IB 131-2015/041

Implementing LEAN and Six-Sigma: a case study in developing the composites production process economically and ecologically

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Braunschweig

March/2015

MH-FA-56-FB01

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtzgemeinschaft
Institut für Faserverbundleichtbau und Adaptronik

IB 131-2015/041

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Braunschweig, May 2014

This report contains:

47 pages

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MH-FA-56-FB01

Implementing LEAN and Six-Sigma: a case study in developing the Composites Production Process economically and ecologically

Projektarbeit

an der Technischen Universität Braunschweig

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im Studiengang: Wirtschaftsingenieurwesen Studienrichtung Maschinenbau, Master

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Bearbeitungszeitraum: 6 Wochen

Abgabedatum am: 31.03.2015

Abstract

An increasing demand for the composite structures made of fiber reinforced polymers (FRP) requires eco-efficient production process. In order to achieve that, both ecological and economic aspects should be assessed during the associated life-cycle stage in order to optimize the production processes performance by implementing the suitable management tools. The aim of this project is to explain the possibility of forming a comprehensive Sustainable Development (SD) framework for the decision-makers to achieve more environmentally friendly and cost efficient processes. In this project, several decision support tools are implemented such as the Life-Cycle Assessment (LCA), the Life-Cycle-Cost Analysis (LCCA), Lean, and Six-Sigma. This comprehensive SD framework is based on a framework that has been developed in a previous author thesis.

Key Words:

Life-Cycle Assessment (LCA); Life-Cycle Cost Analysis (LCCA); manufacturing and assembly of the complex composite structures; Lean; Six-Sigma

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Kurzfassung

Eine steigende Nachfrage nach den Strukturen aus Faserverbundkunststoff (FVK) erfordert ökoeffiziente Herstellungsprozess. Um die steigende Nachfrage zu erreichen, sollten beide ökologische und ökonomische Aspekte in der verbundenen Lebenszyklusphase bewertet werden, und dann sollte die Prozesseleistung sollte durch die Umsetzung der geeigneten Management-Tools optimiert werden. Das Ziel dieses Projektes ist es, die Möglichkeit der Bildung einer umfassenden Sustainable Development (SD) zu erklären. Diese SD dient dem Entscheidungsträgern um umweltfreundlichere und kosteneffiziente Prozesse zu erzielen. Um dies zu erreichen, werden mehrere Entscheidungshilfen umgesetzt, wie der Life-Cycle Assessment (LCA), die Life-Cycle Cost Assessment (LCCA), Lean und Six Sigma. Dieses umfassende SD wurde im Rahmen von einer Masterarbeit des Autors entwickelt.

Acknowledgments

The targets of this project could only be achieved with the great support and assistance from the Institute of Composite Structures and Adaptive Systems (FA) at DLR and the Institute of Adaptronic and Functional Integration (IAF) at TU Braunschweig. I would like to express my appreciation to Prof. Dr.-Ing. Michael Sinapius, the Managing Director of the Institute of Adaptronic and Functional Integration (IAF) at TU Braunschweig, for giving me the opportunity and support to write my master project. It was my honor to work in the Institute of Composite Structures and Adaptive Systems (FA) at DLR under the supervision of Prof. Dr.-Ing. Martin Wiedemann the head of the institute.

Special thanks to my supervisors Dr.-Ing. Henning Schlums and Dipl.-Ing. Philipp Hilmer for the continuous support and assistance he provided me with. Thanks a lot for their useful advice, suggestions and helps which had the crucial effect in achieving the aimed targets of this project.

Declaration

Unless otherwise indicated in the text or references, or acknowledged, this project is entirely the product of my own scholarly work. Any inaccuracies of fact or faults in reasoning are my own and accordingly I take full responsibility. This is to certify that the printed version is equivalent to the submitted electronic one.

Ali Mahmood Hamad Al-Lami Braunschweig, 31th of March 2015

Table of Contents

Abstract ... i

Kurzfassung ... ii

Acknowledgments ... iii

Declaration ... iv

Table of Contents ... v

List of Figures ... vii

List of Tables ... viii

Abbreviations ... ix

1 Introduction and Motivation ... 10

2 State of Art ... 14

2.1 LCA ... 14

2.2 LCCA ... 17

2.3 Production of Complex Composite Structures ... 19

2.3.1 Complex Composite Structures ... 20

2.3.2 Production ... 20

2.4 BPR ... 21

2.5 Six Sigma ... 22

2.5.1 Define ... 22

2.5.2 Measure ... 23

2.5.3 Analyze ... 23

2.5.4 Improve ... 23

2.5.5 Control ... 24

2.6 Lean ... 24

2.6.1 MUDA ... 25

2.6.2 MURA 27
2.2.3 MURI 27
3 BPR, LCA and LCCA Framework and Results 30
3.1 BPR, LCA and LCCA Framework 30
3.2 BPS Compiled Results 31
3.2.1 Compiled LCA Results 31
3.2.2 Compiled LCCA Results 32
4 Comprehensive SD Framework 34
5 Conclusions and Outlook 40
5.1 Conclusions 40
5.2 Outlook 40
6 References 41

List of Figures

Figure 1: LCA Framework, based on (29 p. 17)..15
Figure 2: Simplified Life-Cycle Stages of LCA, based on (7 p. 204) 16
Figure 3: Cumulative Environmental Impacts throughout Product Life-Cycle (31 p. 14) 17
Figure 4: Development Process Chain of Composite Structures, based on (5 p. 201)...............20
Figure 5: Six Sigma Framework based on (50 p. 11)...22
Figure 6: Wastes Categories (53)...26
Figure 7: Combined LCA, LCCA and BPR Framework for Manufacturing and Assembly of Complex Composite Structures, based on (14 p. 48), (19 p. 3) and (32 p. 1366) 30
Figure 8: Cost Categories of Manufacturing Wing Ribs 32
Figure 9: Comparison of Six Sigma with combined BPR, LCA and LCCA Framework, based on (3 p. 17) and (50 p. 11) 35
Figure 10: Comprehensive SD Framework, based on (3 p. 29), (51 pp. 27 and 44), (50 p. 11) and (52 pp. 16–71)...37

List of Tables

Table 1: Comparison of LCA and LCCA in Common Framework, based on (29 p. 17), (36 p. 118), and (14 p. 37) 19

Abbreviations

Abbreviation	Explanation
BPMN	Business-Process Model and Notation
BPR	Business-Process Re-engineering
BPS	Business-Process Simulation
CAGR	Compound Annual Growth Rate
CFRP	Carbon Fiber-Reinforced Polymer
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalent
EU	European Union
FRP	Fiber-Reinforced Polymer
GFRP	Glass Fiber-Reinforced Polymer
GHG	Greenhouse Gas
ISO	International Organization for Standardization
JIT	Just-in-Time
kg	Kilogram: Mass
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory Analysis
LCIA	Life-Cycle Impact Assessment
Lean TPM	Lean Total Process Management
LRI	Liquid Resin Infusion
SD	Sustainable Development
TPS	Toyota Production System
VSM	Value Stream Mapping

1 Introduction and Motivation

Since the Earth Summit at Rio de Janeiro in 1992, the United Nations Conference on Environment and Development (UNCED) announced the sustainability as the targeted development for the mankind future (1). The sustainable development (SD) has been defined as the development methods, techniques, and applications that fulfill the requirements of the current generation and ensure that for the future generations as well. The SD can be achieved by seeking the balance between the essential sustainability aspects, which include protecting the environment, developing the economy and assuring the social equity (2 pp. 1–2).

This project shares the same motivation and introduction of the previous thesis as a further step that is performed to achieve a comprehensive SD framework (3 pp. 1–4). Generally, the design and manufacturing are the decisive life-cycle stages of any product generally and especially the composite material products (4 pp. 3–9). The design stage defines the characteristics of the composite products, whereas this definition is realized within the product manufacturing (5 pp. 199 and 311). Technically, SD should be present in the early design stage. In the design and manufacturing stages the sustainable perspectives can be adopted and the sustainability path throughout the further life-cycle stages can be planned (6 p. 107).

Generally, the SD aspects are affected significantly by each other, while a comprehensive assessment that includes all the SD aspects and the relation between them is required. Nonetheless, in this project, the social equity aspects are excluded. Hence, this project consists of the economic and ecological aspects, which represents an example of seeking the eco-efficiency. Theoretically, eco-efficiency is defined as a management methodology that attempts to optimize either the economic aspects or the ecological aspects without affecting the other one negatively (7 p. 203).

Nowadays, the climate change is considered as the most serious phenomena in the ecological aspects (8). Although the climate has been continuously changed throughout the millions and billions years of the earth existence, the man-made global warming during the last two centuries has caused a deteriorating environmental situation which exceeded the climate change that occurs within the previous 2.5 million years (9). The man-made global warming is a result of the increasing greenhouse gas (GHG) emissions. The GHG's include: carbon dioxide (CO_2), methane, nitrous oxide, and fluorinated gases (10).

Statistically, CO_2 is the most generated GHG, while CO_2 causes about 64 % of the man-made global warming (10). In Germany, CO_2 emissions represented about 88 % from the GHG emissions in 2013, whereas these emissions are majorly produced by two economic sectors. On one hand, the energy sector in Germany emits around 94 % of the CO_2 emissions including about 19 % that is produced due to the energy utilization in the transportation sector. On the other hand, the industrial processes sector produces around 6 % of the total CO_2 emissions (11). Hence, the climate change is so far the most critical challenge that confronted the mankind (12 p. 4). It induces the decision-makers in the world to take urgent and strong paces to combat the global warming by adopting more SD (13 p. 287).

The decision-makers are the individuals or teams who are responsible to perform the strategic planning, priority setting, as well as product or process design or redesign. They can serve the industry, government, or non-government organizations (14 p. 5), whereas decision-makers in this project are represented by the engineers and experts who have the responsibility to perform and develop the production processes of composite structures at DLR.

The European Union (EU) recently announced its new strategies to decrease the GHG emissions in the EU member states by 2030 with a minimum amount of 40 % reduction from its level in 1990 (15). These adopted actions in the EU concentrate specifically on raising the renewable energy production and increasing the efficiency of energy consumption (15). However, in the EU the wind energy shared around 44 % of the renewable energy production in 2013 (16 p. 7). These facts illuminate the necessity of supporting the renewable energy alternatives and adopting more environmentally friendly applications in the industrial processes sector.

The second ingredient of the SD is the economic aspects, whereas it is essential to satisfy and balance the SD aspects to achieve the aimed sustainability (6 p. 107).The economic aspects represent a sensitive side from the SD nowadays, while the whole world struggling to avoid another financial crisis like the one that gripped the world in 2008 which has been ranked as the worst financial crisis in the mankind history (17).

In addition, the energy industry is facing new challenges from the dropping oil price as a consequence of the unbalanced production to demand relation. Although this oil downturn benefits temporarily the EU as an oil consumer (18), the unstable oil price highlights the necessity of more relying on renewable energy. In the EU, the wind energy leads the change in the energy industry, whereas it represents 32 % from the total 35,181 MW new energy capacity installation in 2013 (16 p. 6).

In several economy sectors the composite materials are heavily utilized nowadays, such as the energy sector and the aerospace industry. Generally, the aerospace industry influences both the industrial processes and transportation sectors. Hence, the importance of the aerospace products can be split between the industrial processes sector in the early production life stages, and the transportation sector in the use and operation late life stages (19 p. 3). Statistically, the energy, industrial processes, and transportation sectors have significant impact on the ecological aspects (20 p. 4). In the transportation sector, composite materials play an important role in the aerospace industry. These materials can reduce the aircraft empty weight, whereas this weight reduction can minimize the CO_2 emissions up to 20 % during the operation stage within the aircraft life-cycle (21).

Furthermore, the Compound Annual Growth Rate (CAGR) of the composite materials production is anticipated to reach 7.4 % globally by 2017. This CAGR includes 15 % market increasing in the aerospace segment and 14 % in the wind energy segment (22 p. 19). This increasing demand explains the importance of the composite materials industry in the economic aspects of the SD. An example of the significant influence of the composite materials industry on the eco-efficiency can be detected from the magnitude of the utilized composite structures in the energy and aerospace industries.

On one hand, the composite materials represent the core substances in manufacturing the wind turbines generally and the rotor blades specifically (23 p. 3). The increasing demand for the wind turbines and the exigency of increasing their eco-efficiency during the life-cycle, necessitate applying more SD for the manufacturing and assembly of composite structures in the wind turbine industry (22 p. 24).

On the other hand, modern aerospace industry relies heavily on composite materials, while new designs of commercial aircrafts include more than 50 % of composite structures. Worldwide this trend towards more composite structures in the new commercial aircraft generations is obvious. The European aircraft manufacturer Airbus designed the A 350-XWB all-new wide body family with 53 % composite structures (24). This increasing demand for composite materials in aerospace industry and the trend to optimize the eco-efficiency (25 pp. 8–17), represent a significant reason to perform apply more SD for the manufacturing and assembly of complex composite structures in the aerospace industry. However, in this project the LCA, the LCCA as well as the manufacturing and assembly of the complex composite structures are demonstrated in Chapter 2.

In order to cover a wide range of various complex composite structures, two examples from the major two types of Fiber-Reinforced Polymers (FRPs) are demonstrated in this project, which are Glass Fiber-Reinforced Polymer (GFRP) and Carbon Fiber-Reinforced Polymer

(CFRP) (26 pp. 597–598). On one hand wind rotor blades consist of GFRP as well as CFRP in their structures (27 p. 23), whereas wind rotor blades represent the largest GFRP market segment worldwide (28). On the other hand, aircraft wing ribs are studied in this project as a new promising implementation of a CFRP complex structure in manufacturing the modern commercial aircrafts (25 p. 5). The compiled results of assessing the LCA and LCCA of these examples are utilized in this project as brief examples within the developed comprehensive SD framework.

The LCCA and LCA for the manufacturing and assembly of the complex composite structures are integrated with the Six Sigma and Lean methodologies in a comprehensive SD framework in this project in order to have a structured decision-making system that can improve the manufacturing and assembly processes generally and the eco-efficiency of these processes specifically. Moreover, the possibility of converting this comprehensive SD framework into management simulation tool is also discussed.

2 State of Art

In order to quantify and realize SD, it is essential to select and implement suitable management tools that assess the ecological and economic impacts and implement the required SD direct applications in the life-cycle of the product or as it is called the functional unit (29 p. 10) and (7 p. 203). In this project the comprehensive approach to achieve SD is discussed based in the results of the previous thesis. In the previous thesis only the ecological and economic impact assessment phases are accomplished, while the improvement phases are excluded.

For the ecological impact assessment, the LCA is adopted in the previous thesis due to its systematic framework that fulfills the goal and scope of that thesis. The LCCA can be integrated within the framework of the LCA to have a decision support tool that covers both ecological and economic aspects and addresses the eco-efficiency objectives (30 p. 1734).

Pursuant to the principle of “prevention is better than cure”, the SD is applied in the early design stage (31 p. 13). Therefore, the SD of producing the composite structures are modeled and simulated in order to be controlled in this life-cycle stage. The modeling and simulation are effective methods to evaluate the eco-efficiency of the existing production process as well as the alternative scenarios, which reduces the risks and costs of the development approaches (32 p. 1363). After accomplishing these phases within the combined framework in the previous thesis, in this project the further improvement phases are discussed. Nonetheless, the LCA, LCCA, as well as the modeling and simulation methodologies are elucidated in this chapter. Moreover, the Six Sigma, Lean, and the general definitions of the manufacturing and assembly of selected functional units are also explained.

2.1 LCA

The LCA is a support tool that provides guidelines for decision-makers. This support tool is developed by the International Organization for Standardization (ISO) within the ISO 14000 family of international standards (33 p. 6). It is a relative approach about a functional unit which can be a product or a service (14 p. 6). The LCA as a comprehensive tool identifies all related environmental aspects from a set of environmental performance indicators and evaluate their impact throughout the whole life-cycle of the functional unit from the cradle-to-grave (33 p. 6). The assessment is performed on a product system that includes the elementary and product flows of the related unit processes within the life-cycle of one or several products. This assessment is an iterative transparent technique, which is based on scientific approaches in taking decisions (14 pp. 14–15).

From its definition, the LCA is a tool that is utilized to build a description of the problems from an environmental perspective. This means that the LCA guides the decision-makers to define the solutions as possible improvement applications but it does not include the direct applications themselves (29 p. 35).

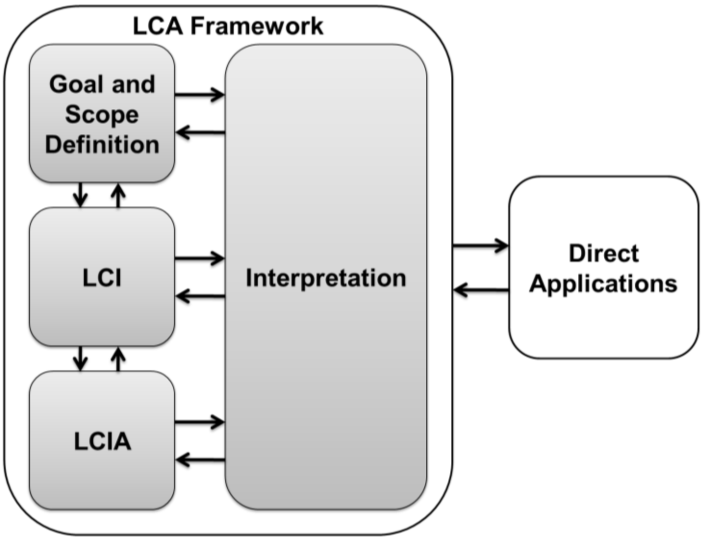

Figure 1: LCA Framework, based on (29 p. 17)

From Figure 1, the LCA is performed through a framework that includes four systematic sequential phases. The first phase in this framework includes defining the goal and scope. The second phase is accomplished by performing the Life-Cycle Inventory Analysis (LCI), whereas the LCI is carried out according to the goal and scope definition in the first phase, as it is illuminated in Chapter 4. The third phase is the Life-Cycle Impact Assessment (LCIA). In this project, the LCIA is concluded from the results of modeling and simulating the collected data of the LCI phase, which is explained in Chapter 6. In the final phase the previous phases are evaluated and the required modifications in each phase of them are applied in an iterative interpretation process (29 pp. 17–18).

The direct intended applications represent any further improvements or actions that the decision-makers apply within the life-cycle of the functional unit according to the accomplished four LCA phases. Although direct applications are not a part of the LCA framework, they necessitate repeating the LCA to assess the behaviors change of the product system due to these applications.

It is essential to mention that the LCA framework is a dynamic iterative approach, whereas each phase affects the other phases and it is also influenced by them (14 p. 48). Moreover, the LCA can be performed for one of two purposes, either it is carried out to compare the environmental impact of different product systems, or to reveal the compiled environmental impact results of a product system to the public (14 p. 16).

The results from the environmental indicators should be gathered for targeted impact categories (14 p. 34), such as; climate change, human health, resources, or/and ecosystem quality (34 p. 324). In the LCA, these results are extracted as potential environmental impacts not exact values (29 p. 18). Technically the LCA guides the decision-makers to select the suitable applications and actions by comparing different products or scenarios and providing comparable non-absolute values (35 p. 569).

Generally, the life-cycle includes all the sequential and connected life stages that covers the product system from the raw material acquisition to the product final disposal (14 p. 7, 14). This physical life-cycle (36 p. 118), which is also known as the cradle-to-grave life-cycle, can be split differently into several gate-to-gate stages due to the definition of the assessment goal and scope. The most crucial point in dividing the life-cycle is to assure that all the life stages are included and sequentially connected.

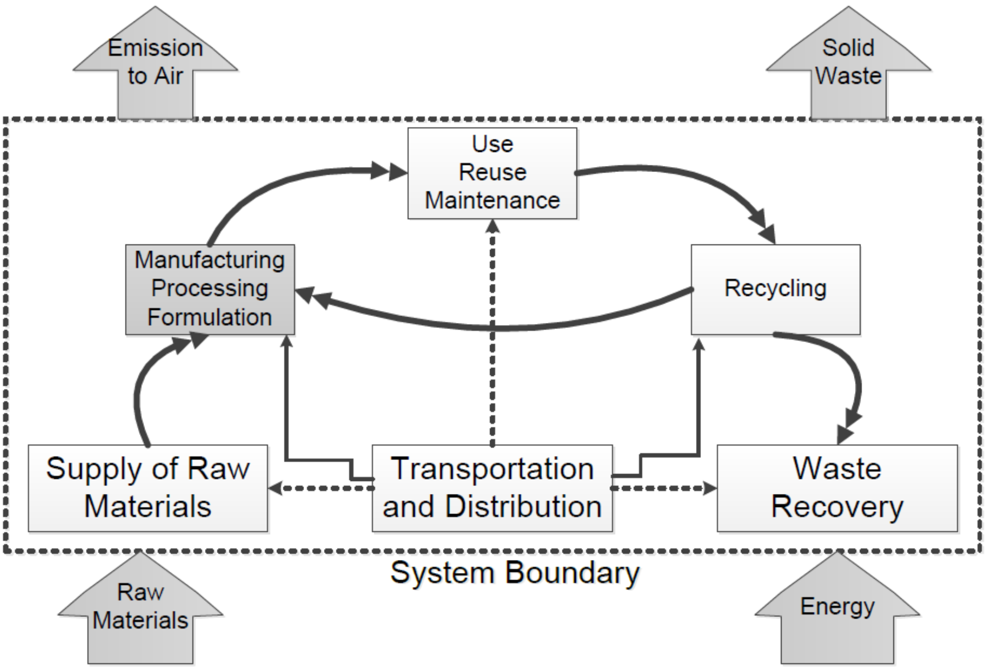

Figure 2: Simplified Life-Cycle Stages of LCA, based on (7 p. 204)

In Figure 2, the product life-cycle is simplified from the LCA perspective, and it is demonstrated as separated product systems of the life-cycle stages. This separation facilitates the elaboration of each stage as a gate-to-gate LCA, which serves the goal and scope of this project. In this project only the manufacturing and assembly stage is included in a simplified gate-to-gate LCA, which is represented by the term; manufacturing, processing and formulation and shaded in Figure 2. As it is illustrated in Figure 2, the system boundary definition is crucial in identifying the system inputs, outputs as well as the excluded aspects within the cut-off criteria (29 p. 10). According to the system boundary definition in this project only the emission to air is assessed and elucidated as an environmental impact, whereas the solid waste and energy waste are converted and presented by this impact category.

Practically, each gate-to-gate stage can be performed as a simplified LCA technique to cover that particular life stage (29 p. 36), which is the case of this project.

Generally, design and manufacturing are crucial life-cycle stages. Considering the particularity of the composite materials, the environmental impact can be immensely controlled in the design and manufacturing stages throughout the entire product life-cycle (31 p. 13) and (5 p. 199).

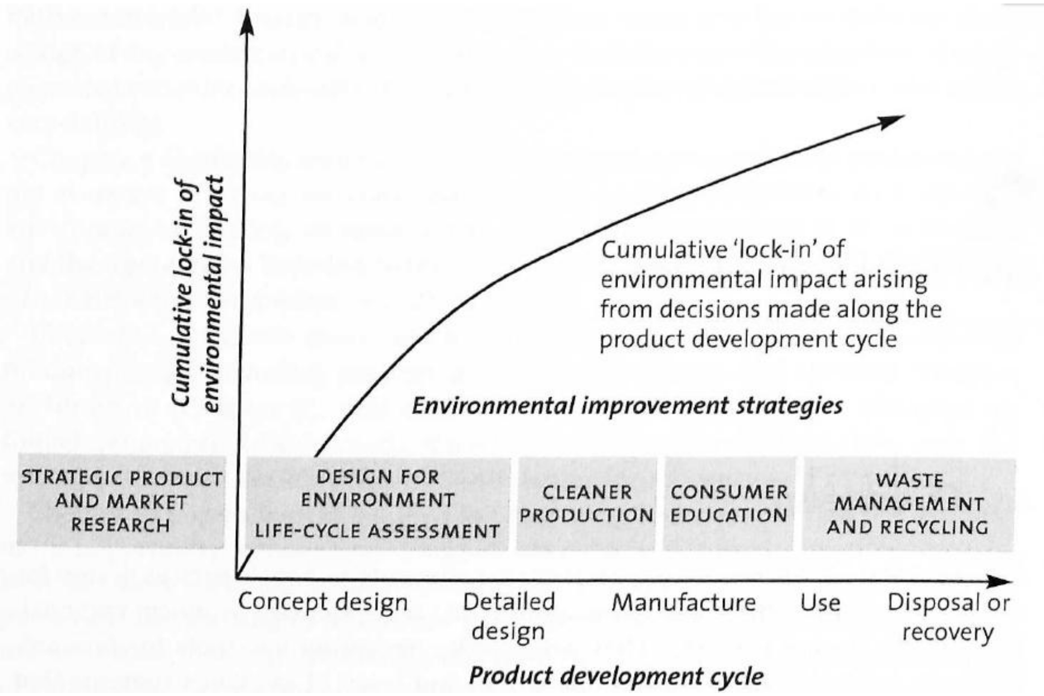

Figure 3: Cumulative Environmental Impacts throughout Product Life-Cycle (31 p. 14)

Although this environmental impact occurs in each life-cycle stage as it is shown in Figure 3, this impact is locked into the design stage when the product characteristics and life-cycle path are defined and realized in the manufacturing stage or the “cleaner production” as it is called in Figure 3 (31 pp. 13–14).

However, in this project the LCA is performed by implementing the modeling and simulation methodologies within the manufacturing and assembly processes of the selected functional units. The comprehensive SD framework is applied within the early design stage which has a critical effect on the entire product life-cycle.

2.2 LCCA

As it has been previously mentioned, Both LCA and LCCA are key decision support tools in promoting the eco-efficiency. Although the LCA does not include the economic aspects (36

p. 118), this technique can be modified and applied to do so (14 p. 6). The LCCA is a systematic decision support tool that analyzes the cost effectiveness of the product system. It evaluates the economic aspects within the product life-cycle by a set of cost associated indicators. The LCCA is a crucial SD support tool especially in the early design stage where the decision-makers can develop the cost effectiveness of the product. Performing the LCCA guides the decision-makers to select the most cost effective alternatives (37 p. 3) and/or develop the required direct applications to achieve that (29 p. 35).

Generally, to understand the economic aspects within the product life-cycle, it is substantial to define the main economic terms; cost, price, and profit. On one hand, the cost is the total expenses that are spent to manufacture the product. On the other hand, the price is defined as the amount of money which is paid by the customer to buy the product, whereas the profit represents the benefit that the product manufacturer gains as a result of subtracting the cost from the price. In practice, these terms are represented by monetary units, such as Euro (€) (38 pp. 2, 3).

The LCA and the LCCA are different methodologies that have various goals, approaches, and perspectives, whereas these methodologies provide the support for the decision-makers to solve completely different problems (36 p. 118). Hence, the differences and the relations between the LCA and the LCCA can be analyzed in a systematic comparison that is based on the common framework, as it is demonstrated in Table 1.

Table 1 illustrates the different goals and scopes of the LCA and LCCA, and the various indicators that are implemented to achieve these goals by compiling miscellaneous results. Furthermore, these results lead the decision-makers to address two different intended direct application types. Nonetheless, both LCA and LCCA can be conducted through the same framework (36 p. 118).

Table 1: Comparison of LCA and LCCA in Common Framework, based on (29 p. 17), (36 p. 118), and (14 p. 37)

Framework Phases	Description of the compared Phases **(The differences are written in bold)**	
	LCA	**LCCA**
Goal and Scope Definition	Evaluating and/or comparing the life-cycle of functional unit(s) from **environmental perspectives**	Evaluating and/or comparing the life-cycle of functional unit(s) from **economic perspectives**
LCI	Observing the product system and measuring the elementary flows (**as physical units**)	Observing the product system and measuring the elementary flows (**as monetary units**)
LCIA	Determining (and comparing) **the category indicator result Ex. Kilograms of CO2-equivalents per functional unit (s) , and identifying the category endpoints**	Determining (and comparing) **the category indicator result Ex. €-equivalents per functional unit (s)**
Direct Applications	**Environmentally friendly** development applications	**Cost effectiveness** development applications
Interpretation	Evaluating the results and the framework from **environmental norms**	Evaluating the results and the framework from **economic norms**

The life-cycle of the product varies between the LCCA and the LCA. According to the different concerns in both decision support tools, the life-cycle of each one starts from disparate beginning point and ends at a different point (7 p. 204). From Table 1, the LCA framework is implemented for both LCA and LCCA in the previous thesis.

2.3 Production of Complex Composite Structures

Generally, in order to perform an accurate SD that is based on the BPR from the previous thesis, it is substantial to have a distinct comprehensive understanding of the selected functional units as well as the applied manufacturing and assembly techniques (39 p. 741).

In this project the same studied composite structures of the previous thesis are adopted. The studied type of composite materials is the FRP (5 p. 317). FRP is a combination of a fiber as filamentary material and a contained matrix (5 p. 350) whereas the most common matrix is the “polymer resin” which is used in manufacturing the selected complex composite structures (40 pp. 2–3). Technically, the structure shape and the implemented materials should be considered in selecting the manufacturing techniques (41 p. 13), whereas unlike other materials, the manufacturing of the FRP builds not only the structure but also creates the constitution of the composite materials (42 p. 28).

As a result of this correlation between the composite structures and materials, on the one side, and the selected manufacturing techniques, on the other side, it is indispensable to define these aspects in the early design stage (4 p. 8). On one hand, optimizing the cost effectiveness of a product is the aim of every manufacturer, whereas the majority of the non-value added processes can be eliminated within the early design stage (43 p. 477). On the other hand, the environmental impacts throughout the composite structures life-cycle are majorly locked into the design stage (31 p. 13).

2.3.1 Complex Composite Structures

Generally, “complex composite structure” is a common term that has been utilized by several researchers (44 p. 241) and (5 p. 349) to represent any composite products that have more complicated geometry than a simple composite plate (45 p. 1). Technically, due to their functionality; the structural frames, stiffeners, as well as the load transmitting formations (such as wing ribs and wind rotor blades) are considered as complex composite structures (5 p. 350). Practically, the selected functional units include a composite product that consists of several assembled complex composite components which is the wind rotor blade, and a single complex composite component which is the wing rib. In this project the composites product are represented by the complex composite structures.

2.3.2 Production

According to the selected system boundary in this project and in order to use the results of the previous thesis, the production is represented by the manufacturing and assembly in this project. The manufacturing and assembly are defined as two parts within the development process chain of the composite structures (5 p. 199). In Figure 4, the assembly phase is shown as a replenishing phase for the production phase, while the manufacturing stage is elucidated as a part of the production phase. According the system boundary definition in Chapter 4, this project covers only the manufacturing, assembly as well as all other interfacing stages.

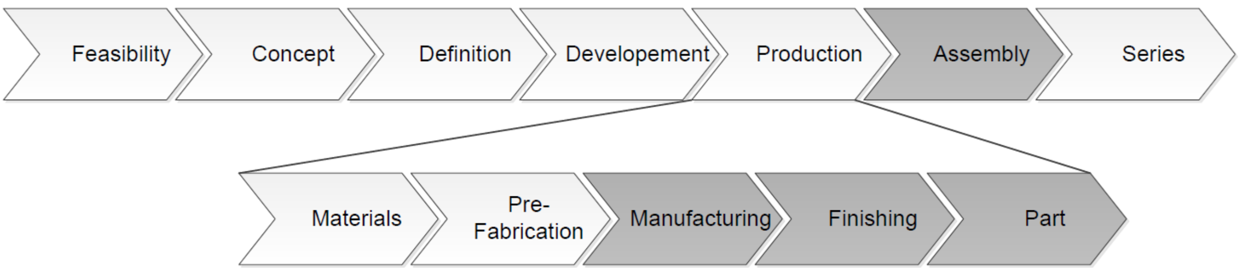

Figure 4: Development Process Chain of Composite Structures, based on (5 p. 201)

The manufacturing process of the composite structures is a decisive life cycle stage where the component form and the material mechanical and physical properties are constructed due to the selected manufacturing technology (46 pp. 2,17 and 3,6). Within the manufacturing process, several crucial input parameters that manipulate the final component specifications and quality are managed (5 p. 311). The assembly process handles only the adhesive bonding between the components of the wind rotor blade, while the wing rib as a single component requires no assembly.

Based on the core implemented materials and the matrix viscosity, the manufacturing technologies of the FRP can be split in two major categories; the Prepregs technology for the high viscosity matrix, and the Liquid Resin Infusion (LRI) technologies for the low viscosity matrix (5 pp. 312 and 349-350). In this project the LRI technologies are applied in manufacturing the selected components.

2.4 BPR

The modeling and simulation methodologies are widely implemented nowadays in several business process management and design engineering sectors (47 p. 1). These sectors include the transportation, logistics, communication and manufacturing (32 p. 1363). In the previous thesis, the LCA and LCCA are performed by modeling and simulating the manufacturing and assembly of the complex composite structures as a Business-Process Re-engineering (BPR) (32 p. 1363).

The BPR is conducted through a systematic approach that can be summarized into these major phases; starting by identifying the process, then modeling it, measuring and gathering the data for that module (*or "model" as it is called by other researchers*), simulating the process module as well as the alternative modules, and finally improving the process due to the module simulation results (48 p. 528). Moreover, these phases are precisely elucidated in Chapter 5.

Technically, the modeling and simulation are separated methodologies within the BPR. On one hand, the modeling, or as it is called the Business-Process Model and Notation (BPMN), is a methodology to document the studied business process (49 p. 1). This methodology provides a structured representation for the process behaviors as a static "as is" module (48 pp. 527–528). On the other hand, the simulation, or as it is known, the Business-Process Simulation (BPS) (48 p. 527) is a planning and forecasting methodology that compares several process scenarios (47 pp. 1,9) in a dynamic "what if" approach (48 pp. 527–528).

It is essential to mention that the BPMN is a prerequisite for the BPS (47 p. 1). From the BPS, a crucial quantative knowledge about the process and the various scenarios can be provided to the decision-makers, which facilitates identifying the bottleneck of the problem and illuminating the possible solutions (32 pp. 1363,1365).

2.5 Six Sigma

Six Sigma is a managerial methodology to optimize the business processes quality through a systematic framework that intends to reduce the process variation. Originally, Six Sigma was developed by Motorola in the early eighties. This methodology can be implemented to achieve several process optimization objectives including; reducing errors and rework efforts, improving the process quality and capability, increasing the predictability of process results, raising the capacity of processes, and motivating the employees who are involved in the process. Moreover, the Six Sigma can lead to further objectives beyond the processes themselves including the significant increase in the customer satisfaction, the improvement of the company results, the reliability increase for both goods and supplies (50 pp. 1–2).

Technically, Six Sigma methodology is performed within a systematic framework. This framework consists of five sequential steps which are also known as the Six Sigma improvement model.

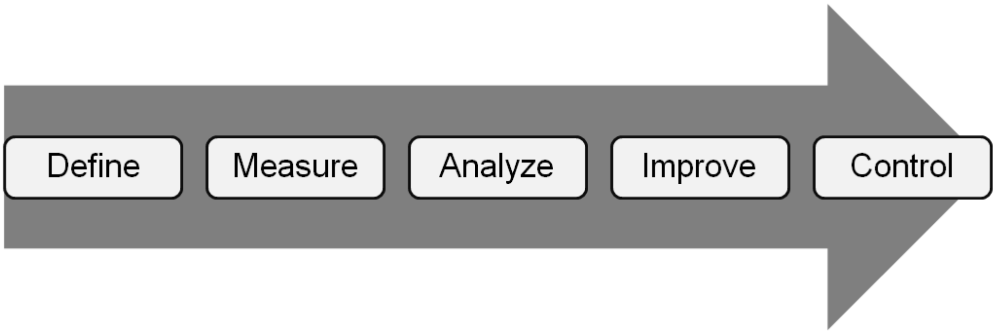

Figure 5: Six Sigma Framework based on (50 p. 11)

Figure 5 illustrates the sequential steps of the Six Sigma framework, which includes the following activities; Define, Measure, Analyze, Improve, Control which is also known as (DMAIC).

2.5.1 Define

In the define phase, the comprehensive project charter is described. This includes the major significant project guidelines by describing the problem, identifying the goal of the project, defining the characteristics of the studied processes, determining the aimed developments that can fulfill the goal, defining the system boundary of the associated project. The define phase is the crucial point when the team need to have a clear understanding about these guidelines in order to perform the other phases successfully. In order to carry out this phase there are three cornerstone requirements need to be fulfilled including identifying the problem from similar business processes, defining the project responsible sponsor who is supposed to define the system boundary then control and support the development project, select the project manager who is benefited from the developments and can afford to support the project financially (50 pp. 11–12).

2.5.2 Measure

After accomplishing the define phase, the second phase in the Six Sigma framework is the measure phase. In the measure phase, the potential causes and facts of the problem are determined, and all the associated data are collected. This includes determining the actual process performance. The data collection is the core of this phase, whereas the data collection covers all the associated processes value stream mapping (VSM) as a detailed process representation. In addition, the data collection includes measuring the inputs and outputs of the studied process (50 pp. 61–62).

Technically this phase includes; identifying, rating and selecting the potential causes of problems in the data collection, analyzing the measuring system, planning the data collection, representing the collected data and finally determining the results (50 p. 60).

2.5.3 Analyze

The third phase is the analyzing phase, where the critical causes are determined. This phase includes analyzing the process of determining the critical causes, analyzing the data which are used in the determination of the critical causes, and analyzing the background information of the critical causes. These analyzing activities are majorly based on a data analyses and process analyses methodologies.

Technically, there are a set of requirements which are needed to carry out this phase. These requirements include building a representative construction diagram with potential causes data and measurements series of the problem and the selected potential causes. Furthermore, graphical representations of the data collection as well as a process documentation overview are also required in order to perform the analyzing (50 pp. 127–128). These requirements are accomplished within the previous theses (3 pp. 31–37). Technically, this phase is the phase where the Six Sigma is integrated with the combined framework from the previous thesis.

2.5.4 Improve

In the improve phase, the solutions are developed, a risk analysis for the developed solutions are carried out, then the solutions can be implemented. The improving phase includes developing, testing and implementing the corrective direct applications that can remedy the causes of the bottleneck. Moreover, the effectiveness of these corrective direct applications should be detected, whereas the changes on the studied process should be continuously evaluated. Technically, this phase can only be achieved after determining the list of the causes behind the problem and the degree of influence these causes have on the problem (50 pp. 181–182). Comparing to the LCA framework, the improvement phase of the Six Sigma represents the direct applications in the LCA framework.

2.5.5 Control

In the controlling phase, the results of the project are evaluated and ensured. This includes performing the following steps sequentially starting from constructing a process management system, then standardizing the processes, training the development team participants, performing the process monitoring activities, passing the development results to the decision-makers, and finally ending the project.

However, there are requirements that must be prepared in order to perform the controlling which include a list of process improvements, list of significant causes, input factors and parameters, and result variables (50 pp. 213–214). This phase can be integrated with the evaluation phase that has been performed in the previous thesis to have comprehensive control process (3 pp. 55–59).

Majorly, Six Sigma is applied with the Lean as a logical combined methodology that serves the business process development (50 pp. 1–2), whereas the Lean is illustrated in this chapter.

2.6 Lean

Lean is a management methodology that consists of several tools and aims to reduce the processes wastes. It is a comprehensive quality development methodology that attempts to achieve multi-objectives including: shortening process cycle time, reducing storage cost, reducing the used capital, increasing process efficiency, raising processes capacity, improving supply chain, motivating the employees, increasing the customer satisfaction, and improving the company outcomes (50 p. 1). However, according to the goal and scope and system boundary definitions of this project, the concentration of the project is on the process related objectives.

Lean, or as it is called Lean Total Process Management (TPM), guides the decision-makers to avoid the losses and wastes in the processes. According to Lean TPM methodology, any process can be split into sub-processes or separated individual activities. This can be applied to any process such as production, marketing, development, supply chain, or any other business process (51 p. 26). However, to keep to a standard definition in this project that matches the LCA system boundary, the term unit processes represents these sub-processes, whereas the targeted processes are the manufacturing and assembly within the production.

Identifying these unit processes and defining their detailed activities facilitate eliminating the non-value added activities in the overall process (51 p. 25). These non-value added processes have been classified by the Toyota Production System (TPS) as the basic structure for the Lean TPM. According to this classification the non-value added processes include:

1. MUDA which is a Japanese term for the waste.
2. MURA which is a Japanese term that represents the unevenness.
3. MURI which is a Japanese term for the overburden (51 p. 27).

These three classes, or as they called the three “Mu”, concentrate on analyzing the production process including the following dimensions; the employees, employees thinking methodology, the applied production techniques and methods, the production time, the used equipment and tools, and the used materials (52 p. 14). However, each dimension of these can be assessed in separated project or a set of projects, while this project concentrates generally on the production techniques and the associated dimensions. Moreover, the three Mu classes are elucidated in this chapter.

2.6.1 MUDA

MUDA represents the most obvious causes of wastes in the production process (52 p. 14). The MUDA can be split into 8 wastes including:

1. T: Transportation
2. I: Inventory
3. M: Motion
4. W: Waiting
5. O: Over-processing (Extra-Processing)
6. O: Over-production
7. D: Defect (51 pp. 29–30)
8. N: Non-used Employee Talent (53).

These wastes are explained in Figure 6.

Figure 6: Wastes Categories (53)

According to the system boundary, as set of selected crucial wastes is discussed in this project. These wastes are majorly represented by the waiting, over-processing, over-production as well as inventory wastes.

Generally, waiting represent the wasted time as a result of the waiting for materials, information, employees, machine downtime, or any other associated waiting reasons. Over-processing or extra-processing is caused by adopting the incorrect or unsuitable process or technique (51 p. 30). It also includes wasting money and effort in providing higher quality than what is demanded (53). The third considered waste is the over-production, which represent the case of producing more products than what is demanded by the internal or external customers (51 p. 30). Over-production considered as the most crucial waste due to the tremendous amount of additional resources, handling, space, staff and administration that are used for to produce non-value added product (52 p. 14). The inventory waste represents the wasted materials or products which enter the production and wasted without being processed (53).

Practically, the production unit processes are observed by what is called the MUDA-Hunting rules which are:

- Observe the process at the production site
- Observe the process in reality, not based on databank or experts knowledge

- Record all process steps that are not value-adding, and categorize them under the waste categories.
- Apply the black or white rule in identifying the non-value added process step, whereas a process step is either value-added or not.
- Don’t look for non-technical explanations and excuses.
- Collect simultaneously the associated data including Facts and figures, including waiting times, inventories, transportation routes, overproduction, scrap and rework, and all other associated data.
- Don’t look for a "guilty", whereas it is not about evaluating the employees but the process (51 p. 31).

The MUDA-Hunting process observation and measurement can be implemented within the LCI which has been accomplished in the previous thesis.

In addition to these wastes, this chapter discuss briefly the two other non-value added processes within the three Mu, which are MURA and MURI.

2.6.2 MURA

MURA represents the unevenness or deviation in the process. MURA is caused by missing or incomplete harmonization of capacities within the production control. This leads to the production queuing delay or non-optimal production capacity utilization (52 p. 15).

From the TPS, the unevenness or deviation can be treated by adopting the strategy from the following statement: "level the volume of production by slowly and steadily working as a turtle, rather than quickly and erratically like a rabbit". This strategy have very positive impact on the process as well as the employees (51 p. 32).

2.2.3 MURI

MURI or overburden refers to losses caused by overstressing in the work process. These losses are sequences of the employees mental overstressing which increases the frequency of work errors or job dissatisfaction (52 p. 15).

In addition to the three Mu, to reduce these non-value added processes and wastes, there are wide range of production management tools that can be implementing in optimizing the process. For instance;

- The management tool for the work place 5S,
- The information exchange tool Andon, which serves the information quality management in the critical situations in the production processes,

- BPR which is demonstrated in Chapter 2,
- Digital Mock-Up (DMU) is an advanced modeling and simulation method that is widely used in the aerospace and automotive industries nowadays.
- Just-in-Time (JIT) which is a concept for the production and logistics strategy to deliver goods at the right time in the right amount at the right place.
- Kanban, which is an elementary flow controlling concept that can be implemented with JIT by mapping the material follow with identification cards (52 pp. 16–71).
- Kaizen or “change for better”, is an improvement strategy that is applied as rapid change events within a short period of time (54 p. 14).

In addition to these examples of the management tools that can be applied to develop the production process, many other tools can be implemented, but they are not discussed in this project. Each tool of these is specialized in solving an exact problem (52 pp. 11–177). Nonetheless, this project constructs the decision-makers comprehensive SD framework in general and gives some examples that match the results from the previous thesis.

Practically, Lean TPM is performed within a continuous process development (51 p. 18).

Lean TPM is concentrated on four major development factors within the production process which are:

1. Human factors such as qualification and leadership.
2. Tool and equipment factors such as independent maintenance as well as preventive maintenance.
3. Material factors like Just-in-Time material and information flows.
4. Production method or/and product improvements factors such as Zero-Defects strategy, Lean Product Development, Lean TPM Administration, as well as Lean TPM for environment, safety and health (51 p. 44).

Within the last development factor it is obvious that there are two separated improvement approaches which are the process associated development and the product associated development. However, due to the system boundary in this project only the process development is considered.

It is essential to mention that although Lean TPM and Six Sigma are project relevant approaches which means that they are performed thorough steps that end within a specific project or projects, these methodologies represent a continuous development cycle (55 p. 1).

Lean TPM as well as Six Sigma are already implemented in developing eco-efficient manufacturing process (55 p. 1). In this project the possibility of constructing a combined comprehensive SD framework based on the Six Sigma, Lean TPM, LCA and LCCA is discussed.

Lean TPM and Six Sigma concentrate on specific stage within the life-cycle of the product which is the production stage. Nonetheless, many firms implement Lean and Six Sigma in the operation and maintenance stage, such as the airlines.

3 BPR, LCA and LCCA Framework and Results

As it has been mentioned preciously the BPMN and BPS are two sequential methodologies of the BPR. These methodologies are applied and elucidated in the previous thesis, while their definitions have been explained in Chapter 2 within this project. After defining the LCA, LCCA, BPR, Six Sigma and Lean for the manufacturing and assembly of the complex composite structures, the combined BPR, LCA and LCCA framework from the previous thesis is briefly demonstrated in this chapter. Moreover, the results that have been compiled from this combined framework are analyzed and discussed in order to be implemented as explanation examples for the developed comprehensive SD framework in this project.

3.1 BPR, LCA and LCCA Framework

Technically, the BPMN and the BPS are applied systematically in hierarchical structured pattern. They are implemented in performing the LCA and LCCA of the manufacturing and assembly scenarios of the targeted functional units. Therefore, a combined LCA, LCCA and BPR framework has been developed in the previous thesis. In Figure 7 this combined framework is demonstrated, whereas the relevant phases are shaded.

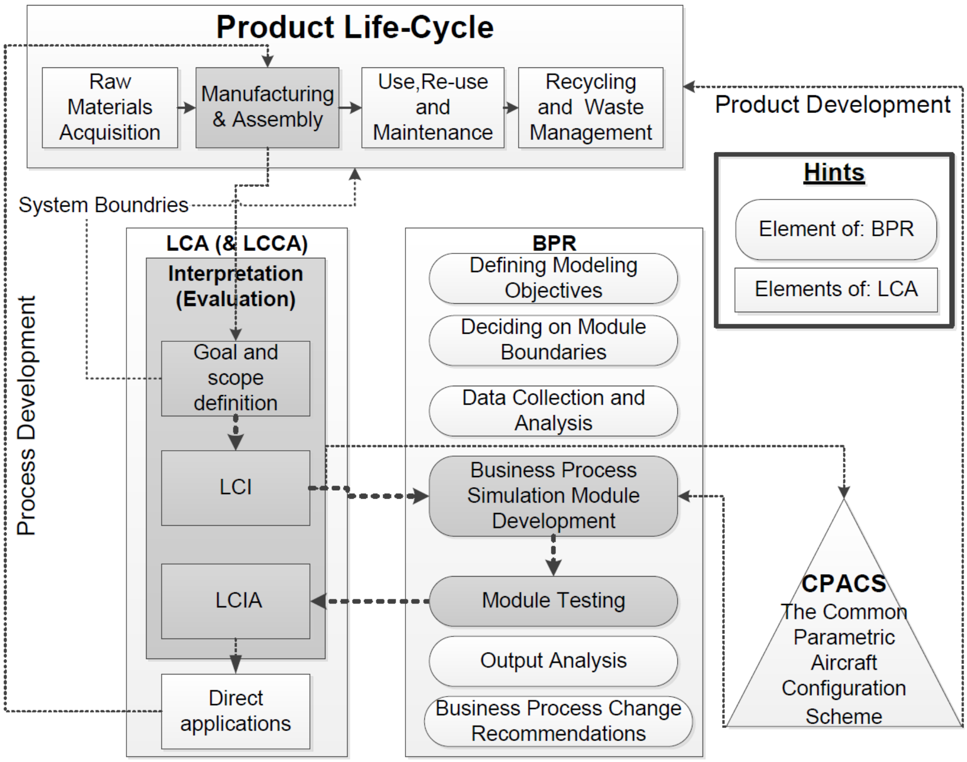

Figure 7: Combined LCA, LCCA and BPR Framework for Manufacturing and Assembly of Complex Composite Structures, based on (14 p. 48), (19 p. 3) and (32 p. 1366)

As it is shown in Figure 7 and according to the definition of the system boundary, this combined framework of the LCA, LCCA and BPR includes only the manufacturing and assembly within the life-cycle of the selected functional units, while this gate-to-gate stage represents the “reality situation” from the BPR point of view (56 p. 103).

The BPS has been performed within the previous thesis based on this framework. In this chapter selected examples of the compiled BPS results for the LCA and the LCCA are reviewed.

3.2 BPS Compiled Results

In this chapter, the BPS outputs for the LCA and LCCA are reviewed from a selected manufacturing and assembly scenario of the complex composite structures.

3.2.1 Compiled LCA Results

The results of the BPS for the LCA illuminate the total product CO_2-e of the CO_2-footprint for both selected functional units as well as the distribution of the CO_2-e among the elementary flows and the unit processes, which is necessary to define the wastes and the development factors.

From the BPS outputs, it is concluded that the wind rotor blade manufacturing and assembly processes produce around 11 kg CO_2-e for each kg of the wind rotor blade.

The compiled results illuminate that the wind rotor blade manufacturing shares about 97 % from the CO_2-e, whereas the assembly shares only 3 %. This CO_2-e distribution guides the decision-makers to concentrate their efforts on the manufacturing processes, where the SD can be more effective in reducing the CO_2-footprint.

From these results, it is essential to analyze the behavior of the CO_2-e between the elementary flows. This behavior shows that the fiber and matrix have the greatest share of about 95 % from the CO_2-e, while the supplies and energy represent 3 % and 2 % respectively. From these quantitative data it is concluded that the material development factor plays the major role in this case.

From the compiled BPS results for the LCA of manufacturing the wing ribs, the CO_2-footprint of the produced wing ribs is around 98 kg CO_2-e for each kg of the wing ribs. This tremendous amount of CO_2-e is an indicator to the bottleneck of manufacturing small-size CFRP when it is compared to the previous example of wind rotor blade. This can lead to more deep analyses that aim to determine the causes behind this extreme CO_2-footprint.

It is assessed that the CO_2-e of the fiber and matrix elementary flow accounted the lion’s share with about 74 % from the CO_2-e, while the energy and supplies represent about 23 % and 3 % respectively, which is similar to the results trend that has been concluded from the other functional unit, but have more energy CO_2-e. Due to the fact that the wing rib is a single component structure, further explanation for the CO_2-e of each unit process has been performed. It is concluded that the cutting has a great share according to the fiber elementary flow within this unit process. The tempering represents about 21 % of the CO_2-e due to the high energy consumption, whereas in the infusion unit process the matrix CO_2-e is added. However, the finishing and demolding unit processes have a very small negligible CO_2-e. This guides the decision-makers to the major development factors which includes reducing the materials waste and the energy consumption.

3.2.2 Compiled LCCA Results

In this section the results of the LCCA for the manufacturing cost of the wind rotor blade as well as the wing rib are discussed.

On one hand, the LCCA results for the wind rotor blade illuminate the major development paths for the decision-makers by explaining the costs allocation. From the BPS outputs, it has been found that the manufacturing process costs about 96 %, while the assembly process costs only 4 %.It is also concluded that the matrix and fiber materials cost has the highest share among other costs, followed by the labor cost. This leads the decision-makers to study the development of the human and material factors within the Lean TPM.

These results of the LCCA explain the behaviors of the wind blade manufacturing as a product system. They can guide the decision-makers to select the manufacturing alternatives and trigger the further required SD.

On the other hand, the LCCA results of the wing ribs manufacturing can be summarized in the following graphical representations. Figure 8 represents the share of each cost category in the total wing ribs manufacturing cost.

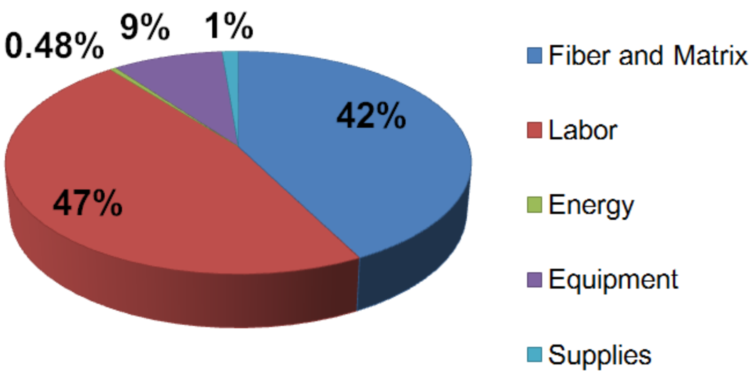

Figure 8: Cost Categories of Manufacturing Wing Ribs

AS it is shown in Figure 8 the fiber and matrix allocation plays again the main role, as well as the labor work.

From the previous thesis results, the compiled CO_2-footprint and cost are analyzed to indicate the non-value added processes and categorized the waste in order to select the development factor and apply the suitable management tool.

Moreover, from analyzing these results, it has been concluded that about 40 % of the fiber and matrix materials are wasted during the wing ribs manufacturing, which can be categorized under the inventory wastes.

These results illuminate the way to identify the problem and the possible solutions within the comprehensive SD framework.

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4 Comprehensive SD Framework

In order to accomplish this project within a systematic approach it is substantial to define the possible solutions for the comprehensive SD. After defining these solutions, they have been rated in order to select the appropriate one. As it has been studied in the previous thesis, the first solution is to separate the assessment phases from the direct improvement applications by applying only the LCA and the LCCA for the manufacturing and assembly of the composite structures, and exclude the direct applications (3 p. 29).

The second solution is to apply the Six Sigma and Lean in the SD, which has been already implemented by several authorities and firms (54 p. 1) and (55 p. 1). Nonetheless, these applications are designed without building a clear framework that can cover several scenarios and products. Moreover, these applications are designed for specified problems within defined cases. They are selected, applied, and manipulated by the decision-makers themselves.

The third solution is to develop a comprehensive SD framework that integrates the LCA, LCCA, BPR, Lean and Six Sigma within clear phases, which is the concept of this project. This framework determines the problems and provides the possible solutions based on the defined management tools. It is essential to mention that this comprehensive SD framework isn’t supposed to be an alternative to the decision-makers, although it provides complete management decision tool.

After assessing and rating the three explained management solutions, the third one is adopted in this project. This framework can be also further developed within a computer-based simulation tool, which is discussed briefly in this project.

As it has been mentioned previously the goal of this project is to discuss the possibility of developing this comprehensive SD management framework. On one hand this comprehensive SD framework consists of the decision support tools for the problems detection including the LCA, LCCA and the BPR, which have been already integrated in a combined framework. On the other hand, the comprehensive SD framework includes also the management actions or direct applications tools such as Six Sigma and Lean TPM, which provide the solutions for these problems.

Theoretically, the Lean TPM and Six Sigma have been implemented as one management set in several sectors worldwide, while these two methodologies are instructed and delivered as training program for the decision-makers, which is also called the Green-Belt-Training (50 p. 4).

From the results of the combined framework of the LCA, LCCA and BPR demonstrate the CO_2-footprint and the cost of the product and explain the allocation of these eco-efficiency indicators among the different relevant process dimensions such as elementary flows, cost categories, and unit processes. Nonetheless, these results explain the total economic or/and environmental impact by comparing the different scenarios, but they cannot explain the detailed reasons behind the problems. This explanation is required to answer the most general question of why there is a need to change and what can be possibly changed. Moreover, the direct applications which represent the solutions for these problems are excluded from that combined framework of the previous thesis (3 p. 6). This project tries to answer these questions.

In order to accomplish this task and achieve the SD, a comprehensive framework that covers all the process performance optimization phases is developed in this project. To accomplish that, it is essential to compare the previously developed framework with the Six Sigma framework. Figure 9, elucidates this comparison.

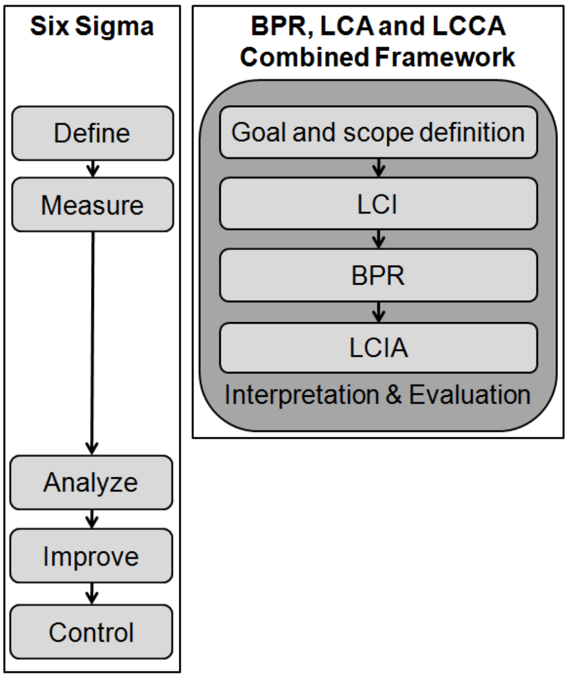

Figure 9: Comparison of Six Sigma with combined BPR, LCA and LCCA Framework, based on (3 p. 17) and (50 p. 11)

In Figure 9 and from the detailed explanation of these management tools and their phases in Chapter 2, it has been concluded that the first two phases are common in both frameworks. Technically, the Six Sigma define phase is the goal and scope definition of the LCA and

LCCA whereas the aimed comprehensive SD framework adopts the eco-efficiency goal of the LCA and LCCA. The measure phase can be replaced by the LCI or added to it if it includes some additional valuable application such as the processes VSM and the MUDA-Hunting.

The BPR application is an integrated phase within the combined framework which has the value of converting the real processes into controllable virtual prototypes. These virtual prototypes are represented by processes modules and simulated in a hierarchical structured pattern in order to assess the reality scenario as well as any alternative scenarios. The BPR can be also implemented within the comprehensive SD framework to simulate the performance of the processes after implementing the direct applications by the management tools.

In the combined framework, the LCIA is the phase where the economic and ecological related outputs are presented to the decision-makers. Although this phase provides decisive quantitative information about the CO_2-footprint and the LCC, this phase doesn't focus neither on analyzing the reasons behind the problems nor on the problems themselves. Therefore, the analyze phase within the Six Sigma is required to analyze the compiled results in order to determine the critical causes, and analyze the background information of these critical causes. After accomplishing the analyze phase within the Six Sigma framework, the bottlenecks as well as the critical causes should be clearly identified.

The next phase in the Six Sigma is to improve the processes. Nonetheless, in this project the three Mu from Lean TPM are integrated in the framework before the improve phase. By this modification the bottlenecks can be categorized within the defined classes of the Lean TPM non-value-added processes. If the MUDA represents the non-value-added processes, this phase should include identifying the MUDA wastes.

From the compiled results of the previous thesis which are presented in Chapter 3 and the selected examples of the possible applied management tools in Chapter 2, selected management tools are integrated within the developed comprehensive SD framework in this project. They are applied as explanation examples, while any other management tools can be added to the framework according to any different compiled results and problems.

The developed comprehensive SD framework of this project is demonstrated in Figure 10.

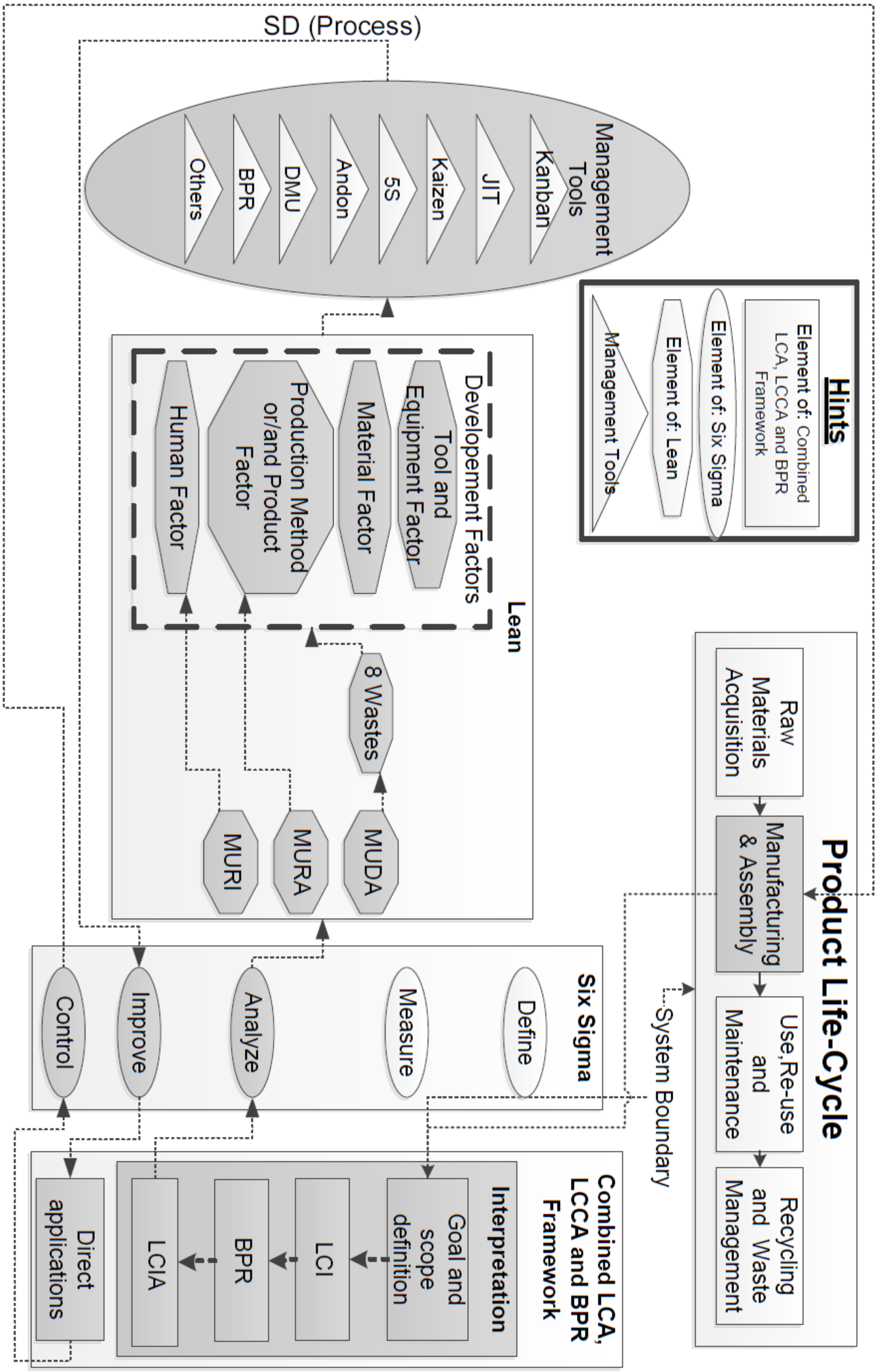

Figure 10: Comprehensive SD Framework, based on (3 p. 29)**,** (51 pp. 27 and 44)**,** (50 p. 11) **and** (52 pp. 16–71)

As it is shown in Figure 10, the developed framework consists of the following main phases:

- The goal and scope definition within the LCA and LCCA.
- The LCI as a part of the LCA and LCCA framework.
- The process simulation module development within the BPR.
- Then the results of the BPR are shifted to the LCA and LCCA framework to determine the LCIA.
- The LCIA detailed results are further analyzed within the Six Sigma analyze phase to determine the non-value added processes that cause the problem.
- The next phase includes categorizing the non-value added processes within the three Mu in the Lean TPM.
- If the non-value added processes are categorized within the MUDA, then they should be further classified by the 8 wastes.
- In the Lean TPM the wastes should be allocated within the associated four major development factors.
- According to the previous phases the management tool that can afford the most appropriate solution for the studied case can be selected from the wide range of the available management tools.
- The next step is to apply the selected management tool in the improve phase of the Six Sigma, which represents the direct application phase in the LCA framework
- The final phase is to control and evaluate the results of the SD as well as the local results of each phase which is a part of the Six Sigma or/and the LCA framework.

As it is illustrated in Figure 10, the MURI is majorly related to the human development factor, while the MURA is associated to the production method or/and product development factor. However, the management tools represent the direct application of the LCA that are applied to achieve the SD. These management tools are not completely covered in this project, whereas only selected set of them has been elucidated in Chapter 2.

Similar to the framework that has been developed in the previous thesis, the comprehensive SD framework in Figure 10 is limited to the manufacturing and assembly processes life stage due to the system boundary. It is also essential to mention that according to the system boundary, only the processes development is considered while the product development is beyond the project goal and scope.

These phases may be constructed as a BPR tool. This further developed computer-based tool analyzes the processes data and clarifies the possible solutions as suggestions that are approved by the decision-makers. This tool can be based on the existing LCA and LCCA simulation tool from the previous thesis.

For the selected two composite structure examples in this project, this framework can be applied to identify the possibility of its implementation. After analyzing the results in Chapter 3 it is clear that the material factor is the most important development factor for the LCA and LCCA. By applying the comprehensive SD framework theoretically for this specific case, the fiber and matrix wastes can be categorized under the inventory waste within the MUDA. After analyzing these facts by the internal DLR experts, who represent the decision-makers, it has been concluded that these wasted materials can be utilized in other production processes with smaller sizes and/or less quality requirements. Based on that conclusion, two possible management tools can be implemented, which are the Kanban and Andon. On one hand, Kanban system represents the material flow clearly for the decision-makers. On the other hand, Andon offers an effective information exchange between the different teams, which make it possible to identify which wastes can be used in other production processes.

As it has been found from the LCA results, the labor cost represents the second highest cost. After analyzing these results and identifying the causes behind them, it is clear that the human factor is the proper development dimension for this problem. Unlike, the previous case several non-value added processes can cause this problem, such as MURI or non-used employee talent as a part of MUDA. Hence, the comprehensive SD framework should be supplied by all the crucial data about the processes and it should be rich with the required data about each process scenario within its different phases. It is essential to mention that in order to build a comprehensive SD framework a tremendous amount of data is required. These data can also include some previous internal experiences about the discussed problems. Finally the proper management tools are suggested by the comprehensive SD framework. These suggested management tools are presented to the decision-makers in order to apply them and control the processes behaviors under their application.

From Figure 10, the concept of the comprehensive SD framework is realized, which makes developing this framework possible in reality. However, the evaluation of the framework effectiveness is still a challenge that is accomplished within this project.

5 Conclusions and Outlook

After developing the comprehensive SD framework, in this chapter the conclusions are summarized, and the further possible paces are discussed.

5.1 Conclusions

The developed comprehensive SD framework of this project offers a complete management structure that can be applied to achieve more eco-efficient production processes. This framework is an assistant approach for the decision-makers to develop the process performance in the composite structures production as well as other relevant processes. By applying the compiled results of the previous thesis, examples of this framework applications possibility have been presented. It is important to mention that there are many other management tools that can be applied to achieve the SD, which are not included in this project. In the aimed comprehensive SD framework, all the available unique management tools should be added to the simulation tool to cover all the possible solutions.

Unfortunately, according to the 6 weeks' time limitation of this project, it is not possible to apply these SD and perform the controlling and evaluation phase.

5.2 Outlook

The first possible development that can be performed is to apply the suggested management tools on the studied manufacturing and assembly processes and control the processes in order to evaluate the direct application results.

The second major possible development is to convert the comprehensive SD framework into computer-based simulation tool that is based on the accomplished simulation tool of the LCA and LCCA from the previous thesis. This simulation tool can perform the LCA and LCCA as well as suggesting the proper solutions by a complex hierarchical data analysis.

Generally, several developments can be performed in each phase of the comprehensive SD framework in order to increase its effectiveness.

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