic, environmental and social impacts, the third case study remained limited in indicating the balance due to the narrow selection of requirements with a major impact on the economy.

Glocalization is applied in two ways in the case studies. (1) The first case study investigates how the individual value creation modules contribute to local value creation in Cyprus. The outreach of the modular and adaptable production system with hybrid energy and water generation is discussed and documented in detail. This case study can easily inspire repetitions elsewhere with political, social, economic and environmental limitations. Repetitions could widely spread in the world to demonstrate how offering teamwork between developed and partner countries support emerging and developing countries in supporting self-help. (2) The other two case studies exemplify the creation of local solutions. The project team as well as the respective stakeholders observe the application of the architecture, personally experience and test how to create sustainable value in manufacturing. When this experience can motivate them to follow the principle of sustainable manufacturing for similar matters, it poses a conveyed leverage effect on the economy, environment and society through continuously adapted sustainable solutions.

Further research should focus on increasing inter-project cooperation to develop theoretically an integrated sustainable manufacturing framework for how to create win-win situations among multiple research projects and project-based courses. The goal of this framework should be to deliver a standard and comprehensive solution finding methodology and enabling relevant stakeholders to consider principles of sustainable manufacturing in multiple decisions and actions. Where applicable, case studies should be verified by more than one project team to test the superiority of the results. For verification, capabilities of project team and stakeholders should be identified to compare before and after the project work what capabilities are enhanced in both groups. Results should balance economic, environmental and social impacts of value creation, where social impacts are evaluated for whether research projects and project-based courses have enhanced the required capabilities by both groups. If applicable, these insights should be used to upgrade the developed sustainable manufacturing framework.

6 Conclusions and Future Perspectives

This research reviews value creation in manufacturing with a focus on sustainable development. Value creation flows from analysis to synthesis iteratively in manufacturing. In order to promote economic profit, while decreasing environmental burden and increasing social benefits, engineers must be aware of principles of sustainable development and be capable of analysis and synthesis. As balancing economic, environmental and social impacts must become a vital part of institutional and individual decisions and actions, it is time to recall Einstein's words from seven decades ago: "The world we have created is a product of our thinking. It cannot be changed without changing our thinking" [Lu-07, p. 629]. Changing thinking habits and using the new thinking in industrial application or applied research requires a significant change of programs in higher education to provide the required engineering capabilities.

This research studies the contribution of industrial engineering to sustainable manufacturing. The goal of the proposed architecture is to support industrial engineering in education, training, practice and research by decision-making and acting to enable the integration of new solutions into existing production systems. The proposed transformative industrial engineering must serve and enable sustainable development of the economy, environment and society through the transformation of value creation factors, modules and production systems. Potential effects of changing the current thinking toward transformative industrial engineering practices go beyond enhancing engineering knowledge and skills. Two pieces, one in education and the other one in applied research, promoting help-for-self-help within the big picture for sustainable value creation are investigated.

For generating industrial engineering capabilities towards sustainability in industrial applications, engineering programs in higher and professional education are transformed using the developed framework for transformative industrial engineering. The application of transformative attributes through enhanced capabilities leads to multiplier effects by implementing the new architecture for sustainable manufacturing in higher education and research. Two case studies are presented to demonstrate the effects of transforming an educational program between a set of countries: (1) An undergraduate industrial engineering program for the TDU between Germany and Turkey, and (2) a graduate dual degree engineering program between the KAIST in Korea and the TU Berlin in Germany.

Understanding the challenges of sustainable development and having the capabilities to cope with these challenges creates new patterns of thinking, decision-making and acting. These new patterns demonstrate a transformative power of industrial engineering to pursue for developing and leveraging sustainable value. Some developed and emerging countries suffer to some extent from limited environmental conditions, and uncertainty of human rights and fundamental freedoms. Once students are capable of applying principles of sustainable manufacturing, they can practice transformative industrial engineering in order to contribute to designing initially creative solutions for various value creation samples to meet these challenges. Educational programs are verified to confirm whether the application of transformative attributes establishing an interdisciplinary, IT-, problem-solving, sustainability-, and project-based glocalized focus lead to a new good practice. The results indicate that the framework for transformative industrial engineering provides a novel methodology to upgrade engineering programs anywhere and for any set of countries. By looking beyond analysis and synthesis of new solutions in research projects and project-based courses in manufacturing, industrial engineers are actively being engaged to shape, creatively manipulate, configure, diffuse and utilize sustainable solutions in practice.

To illustrate the wide range of opportunities that interdisciplinary and international stakeholders should explore through application of different methodologies and attributes, three further case studies are presented. Potential solutions are evaluated in balancing economic, environmental and social impacts according to the identified requirements of relevant stakeholders. While the relative importance of each requirement differs by each case study, it is essential to identify the levers for balanced impacts. In each case study, opportunities exist to use the leverage of synthesizing new solutions for sustainable value creation. The case studies demonstrate the development of a hybrid product service system for agricultural production, physical realization of an ergonomic handling equipment for remanufacturing of high-value components, and reconfigurable scheduling for an automotive maintenance network. While the first and third case studies develop model-based new solutions with balanced impacts, the second case study tests, verifies and implements the designed solutions.

Two educational case studies, as presented in Section 5.1, and three industrial case studies, as presented in Section 5.2, demonstrate changes in value creation to verify the applicability of the architecture for sustainable manufacturing. The case studies represent a small step for engineers as researchers and students in comparison to technological advances. The capability of industrial engineers to leverage their influence in order to promote sustainable impacts is augmented by acting as a bridge between a set of disciplines, countries and paradigms.

All five case studies confirm the multiplier effect of enhanced capabilities to exert leverage over regional boundaries and interdisciplinary stakeholders. Multiplier effects are realized and observed through using interrelated methodologies in technology and management as well as conducting research for next-generation manufacturing.

The usefulness of the architecture for sustainable value creation is verified through comparison of results. The architecture for sustainable manufacturing provides a useful methodology that can be applied to future practice and research of industrial engineering. The continuous quest for transformative industrial engineering will expand the proper understanding of industrial engineering as a scientific engineering discipline and challenge of industrial engineering as a practical profession to promote sustainable manufacturing. A new frontier for a broader research field of engineering can be gradually discovered through the scientific pursuits of transformative industrial engineering. Future research will address the cause-effect relations among multiplier effects, methodologies, educational approaches and industrial engineering capabilities. Their contribution to value creation by applying principles of sustainable manufacturing should be investigated in order to support decision-making through presenting the consequences of decisions and actions in industrial case studies.

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8 Appendices

8.1 Appendix A: Capabilities for Sustainable Manufacturing

8.1.1 Comparison of Countries

Table 8-1: Data for comparison of countries

Selected countries	***Cyprus***	***Germany***	***Korea***	***Turkey***	***USA***	***Vietnam***
Share of GDP of each sector	in percentage [CIA-13]					
Primary sector including agriculture	2.1%	0.7%	2.3%	8.1%	1.6%	17.4%
Secondary sector including industry	10.3%	30.2%	47.0%	27.7%	20.8%	38.8%
Tertiary sector including services	87.4%	69.1%	31.0%	64.2%	77.6%	43.7%
Pillars of competitiveness	in rank among 140 countries [WEC-15a, p. 150 ff.]					
Competitiveness	65	4	26	51	3	56
Transport infrastructure	48	8	11	23	9	67
Quality of the education system	17	10	66	92	18	78
On-the-job training	47	8	39	80	14	94
Goods market efficiency	28	23	26	45	16	83
Flexibility of labor market	26	106	121	111	8	85
Efficient use of talent	63	11	53	131	2	42
Female participation in labor markets	62	43	91	128	52	23
Financial market development	108	18	87	64	5	84
Technological adaptation	48	16	37	45	8	112
IT use	45	11	22	70	20	85
Domestic market size	118	5	13	14	1	35
Business sophistication	47	3	26	58	4	100
Innovation	44	6	19	60	4	73
Company spending on research and development	70	6	21	79	3	57
University-industry cooperation in research and development	40	10	26	61	2	92
Availability of scientists and engineers	20	15	40	50	4	75

8.1.2 **Catalog for Categories of Requirements**

Table 8-2: Requirements extracted from secondary data [Bil-15, p. 302]

Category of requirements	***Requirements***	***References***
Ability for cradle-to-cradle through 6R	Zero waste	[Jaw-06, p. 4]
Changeability	Changeover ability, agility, reconfigurability, transformability, flexibility, adaptability, modularity	[Wie-07, p. 786]
Condition and functionality	Satisfaction, price, functional effectiveness	[Ued-09, p. 684] [VDI-00, p. 13]
Cost efficiency	Productivity, inventory, storage, profit	[Sch-12, p. 605] [VDI-00, p. 14]
Educational capability	Creativity, self-sufficient, autonomous people	[EU -08] [VDI-00, p. 20 ff.]
Quality	Performance, innovation	[Rog-83, p. 205 ff.] [Zim-05, p. 235]
Resource eco-efficiency	Environmental load, ecological balance	[Ued-09, p. 697] [VDI-00, p. 19 f.]
Security and safety	Ergonomics	[Ued-09, p. 694] [VDI-00, p. 15 f.]
Service integrity	Technical support, availability, accessibility, connectivity, reliability	[DIN-10, p. 13] [Mei-10, p. 607 ff.] [VDI-00, p. 13 ff.]
Stakeholder empowerment	Collaborative, social well-being, fair trade	[Sel-11b, p. 8] [VDI-00, p. 20 ff.]
Standardization	Environmental load, ecological balance	[DIN-09, p. 8 ff.]
Time efficiency	Over production, extra processing	[Ost-06]
Transparency	Diagnosability of the current state	[DIN-09, p. 8 ff.] [VDI-06, p. 11] [Zim-05, p. 235]

Table 8-3: List of requirements classified in six categories

Category	*Requirement*	*Case study*		
		Hybrid Production System	***Redesigned Handling Equipment***	***Simulated Maintenance Network***
$c_1(r_i)$ = Changeability	r_1 = High compatibility		x	
	r_2 = High mobility	x		
	r_3 = High modularity	x	x	
	r_4 = High scalability	x	x	
$c_2(r_i)$ = Productivity	r_5 = Low area and space	x	x	
	r_6 = Low investment	x	x	
	r_7 = Low life-cycle costs	x		
	r_8 = High load and upload efficiency and velocity		x	
	r_9 = Low maintenance efforts		x	
	r_{10} = High capacity utilization	x		x
	r_{11} = Low inventories			x
	r_{12} = Low throughput time			x
$c_3(r_i)$ = Functionality	r_{13} = Low dust contamination		x	
	r_{14} = Low coating fragmentation during logistics		x	
	r_{15} = Low damage during logistics		x	
	r_{16} = High satisfaction	x		
	r_{17} = High added value	x		
	r_{18} = Technical support	x		
$c_4(r_i)$ = Resource efficiency	r_{19} = Protection of ground water	x		
	r_{20} = High potential of resources	x	x	
	r_{21} = Temporal distribution of resources	x		
	r_{22} = Low CO_2 emission	x		
	r_{23} = Application of 6R	x		
	r_{24} = Low power demand	x		
$c_5(r_i)$ = Ergonomics	r_{25} = Transparent documentation for easy use		x	
	r_{26} = Transparent documentation of workflow		x	
	r_{27} = Ergonomic load and upload of components		x	
	r_{28} = Ergonomic handling of equipment		x	
$c_6(r_i)$ = Stakeholder engagement	r_{29} = Creating win-win situations	x		
	r_{30} = Upgrading know-how	x		

8.2 Appendix B: Instructions for House of Quality

Table 8-4 presents instructions on how to build a house of quality including all seven steps for a case study based on Figure 8-1 and Subsection 4.2.1.

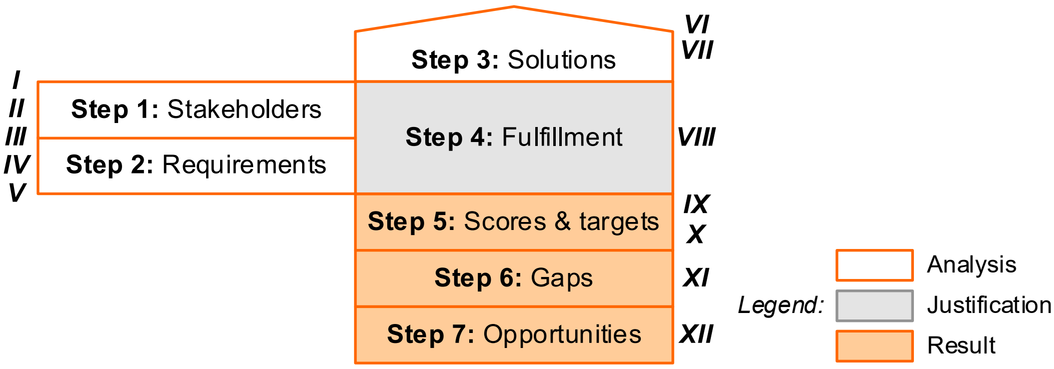

Figure 8-1: House of quality with numbered instructions

Table 8-4: Instructions for building a house of quality

Step	*No.*	*Title*	*Instruction*	*Constraints*
1	I	Name of the QFD	Enter the name of the QFD	
	II	Identify stakeholders	List scope, name, position, institution and country of stakeholders	
2	III	Category of requirements	Identify the category of each requirement	$c_k(r_i)$, $where\ k\ \in\ [2, \ldots, u]$
	IV	Requirements	Identify the case-specific requirements	r_i, $where\ i\ \in\ [k+1, \ldots, n]$
		Order of c and d are interchangeable		
	V	Importance	Identify the importance of individual requirements or categories	See Equation (1)
3	VI	Category of solutions	Identify the category of each solution	$c_h(o_j)$, $\text{where}\ h\ \in\ [2, \ldots, v]$
	VII	Solutions	Identify existing and potential solutions	o_j, $where\ j\ \in\ [h+1, \ldots, m]$
		Order of f and g are interchangeable		
4	VIII	Fulfillment	Assign the level of fulfillment of each requirement by individual solutions	At least $s(r_i, o_j)\ \forall\ o_j$ and $s(r_i, o_1)\ and\ s(r_i, o_2) \forall\ r_i$ must exist
5	IX	Scores	Calculate the score for each solution	See Equation (6)
	X	Targets	Build the targets	See Equations (7) to (10)
6	XI	Gaps	Calculate the difference between targets and scores	See Equation (12)
7	XII	Opportunities	Identify opportunities to change solutions	See Equation (13)

8.3 Appendix C: Case Studies with Transformed Programs

8.3.1 Industrial Engineering Program

Table 8-5 presents a curriculum planner worksheet according to the course categories, which are described in Subsection 5.1.1.

Table 8-5: Curriculum planner worksheet for the industrial engineering program

Code	Category of courses	Sum of ECTS	Sum of SWS	Share in ECTS
a c	Fundamentals in mathematics and natural sciences Fundamentals in technological and management sciences	28	23	12%
d	Engineering science	76	56	32%
e	Economic science	42	31	18%
b h	Technical internship and soft skills International internship or exchange semester	20	22	8%
f	IT-based sustainable manufacturing science	51	35	21%
g i	Project-based courses Bachelor thesis	23	8	10%
	Sum:	240	175	100%

Legend:
ECTS: Credit points according to the European Credit Transfer and Accumulation System
SWS: Hours of a course in a week during a certain semester

Figure 8-2 presents the detailed curriculum of the industrial engineering program at the TDU.

Undergraduate Industrial Engineering Program at the TDU, Degree: Bachelor of Science, Spezialization: Sustainable Manufacturing													
1st year	fall	**Semester 1**	Integral calculus	Physics	Technical drawing and computer aided design	Business administration	Introduction to computing and programming	Introduction to engineering		Advanced German for engineering	**Sum of ECTS**	**Sum of SWS**
		ECTS	6	4	6	4	6	2		2	30	
		SWS	5	3	4	4	4	1		2		23
	spring	**Semester 2**	Linear algebra	Engineering Tools	Introduction to statics and solid mechanics	Accounting	Macroeconomics			Wirtschaftsdeutsch		
		ECTS	6	6	5	5	6			2	30	
		SWS	5	4	4	4	4			2		23
2nd year	fall	**Semester 3**	Differential calculus	Electronics I	Exploration engineering design of mechanical components	Marketing	Basic statistical methodologies	Technical internship	Principles of Turkish History and Reforms of Ataturk I	Englisch I		
		ECTS	6	4	6	4	6	2	2	0	30	
		SWS	5	3	5	4	4	0	2	3		26
	spring	**Semester 4**	Probability	Electronics II	Introduction to dynamics and vibrations	Thermodynamics I		Innovation and technology management with applications	Principles of Turkish History and Reforms of Ataturk II	Englisch II		
		ECTS	6	6	6	5		5	2	0	30	
		SWS	5	4	5	4		4	2	3		27
3rd year	fall	**Semester 5**	Machine tools and production technology	Measurement and test engineering	Materials science	Corporate finance and investment	Operations research			Turkish I		
		ECTS	6	6	4	6	6			2	30	
		SWS	4	4	3	4	4			2		21
	spring	**Semester 6**	Assembly technology	Commercial law	Controlling	Project management	Inttroduction to factory management	Supply chain management	IT-based factory planning	Turkish II		
		ECTS	4	3	6	2	6	3	4	2	30	
		SWS	3	2	4	1	4	2	3	2		21
4th year	fall	**Semester 7**	Automation technology	Labour law	Introduction to database systems	Human factors of engineering and ergonomics	Quality management	Project about shaping global value creation		Scientific research and writing		
		ECTS	6	3	4	3	6	6		2	30	
		SWS	4	2	3	2	4	4		2		21
	spring	**Semester 8**	Industrial information technology and virtual product design			Entrepreneurship	Life-cycle assessment	Bachelor thesis	International internship	Research field of industrial engineering		
		ECTS	6			3	5	12	2	2	30	
		SWS	5			2	4	0	0	2		13
											240	**175**

Legend: ECTS: Credit points according to the European Credit Transfer and Accumulation System
SWS: Hours of a course in a week during a certain semester

Figure 8-2: Detailed curriculum of the industrial engineering program at the TDU

The following tables present the verification of existing and transformative attributes by the implementation of the undergraduate industrial engineering program at the TDU. Table 8-5 in Appendix 8.3.1 presents the verification of the interdisciplinary attribute. Table 8-6 presents a sample how the digitalization of knowledge and skills are integrated into IT-based courses by applying multiple software tools.

Table 8-6: IT-based courses

Code	***IT-based courses***	***Applied software***
a+c	Integral calculus	MATLAB
a+c	Linear algebra	MATLAB
a+c	Differential calculus	MATLAB
a+c	Probability	MATLAB
d	Technical drawing and computer aided design	SolidWorks, SolidEdge
d	Exploration engineering design of mechanical components	SolidWorks, SolidEdge
d	Engineering Tools	Maxwell, Labview, Phyton, C, C++
e	Controlling	SAP
b+h	Technical internship	Siemens SPS, Catia
b+h	Scientific research and writing	Citavi, Jabref, LaTex, Xmind
f	Introduction to computing and programming	MATLAB, Simulink, Java, XML
f	Basic statistical methodologies	SPSS
f	Operations research	MATLAB
f	Supply chain management	ERP, MES
f	IT-based factory planning	Tecnomatix, Arena
f	Introduction to database systems	SQL, Java
f	Life-cycle assessment	GaBi

Legend of the software applied in IT-based courses:

Arena	A discrete event simulation and automation software
C	A general-purpose, imperative computer programming language
C++	A general-purpose programming language with imperative, object-oriented and generic programming features
CATIA	Computer aided three-dimensional interactive application for CAD- and computer-aided engineering (CAE)-based manufacturing
Citavi	Literature reference management software used for Windows
ERP	Enterprise resource planning software for business management
GaBi	A life-cycle assessment modeling software
Jabref	Literature reference management software used for LaTex
Java	A general-purpose computer programming language that is concurrent, class-based, object-oriented
LabView	Laboratory Virtual Instrument Engineering Workbench for system design and development using a visual programming language
LaTex	Lamport TeX as document markup language for word processing
MATLAB	Matrix Laboratory for numerical computing
Maxwell	Unbiased 3D stand-alone software for product design visualization
MES	Manufacturing execution system software used in manufacturing
Phyton	A high-level, general-purpose, interpreted, dynamic programming language
SAP	Enterprise software for systems, applications, products in data processing
PLC	A software for programmable logic controlling of industrial electromechanical processes
Simulink	A graphical software for modeling, simulating and analyzing multi-domain dynamic systems
SolidEdge	3D CAD, parametric feature, history-based and synchronous technology solid modeling software
SolidWorks	Solid modeling CAD and CAE software
SPSS	Statistical software package for the social sciences
SQL	Structured Query Language as a special-purpose programming language designed for managing data held in a stream processing and relational database management system
Tecnomatix	Software for manufacturing process management and product life-cycle management
Xmind	A mind mapping and brainstorming software
XML	Extensible Markup Language for representation of arbitrary data structures used in web services

Problem-solving and project-based attributes are instantiated by the Framework for the practical elements in Figure 5-6. Table 8-7 presents a sample list of courses with a minor, which presents medium level, or major, which presents high level, focus on sustainability and glocalization.

Table 8-7: Focus of courses on sustainability and glocalization

Code	*Courses*	*Focus on* sustainability	*Focus on* glocalization
d	Assembly technology	◑	◑
d	Automation technology	◑	
d	Industrial information technology and virtual product design	◑	◑
d	Materials science	◑	◑
d	Measurement and test engineering	◑	
e	Business administration		◑
e	Corporate finance and investment		◑
e	Entrepreneurship	◑	◑
e	Macroeconomics		◑
e	Marketing	◑	◑
e	Project management	◑	◑
b+h	Advanced German for economics		◑
b+h	Advanced German for engineering		◑
b+h	English I		◑
b+h	English II		◑
b+h	International internship	●	●
b+h	Research field of industrial engineering	◑	
b+h	Technical internship	◑	
b+h	Turkish I		◑
b+h	Turkish II		◑
f	Basic statistical methodologies	◑	
f	Human factors of engineering and ergonomics	●	◑
f	Introduction to engineering	◑	
f	Introduction to factory management	◑	◑
f	IT-based factory planning	◑	◑
f	Life-cycle assessment	●	◑
f	Operations research	◑	
f	Quality management	●	◑
f	Supply chain management	◑	●
g+i	Innovation and technology management with applications	●	◑
g+i	Project about shaping global value creation	●	●
g+i	Bachelor thesis	◑	◑

Legend: ◑ Partly applied

● Completely applied

8.3.2 **Sustainable Manufacturing Program**

Table 8-8 presents a curriculum planner worksheet according to the course categories, which are described in Subsection 5.1.2.

Table 8-8: Curriculum planner worksheet for the dual degree program

Code	Category of courses	Sum of ECTS	Share in ECTS
c	Computer and material sciences	12	10%
d	Engineering science	30	25%
e	Management science	9	8%
h	International internship, soft skills and exchange semesters	15	13%
f	Manufacturing science	30	25%
g	Project-based and laboratory courses	24	20%
i	Master thesis		
	Sum:	120	100%

Legend: ECTS: Credit points according to the European Credit Transfer and Accumulation System

Figure 8-3 presents the detailed curriculum of the dual degree program in sustainable manufacturing between the KAIST and the TU Berlin.

Graduate Dual Degree Program in Sustainable Manufacturing at the KAIST and TU Berlin, Degree: Master of Science										
1st year	fall	Semester 1	Course in computer science	Course in material science	Course 1 in engineering science	Course 1 in manufacturing	Course 2 in manufacturing	Project management	German electives	Sum of ECTS
		ECTS	6	6	6	6	6	3	3	36
	spring	Semester 2		Course 2 in engineering science	Course 3 in engineering science	Course in sustainable manufacturing	Life-cycle assessment	Project about shaping global value creation	English electives	
		ECTS		6	6	6	6	6	3	33
2nd year	fall	Semester 3		Course 4 in engineering science	Course 5 in engineering science	Course 3 in manufacturing	Course in management	Scientific research in KAIST laboratories	Korean electives	
		ECTS		6	6	6	6	0	3	27
	spring	Semester 4						Master thesis	International internship	
		ECTS						18	6	24
										120

Legend: ECTS: Credit points according to the European Credit Transfer and Accumulation System

Figure 8-3: Detailed curriculum of the dual degree program

Table 8-9 presents a sample list of elective courses, which are offered at the KAIST and the TU Berlin from fall 2015 to spring 2016, according to the categories within the frame of the dual degree program.

Table 8-9: Sample list of elective courses offered at the KAIST and TU Berlin

Category	TU Berlin	Language	ECTS	KAIST	Language	ECTS
Computer and material sciences						
	Electrical and Magnetic Properties of Materials	EN	6	Composite Materials	EN	6
	IT Solution for Digital Factory	EN	6	Knowledge-based Design System	EN	6
	Mechanical Properties of Nanostructured Materials	EN	6	Materials and Processing in Photovoltaic Devices	EN	6
	Principles of Industrial Information Technology	DE	6	Photovoltaic Materials	EN	6
	Virtual Product Creation Technologies	DE	6	Waves and Materials	EN	6
Engineering science						
	Assembly Technology	EN	12	Automatic Control	EN	6
	Functional Componetns of Mikrotechnology	DE	6	Deformation, Fracture and Strength	EN	6
	Joining and Coating Design-Completion	DE	6	Introduction to Finite Element Method (FEM)	KR	6
	Pressing Technology in Manufacturing	DE	6	Introduction to Nanotech Processing	EN	6
	Safety of Joined Components	DE	6	Joining Engineering	EN	6
				Metrology	EN	6
				Principle of Laser and Application	EN	6
				Special Topics in Mechanical Engineering	EN	6
				Vehicle Dynamics	EN	6
Management science						
	Innovation Management	DE	3	Decision Analysis and Risk Management	EN	3
	Logistics and Supply Chain Management	EN	12	Financial Management	EN	3
	Project Management	DE	3	Internet Business and Management	EN	3
	Quality Management	EN	6	IT Economics and Management	EN	3
	Supply Network Planning and Advanced Planning Systems	EN	12	Nonlinear Planning	EN	3
	Technology Management	DE	3	Project Management	KR	3
				Supply Chain Management	EN	3
Manufacturing science						
	Automation Engineering	DE	6	Design of Composite	KR	6
	Factory Management	EN	6	Design of Precision Machine System	KR	6
	Machine Tools	DE	6	Introduction to Robotics Engineering	EN	6
	Production Technology	EN	6	Manufacturing Systems Engineering	EN	6
	System Analysis and Six Sigma	DE	6			
Sustainable Manufacturing Science						
	Environmental Management Systems and Tools	EN	6	Sustainability Aspects	EN	6
	Environmental Optimization of Companies	EN	6			
	Life-cycle Assessment	EN	6			
	Management of Sustainable Development - Methods and Tools	EN	6			
	Management of Sustainable Processes	EN	6			
International internship, soft skills and exchange semesters						
	Industrial Internship at least six weeks	DE/EN		Industrial Internship at least six weeks	EN/KR	
Project-based and laboratory courses						
	Project Automation Engeneering	DE	6	Production Technological Project	EN	6
	Project Machine Tools and Manufacturing Technology	EN	6	Special Topics in Production Engineering	EN	6
	Project Work on Sustainability	EN	6			
Master Thesis						
	Master Thesis	EN/DE	18	Master Thesis	EN/KR	6

Legend: DE German
EN English
KR Korean

8.4 Appendix D: Case Studies with Sustained Value Creation

8.4.1 Hybrid Production System

Table 8-10: Classification of requirements for hybrid production system

Category	Importance	Requirement	Importance	Value creation factor				
				Product	***Process***	***Equipment***	***Organization***	***People***
$c_1(r_i)$ = Changeability	$p(c_1) = 9$	r_2 = High mobility	$p(r_2) = 9$			x		
		r_3 = High modularity				x		
		r_4 = High scalability			x	x		
$c_2(r_i)$ = Productivity	$p(c_2) = 9$	r_5 = Low area and space	$p(r_5) = 1$			x		
		r_6 = Low investment	$p(r_6) = 3$			x		
		r_7 = Low life-cycle costs	$p(r_7) = 3$			x		
		r_{10} = High capacity utilization				x	x	
$c_3(r_i)$ = Functionality	$p(c_3) = 3$	r_{16} = High satisfaction		x				
		r_{17} = High added value		x				
		r_{18} = Technical support				x		
$c_4(r_i)$ = Resource efficiency	$p(c_4) = 9$	r_{19} = Protection of ground water	$p(r_{25}) = 9$		x	x		
		r_{20} = High potential of resources	$p(r_{26}) = 3$			x		
		r_{21} = Temporal distribution of resources	$p(r_{27}) = 9$		x	x		
		r_{22} = Low CO_2 emission	$p(r_{28}) = 9$			x		
		r_{23} = Application of 6R			x	x		
		r_{24} = Low power demand	$p(r_{29}) = 1$		x	x		
$c_6(r_i)$ = Stakeholder engagement	$p(c_6) = 3$	r_{29} = Creating win-win situations					x	x
		r_{30} = Upgrading know-how					x	x

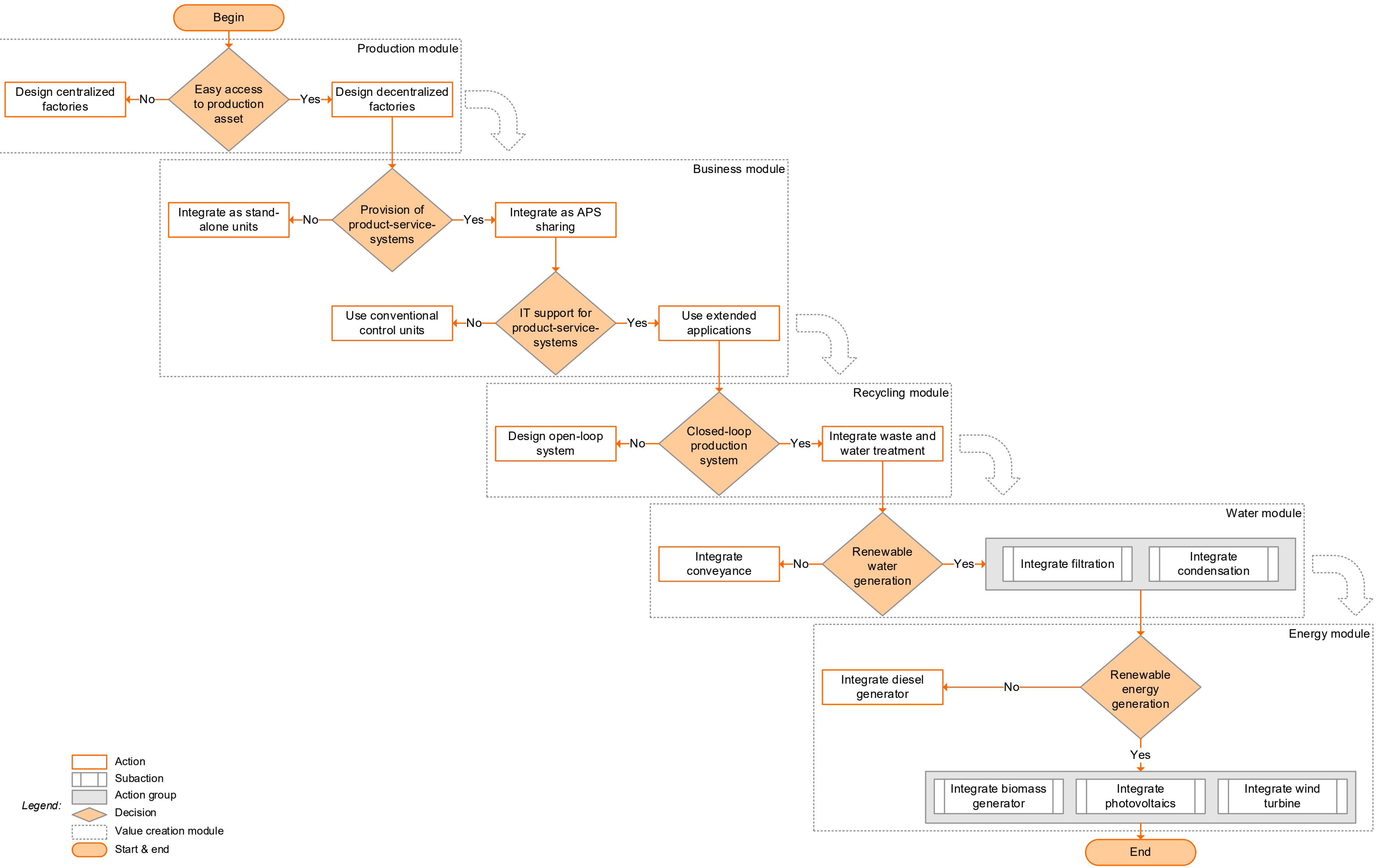

Figure 8-4: Decision tree for the Cypriot agricultural production system

The score of a solution is built by the multiplied combination of the importance $p(c_k)$ of all categories c_k and its fulfillment $s\big(c_k(r_i), o_j\big)$ by a solution o_j. A score $S\big(o_j\big)$ presents a summed up score for the jth solution, as presented by Equation (14):

$$S(o_j) = \sum_{k=1}^{u} \big[s\big(c_k(r_i), o_j\big) * p(c_k)\big] = s\big(c_1(r_i), o_j\big) * p(c_1) + s\big(c_2(r_i), o_j\big) * p(c_2) + \cdots + s\big(c_u(r_i), o_j\big) * p(c_u) \tag{14}$$

The following assessment methodology is selected for the water and energy module. Specific evaluation criteria w_z are defined for every requirement. A criterion can be a statement or an indicator. In case of a statement, an agreement is marked with ☒, a disagreement is marked as ☐. The scoring of the requirement depends on the agreement to the statements.

For the requirement r_{19} two "either/or" statements are identified. Table 8-11 presents the indication of the requirement's value to fulfillment levels.

Table 8-11: Indication of values to fulfillment levels for two statements ($z = 1, 2$)

Value of the requirement	***Notation***	
	$s(w_1, o_j)$ = "No use of ground water"	$s(w_2, o_j)$ = "Use of ground water"
$s\big(r_i(w_z), o_j\big) = 9$	☒	☐
$s\big(r_i(w_z), o_j\big) = 0$	☐	☒

For the requirement r_{20}, three statements are identified for each requirement. Table 8-12 presents the indication of the requirement's value to fulfillment levels. The assignment of agreement are interchangeable among evaluation criteria w_z.

Table 8-12: Indication of values to fulfillment levels for three statements ($z = 1, 2, 3$)

Value of the requirement	***Notation***		
	$s(w_1, o_j)$	$s(w_2, o_j)$	$s(w_3, o_j)$
$s\big(r_i(w_z), o_j\big) = 0$	☐	☐	☐
$s\big(r_i(w_z), o_j\big) = 1$	☐	☐	☒
$s\big(r_i(w_z), o_j\big) = 3$	☐	☒	☒
$s\big(r_i(w_z), o_j\big) = 9$	☒	☒	☒

For the requirements r_2, r_5, r_{21}, the statements are ordered by the level of fulfillment. The first statement represents the highest degree of fulfillment, the last one represents the lowest degree of fulfillment, as presented by Table 8-13. A fulfilled statement is marked with ☒.

Table 8-13: Indication of values to fulfillment levels

Value of the requirement	Notation		
	$s(w_1, o_j)$	$s(w_2, o_j)$	$s(w_3, o_j)$
$s(r_i(w_z), o_j) = 0$	☐	☐	☐
$s(r_i(w_z), o_j) = 1$	☐	☐	☒
$s(r_i(w_z), o_j) = 3$	☐	☒	☐
$s(r_i(w_z), o_j) = 9$	☒	☐	☐

In case of an indicator, $b(w_z, o_j)$ is the value of the zth indicator for the jth solution expressed in [TEUR] for r_6 and r_7, [kg/MWh] for r_{22}, and [kW] for r_{24}. $b^*_{max}(w_z)$ represents the adjusted realized maximum value for a specific indicator. The real maximum was eliminated to avoid a distortion of the results. $b_{min}(w_z)$ represents the realized minimum value. $b_{diff}(w_z)$ is the difference between the adjusted maximum and minimum value for a certain indicator, as presented by Equations (15)-(17).

$$b_{min}(w_z) \leq b(w_z) \tag{15}$$

$$b^*_{max}(w_z) \geq b(w_z) \tag{16}$$

$$b_{diff}(w_z) = b^*_{max}(w_z) - b_{min}(w_z) \tag{17}$$

$s(w_z, o_j)$ scores the significance between the zth indicator and jth solution, as presented by Equation (18).

$$s(w_z, o_j) = \begin{cases} 9, & if \quad b_{min}(w_z) \leq b(w_z, o_j) \leq b_{min}(w_z) + 25\% * \ b_{diff}(w_z) \\ 3, & if \quad b_{min}(w_z) + 25\% * \ b_{diff}(w_z) < b(w_z, o_j) \leq b_{min}(w_z) + 50\% * \ b_{diff}(w_z) \\ 1, & if \quad b_{min}(w_z) + 50\% * \ b_{diff}(w_z) < b(w_z, o_j) \leq b_{min}(w_z) + 75\% * \ b_{diff}(w_z) \\ 0, & if \quad b_{min}(w_z) + 75\% * \ b_{diff}(w_z) < b(w_z, o_j) \leq \ b_{max}(w_z) \end{cases} \tag{18}$$

The score of a category c_k, $s(c_k(r_i), o_j)$, is built by the multiplied combination of the importance $p(r_i)$ of the requirements r_i related to the category c_k, and its fulfillment $s(r_i, o_j)$ by a solution o_j, as presented by Equation (19).

$$s(c_k(r_i), o_j) = \sum_{i=1}^{n} [s(r_i, o_j) * \ p(r_i)] = s(r_1, o_j) * p(r_1) + s(r_2, o_j) * p(r_2) + \cdots + s(r_n, o_j) * p(r_n) \quad , \forall \ r_i \mapsto c_k \tag{19}$$

A score of a solution $S(o_j)$ presents a summed up score for the jth solution, as presented by Equation (20):

$$S(o_j) = \sum_{k=1}^{u} s(c_k(r_i), o_j) = s(c_1(r_i), o_j) + s(c_2(r_i), o_j) + \cdots + s(c_u(r_i), o_j) \tag{20}$$

The maximum target $t_{max}(o_j)$ is selected as a whole number around the maximum limit, the minimum target $t_{min}(o_j)$ around the minimum limit. For future solutions, the maximum target $t_{max}^{TO-BE}(o_j)$ is equal to the calculated maximum, as presented in Equation (21):

$$t_{max}^{TO-BE}(o_j) = \sum_{i=1}^{n} [9 * p(r_i)] \qquad \forall\, r_i \mapsto c_k \tag{21}$$

The maximum target for current solutions $t_{max}^{AS-IS}(o_j)$ is the half of the calculated maximum, as presented in Equation (22):

$$t_{max}^{AS-IS}(o_j) = \frac{\sum_{i=1}^{n} [9 * p(r_i)]}{2} \qquad \forall\, r_i \mapsto c_k \tag{22}$$

The maximum target $t_{max}(o_j)$ is halved to determine the minimum target $t_{min}(o_j)$, as presented by Equations (23)-(24).

$$t_{min}^{TO-BE}(o_j) = \frac{t_{max}^{TO-BE}(o_j)}{2} \tag{23}$$

$$t_{min}^{AS-IS}(o_j) = \frac{t_{max}^{AS-IS}(o_j)}{2} \tag{24}$$

8.4.2 **Redesigned Handling Equipment**

Table 8-14: Classification of requirements for redesigned handling equipment

Category	*Importance*	*Requirement*	*Importance*	*Value creation factor*: *Product*	*Process*	*Equipment*	*Organization*	*People*
$c_1(r_i)$ = Changeability	$p(c_1) = 3$	r_1 = High compatibility with other handling equipment	$p(r_1) = 3$		x	x		
		r_1 = High mobility with work places of individual processes	$p(r_1) = 3$			x		
		r_3 = High modularity	$p(r_3) = 9$			x		
		r_4 = High scalability	$p(r_4) = 3$		x	x		
$c_2(r_i)$ = Productivity	$p(c_2) = 3$	r_5 = Low area and space	$p(r_5) = 3$			x		
		r_6 = Low investment	$p(r_6) = 3$			x		
		r_8 = High load and upload efficiency and velocity	$p(r_7) = 9$			x		
		r_9 = Low maintenance efforts	$p(r_8) = 1$		x	x		
$c_3(r_i)$ = Functionality	$p(c_3) = 9$	r_{13} = Low dust contamination	$p(r_9) = 1$			x		
		r_{14} = Low coating fragmentation during logistics	$p(r_{10}) = 9$			x		
		r_{15} = Low damage during logistics	$p(r_{11}) = 3$			x		
$c_4(r_i)$ = Resource efficiency	$p(c_6) = 9$	r_{20} = High potential of resources	$p(r_{16}) = 1$			x		
$c_5(r_i)$ = Ergonomics	$p(c_4) = 9$	r_{25} = Transparent documentation for easy use	$p(r_{12}) = 1$		x			x
		r_{26} = Transparent documentation of workflow	$p(r_{13}) = 1$		x			x
		r_{27} = Ergonomic load and upload of components	$p(r_{14}) = 9$			x		
		r_{28} = Ergonomic handling of equipment	$p(r_{15}) = 3$			x		x

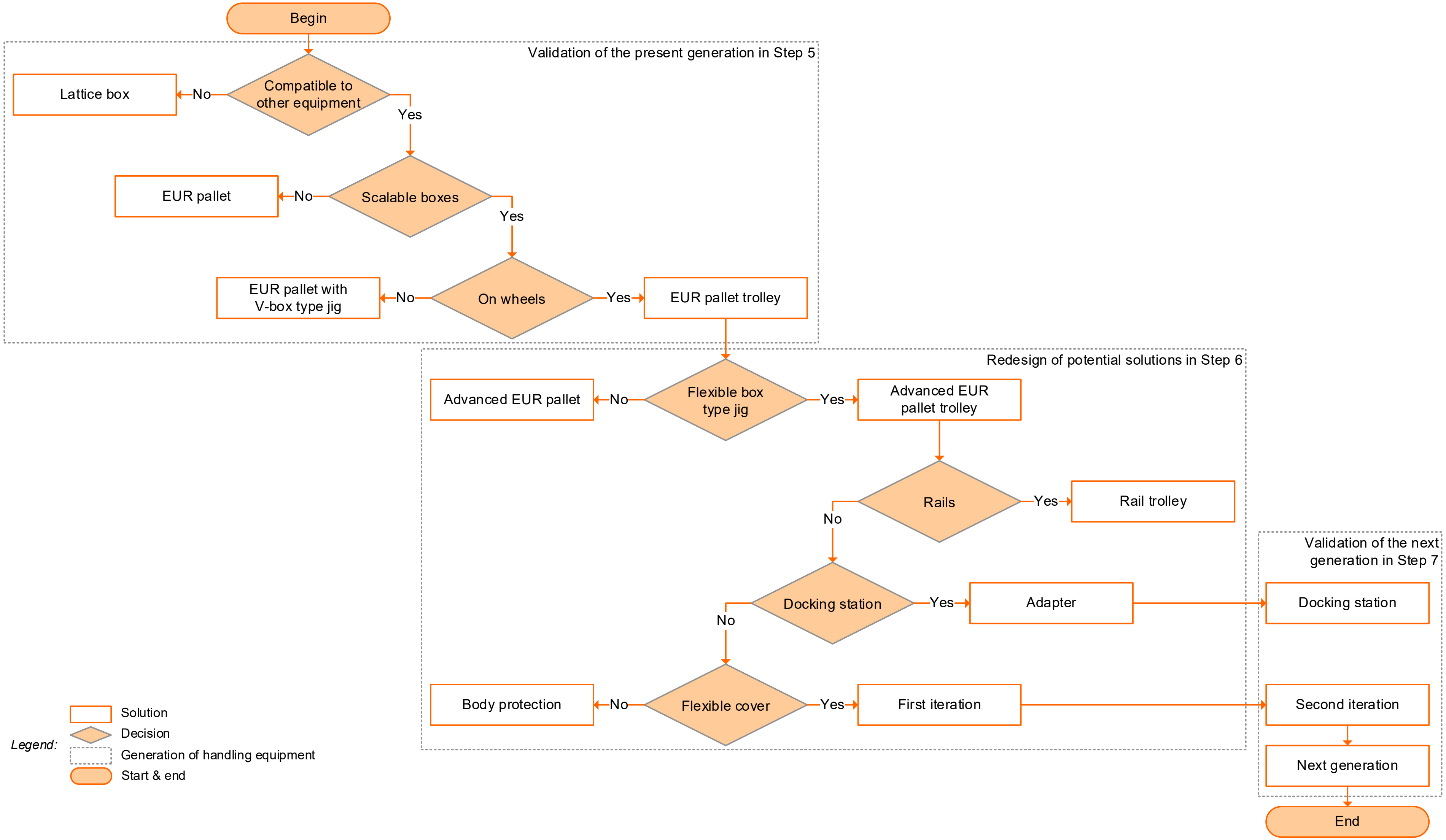

Figure 8-5: Decision tree for the redesign of handling equipment

Table 8-15: Scores for two categories of redesigned handling equipment

				$c_1(o_j)$ = Present generation				$c_2(o_j)$ = Potential solutions						$c_3(o_j)$ = Next generation		
				AS-IS	AS-IS	AS-IS	AS-IS	AS-IS	AS-IS	TO-BE	TO-BE	TO-BE	TO-BE	TO-BE	TO-BE	TO-BE
Category	*Importance*	**Requirement**	*Importance*	***o_1 = Lattice box***	***o_2 = EUR pallet***	***o_3 = Advanced EUR pallet***	***o_4 = EUR pallet with V-box type jig***	***o_5 = EUR pallet trolley with V-box type jig***	***o_6 = Advanced EUR pallet trolley***	***o_7 = Roller conveyor***	***o_8 = Body protection***	***o_9 = First iteration***	***o_{10} = Adapter***	***o_{11} = Docking station***	***o_{12} = Second iteration***	***o_{13} = Next generation***
$c_1(r_i)$ = Changeability		**r_1** = High compatibility with other handling equipment	$p(r_1)$ = 3	$s(r_1,o_1)$ = 0	9	9	9	9	9	9	9	9	9	9	9	9
		The equipment is compatible with manual and automated hand lifts.			x	x	x	x	x	x	x	x	x	x	x	x
		The equipment is compatible with forklifts.			x	x	x	x	x	x	x	x	x	x	x	x
		The equipment is compatible with the lattice boxes.			x	x	x	x	x	x	x	x	x	x	x	x
		r_1 = High compatibility with work places of individual processes	$p(r_1)$ = 3	$s(r_1,o_1)$ = 1	3	3	9	1	3	9	3	9	9	3	9	9
		The equipment is compatible with future manipulators.					x		x	x		x	x		x	x
		The equipment can be stored in existing buffer stocks.		x	x	x	x	x	x	x	x	x	x	x	x	x
		The equipment is compatible with automated material flow systems.			x	x	x			x	x	x	x	x	x	x
		r_3 = High modularity	$p(r_3)$ = 9	$s(r_3,o_1)$ = 1	3	9	9	3	9	9	9	9	9	9	9	9
		The equipment has standardized interfaces for the turbine blades.				x	x		x	x	x	x	x	x	x	x
		The equipment has standardized interfaces to be moved by a conveyor vehicle.			x	x	x	x	x	x	x	x	x	x	x	x
		The equipment has standardized inferfaces to be connected to a workplace.		x	x	x	x	x	x	x	x	x	x	x	x	x
		r_4 = High scalability	$p(r_4)$ = 3	$s(r_4,o_1)$ = 3	9	1	0	9	0	0	9	3	3	3	3	9
		The equipment can be used for all guide and rotor blades.			x			x			x					x
		The equipment can be used for at least 4 differnt kinds of blade types.		x								x	x	x	x	
		The equipment can be used for at least 2 differnt kinds of blade types.				x										
	$p(c_1)$ = 3			**$s(c_1(r_i),o_1)$ = 21**	**90**	**120**	**135**	**84**	**117**	**135**	**144**	**144**	**144**	**126**	**144**	**162**
$c_2(r_i)$ = Productivity		**r_5** = Low area and space	$p(r_5)$ = 3	$s(r_5,o_1)$ = 3	3	3	3	3	3	3	3	3	3	3	1	3
		*floor space (new) < 0,5*floor space (today)*														
		floor space (new) =< floor space (today)		x	x	x	x	x	x	x	x	x	x	x		x
		*floor space (new) < 2*floor space (today)*													x	
		r_6 = Low investment	$p(r_6)$ = 3	$s(r_6,o_1)$ = 3	9	9	9	3	3	9	3	3	3	3	3	3
		The investment in new equipment has a payback period of less than 6 months.			x	x	x			x						
		The investment in new equipment has a payback period of less than 1 year.		x				x	x		x	x	x	x	x	x
		The investment in new equipment has a payback period of less than 3 years.														
		r_8 = High load and upload efficiency and velocity	$p(r_8)$ = 9	$s(r_8,o_1)$ = 3	9	3	9	9	9	9	1	3	3	3	3	3
		Loading and uploading one turbine blades does not take more than 2 seconds.			x		x	x	x	x						
		Loading and uploading one turbine blades does not take more than 5 seconds.		x		x						x	x	x	x	x
		Loading and uploading one turbine blades does not take more than 10 seconds.									x					
		r_9 = Low maintenance efforts	$p(r_9)$ = 1	$s(r_9,o_1)$ = 9	9	9	9	9	9	9	9	9	9	9	9	9
		The equipment can be maintained without special knowledge.		x	x	x	x	x	x	x	x	x	x	x	x	x
		The equipment has to be maintained by a trained TACR-worker.														
		The equipment has to be maintained by an external expert or by the manufacturer.														
	$p(c_2)$ = 3			**$s(c_2(r_i),o_1)$ = 54**	**126**	**72**	**126**	**108**	**108**	**126**	**36**	**54**	**54**	**54**	**48**	**54**

Table 8-16: Scores for three categories of redesigned handling equipment

				$c_1(o_j)$ = Present generation					$c_2(o_j)$ = Potential solutions						$c_3(o_j)$ = Next generation		
				AS-IS		AS-IS	AS-IS	AS-IS	AS-IS	AS-IS	TO-BE	TO-BE	TO-BE	TO-BE	TO-BE	TO-BE	TO-BE
Category	*Importance*	**Requirement**	*Importance*		o_1 = *Lattice box*	o_2 = *EUR pallet*	o_3 = *Advanced EUR pallet*	o_4 = *EUR pallet with V-box type jig*	o_5 = *EUR pallet trolley with V-box type jig*	o_6 = *Advanced EUR pallet trolley*	o_7 = *Roller conveyor*	o_8 = *Body protection*	o_9 = *First iteration*	o_{10} = *Adapter*	o_{11} = *Docking station*	o_{12} = *Second iteration*	o_{13} = *Next generation*
$c_3(r_i)$ = Functionality		r_{13} = Low dust contamination	$p(r_{13})$ = 1	$s(r_{13},o_1)$ =	3	3	3	3	3	3	3	1	1	3	3	1	3
		The equipment has its own cleaning mechanism.															
		The equipment can be cleaned by using compressed or suction air with little effort.			x	x	x	x	x	x	x			x	x		x
		The equipment must be cleaned under high effort.										x	x			x	
		r_{14} = Low coating fragmentation during logistics	$p(r_{14})$ = 9	$s(r_{14},o_1)$ =	0	0	3	9	0	9	9	9	9	9	9	9	9
		The turbine blades cannot bump into one another during transportation in the hall.					x	x		x	x	x	x	x	x	x	x
		The turbine blades cannot bump into one another during loading and uploading.					x	x		x	x	x	x	x	x	x	x
		The turbine blades cannot bump the equipment.						x		x	x	x	x	x	x	x	x
		r_{15} = Low damage during logistics	$p(r_{15})$ = 3	$s(r_{15},o_1)$ =	0	0	1	3	0	3	3	9	9	9	9	9	9
		The turbine blades are protected from weather and dirt.									x	x	x	x	x	x	x
		The turbine blades cannot bump into one another during transportation between the halls.					x	x		x		x	x	x	x	x	x
		The turbine blades cannot bump the equipment.						x		x	x	x	x	x	x	x	x
	$p(c_3)$ = 9			**$s(c_3(r_i),o_1)$ =**	**3**	**3**	**33**	**93**	**3**	**93**	**93**	**109**	**109**	**111**	**111**	**109**	**111**
$c_4(ri)$ = Resource efficiency		r_{20} = High potential of resources	$p(r_{26})$ = 1	$s(r_{26},o_1)$ =	1	3	9	9	3	9	9	9	9	9	9	9	9
		The materials used are heat-resistant.			x	x	x	x	x	x	x	x	x	x	x	x	x
		The materials used are acid-resistant.				x	x	x	x	x	x	x	x	x	x	x	x
		The materials used are mostly renewable.					x	x		x	x	x	x	x	x	x	x
	$p(c_6)$ = 9			**$s(c_6(r_i),o_1)$ =**	**1**	**3**	**9**	**9**	**3**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**
$c_5(ri)$ = Ergonomics		r_{25} = Transparent documentation for easy use	$p(r_{19})$ = 1	$s(r_{19},o_1)$ =	3	3	1	1	3	1	1	3	3	9	3	3	3
		The Registration-ID can be read without any major physical effort of the workers.			x	x			x					x			
		The equipment contains instructions for load and upload for all relevant blade types.										x	x	x	x	x	x
		r_{26} = Transparent documentation of workflow	$p(r_{20})$ = 1	$s(r_{20},o_1)$ =	9	1	1	1	3	3	3	3	9	9	9	9	9
		The order papers are fixed at a height of at least 120 cm (eye height).			x								x	x	x	x	x
		The order papers are fixed at a height of at least 85 cm.							x	x	x	x					
		The order papaers are easy to load or remove, but are fixed at a height of under 80 cm.				x	x	x									
		r_{27} = Ergonomic load and upload of components	$p(r_{21})$ = 9	$s(r_{21},o_1)$ =	0	1	1	1	3	3	9	1	9	9	3	9	9
		Workers do not have to stoop to move little blades. The blades are delivered at the working height of ca. 85 cm.							x	x	x	x	x	x	x	x	x
		Workers do not have to move big blades manually and without stretching.									x		x	x		x	x
		Workers do not have to turn their upper body to remove the blades.				x	x	x	x	x	x		x	x	x	x	x
		r_{28} = Ergonomic handling of equipment	$p(r_{22})$ = 3	$s(r_{22},o_1)$ =	9	0	0	0	9	9	9	9	9	9	9	9	9
		The equipment can be moved manually.			x				x	x	x	x	x	x	x	x	x
		The manual movement of the equipment is possible without any major physical effort of the workers.			x				x	x	x	x	x	x	x	x	x
		The manual braking of the equipment is possible without any major physical effort of the workers.															x
	$p(c_4)$ = 9			**$s(c_4(r_i),o_1)$ =**	**39**	**13**	**11**	**11**	**60**	**58**	**112**	**42**	**120**	**126**	**66**	**120**	**120**
			$S(o_j)$	**$S(o_1)$ =**	**612**	**819**	**1053**	**1800**	**1170**	**2115**	**2709**	**1980**	**2736**	**2808**	**2214**	**2718**	**2808**
			$t_{min}(o_j)$	**$t_{min}(o_1)$ =**	**796,5**	**796,5**	**796,5**	**796,5**	**796,5**	**796,5**	**1593**	**1593**	**1593**	**1593**	**1593**	**1593**	**1593**
			$t_{max}(o_j)$	**$t_{max}(o_1)$ =**	**1593**	**1593**	**1593**	**1593**	**1593**	**1593**	**3186**	**3186**	**3186**	**3186**	**3186**	**3186**	**3186**

8.4.3 **Simulated Maintenance Network**

Equations (25), (26) and (27) present how mean times to repair (MTBR), between repairs (MTBR) and between failures (MTBF) are calculated for each vehicle type, as presented by $MT.._{Vehicle}$, where

- x_{MRO} is the number of maintenance orders including all vehicles of a certain vehicle type,
- t_{MRO} is the throughput time of maintenance orders, and
- $t_{Operation}$ is the time between two maintenance orders.

$$MTTR_{Vehicle} = \frac{\sum t_{MRO}}{x_{MRO}} \quad (25)$$

$$MTBR_{Vehicle} = \frac{\sum t_{Operation}}{x_{MRO}} \quad (26)$$

$$MTBF_{Vehicle} = \frac{MTTR_{Vehicle} + MTBR_{Vehicle}}{x_{MRO}} \quad (27)$$

All requirements to achieve this goal are identified and assigned to value creation factors based on their most relevant impact on the economy in Table 8-17.

Table 8-17: Classification of requirements for simulated maintenance network

Category	Requirements	Indicators	Importance	Value creation factor: Product	Process	Equipment	Organization	People
$c_2(r_i)$ = **Productivity**	r_{10} = High capacity utilization	w_1 = Workshop utilization	$p(w_1)$ = 9			x	x	
		w_2 = Availability of movables	$p(w_2)$ = 9			x	x	
		w_3 = Mean Time Between Repair-ratio	$p(w_3)$ = 9			x	x	
	r_{11} = Low inventories			x			x	
	r_{12} = Low throughput time	w_4 = Productivity	$p(w_4)$ = 9				x	
		w_5 = Mean Time to Repair-ratio	$p(w_5)$ = 9				x	
		w_6 = Transfer ratio	$p(w_6)$ = 3				x	

Table 8-18 presents a sample data mining sheet, which is used as input for modeling and simulation of the material flow in the maintenance network.

Table 8-18: Sample data mining sheet

Workshop location	***Maintenance order number***	***Maintenance order type***	***Vehicle type***	***Vehicle type***	***Order item***	***Service description***	***Date***	***Throughput time (dd.hh.mm.ss)***
MW1	52840765	Preventive	Garbage truck	19	001	Full inspection	12.01.2009	01:11:33:44
					002	Replacements	12.01.2009	00:08:26:01
W8	52846969	Corrective	Collection vehicle	1	001	Installation auxiliary heating	12.01.2009	00:02:37:43
MW2	52840773	Corrective	Road sweeper	18	001	Small inspection	13.01.2009	00:05:51:18
					002	Replacement break light	13.01.2009	00:02:37:43
					003	Replacement gear system	14.01.2009	00:13:23:58
					004	Deletion of failure memory	14.01.2009	00:00:09:32
					...	...	...	...
MW1	52841420	Preventive	Collection vehicle	1	001	Replacement break system	12.01.2009	01:07:16:23
W3	52847738	Corrective	Garbage truck	19	001	Replacement of lubricants	13.01.2009	00:02:12:35
					002	Filter cleaning	13.01.2009	00:01:53:51
					003	Replacement alternator	14.01.2009	00:03:06:26
					004	Replacement Wipers	14.01.2009	00:01:17:34
MW1	52842108	Corrective	Rinsing vehicle	5	001	Replacement of lubricants	13.01.2009	00:02:33:44

Table 8-19: Scores for all scenarios of simulated maintenance network

Category	Requirement	Indicator	Importance		AS-IS o_1 = Present network	TO-BE o_2 = Scenario A1	TO-BE o_3 = Scenario A2	TO-BE o_4 = Scenario B1	TO-BE o_5 = Scenario B2	TO-BE o_6 = Scenario C1	TO-BE o_7 = Scenario C3	TO-BE o_8 = Best case
$c_2(r_i)$ = Productivity	$r_{10}(w_z)$ = High capacity utilization			$s(r_{10},o_1)$ =	45	9	36	171	45	9	27	108
		w_1 = *Workshop utilization*	$p(w_1)$ = 9	$s(w_1,o_1)$ =	1	0	0	9	1	1	3	0
				$b(w_1,o_1)$ =	52,96%	53,85%	53,45%	51,79%	53,43%	53,01%	52,64%	53,98%
		w_2 = *Availibility of movables*	$p(w_2)$ = 9	$s(w_2,o_1)$ =	3	1	3	1	3	0	0	9
				$b(w_2,o_1)$ =	89,79%	89,35%	89,65%	89,54%	89,68%	88,50%	88,87%	90,71%
		w_3 = *Mean Time Between Repair-ratio*	$p(w_3)$ = 9	$s(w_3,o_1)$ =	1	0	1	9	1	0	0	3
				$b(w_3,o_1)$ =	12,83%	12,72%	12,76%	13,13%	12,82%	12,62%	12,67%	12,94%
	$r_{11}(w_z)$ = Low inventories			$s(r_{11},o_1)$ =	-	-	-	-	-	-	-	-
	$r_{12}(w_z)$ = Low throughput time			$s(r_{12},o_1)$ =	54	45	81	36	54	27	36	165
		w_4 = *Productivity*	$p(w_4)$ = 9	$s(w_4,o_1)$ =	3	1	3	3	3	0	1	9
				$b(w_4,o_1)$ =	24,69%	24,08%	25,25%	25,43%	25,11%	22,21%	23,66%	27,04%
		w_5 = *Mean Time to Repair-ratio*	$p(w_5)$ = 9	$s(w_5,o_1)$ =	3	1	3	1	3	0	0	9
				$b(w_5,o_1)$ =	98,54%	98,48%	98,53%	98,47%	98,54%	98,36%	98,41%	98,68%
		w_6 = *Transfer ratio*	$p(w_6)$ = 3	$s(w_6,o_1)$ =	0	9	9	0	0	9	9	1
				$b(w_6,o_1)$ =	99,89%	100,00%	99,98%	99,91%	99,91%	100,00%	99,98%	99,92%
			$S(o_j)$	**$S(o_1)$ =**	**99**	**54**	**117**	**207**	**99**	**36**	**63**	**273**
			$t_{min}(o_j)$	**$t_{min}(o_1)$ =**	**54**	**108**	**108**	**108**	**108**	**108**	**108**	**108**
			$t_{max}(o_j)$	**$t_{max}(o_1)$ =**	**108**	**216**	**216**	**216**	**216**	**216**	**216**	**216**