Designing Repair Processes by Introducing a Return Quality Control Model
A Method for Sustainable Initial Repair Process Design

D. Haak - 4207580
2019.TEL.8356
Designing Repair Processes by Introducing a Return Quality Control Model

A Method for Sustainable Initial Repair Process Design

by

D. Haak

MSc Mechanical Engineering - Transport Engineering & Logistics

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday August 29, 2019 at 10:00 AM.

Student number: 4207580
Report number: 2019.TEL.8356
Project duration: December 1, 2018 – August 29, 2019
Thesis committee: Dr. ir. D. L. Schott, TU Delft, Faculty 3mE, chair
Dr. W. W. A. Beelaerts van Blokland, TU Delft, Faculty 3mE, supervisor
Dr. J. M. Vleugel, TU Delft, Faculty CITG
A. Gortenmulder, KLM Engineering & Maintenance, supervisor
G. Philips van Buren, KLM Engineering & Maintenance, supervisor

An electronic version of this thesis is available at http://repository.tudelft.nl/.
Aircraft have always impressed me. During my childhood I was attracted by the magic that brought and kept them in the air. Even after learning the mechanisms that exemplify that magic the fascination remained. The last few months I received the opportunity to dive into the operations that keep those fascinating aircraft in the air during my graduation internship at KLM Engineering & Maintenance.

This report represents the result of my master thesis research for the master Mechanical Engineering, track Transport Engineering & Logistics, at the Delft University of Technology. It was an educational experience full of challenges, up and downs but especially new insights. The aim of this research was to develop a method for sustainable initial repair process design to contribute to literature and enhance the performance of KLM Engineering & Maintenance.

I could not have completed my master thesis research without the help of many others. I would like to use this opportunity to express my appreciation for their input, guidance and support.

First, I would like to thank KLM and my KLM supervisors Alex Gortenmulder, Guus Philips van Buuren and Axel Colen for providing the opportunity to conduct my research at the Engine Services department in combination with the Lean Six Sigma office. Moreover, the discussions on strategic and operational level were stimulating and provided refreshing insights that enhanced the foundation of my research. Likewise, I would like to thank my colleagues at Engine Services and fellow graduate students for their knowledge, discussions and support.

Second, I would like to thank my graduation committee. Dr. Wouter Beelaerts van Blokland, my daily supervisor, thank you for the challenging discussions, crucial directions and expertise that elevated my line of reasoning and research development. Dr. ir. Dingena Schott, thank you for the critical but constructive questions and remarks that guided my research towards a scientific level. Dr. Jaap Vleugel, thank you for your time and effort.

As last, I would like to thank my friends and family for their listening, patience, distraction and infinite support.

Enjoy reading my thesis!

D. Haak
Delft, August 2019
Abstract

This research presents a method for sustainable initial repair process design based on application and adaptation of proven theory. For this purpose, it introduces a return quality control model with a product return quality controller to enable definition of a machine capacity upscale, arrangement and innovation strategy. The KLM Engineering & Maintenance (E&M) Engine Services (ES) environment is used to invigorate the model development by practical observations. The main research question this research aims to answer is: What method can be proposed for sustainable initial repair process design from a return quality perspective?

The research initiated with identification of criteria present in the research field that require control for sustainable initial repair process design. The identified criteria are process input quantity and quality variance, classification of process maturation, definition of process future expansion, determination of machine capacity arrangement and implementation of innovation. It was recognized that application of theory to control these criteria required a shift to the front end of the process. Accordingly, a theory analysis was carried out to identify theory appropriate for that process front end application approach. The Theory of Constraints (ToC), Statistical Process Control (SPC) and pre-control, Industry 4.0 principles and partly the Business Process Re-engineering (BPR) theory turned out suitable with application adjustments.

Using the theory a multi-layer return quality control model was designed that represents a method for sustainable initial repair process design and implementation. With a return quality controller and process maturation classification the product return quality is controlled and process input bandwidth established. This bandwidth enables definition of a machine capacity upscale strategy combined with machine capacity arrangement determination and a systematic approach for implementation of innovation. As last part of the model, integration of its output in the organizational supply chain is enabled by definition of a combination of standardized swimlane and Value Stream Mapping (VSM) diagrams with a Robot Operating System (ROS)-based data infrastructure.

A corresponding developed process design generator translated the model into functional output to illustrate the elementary behaviour and functionality of the design method. The return quality controller proved suitable for return quality variance reduction and bandwidth establishment. Based on the product return quality bandwidth the upscale strategy calculation with machine capacity arrangement provided reasonable output that facilitates sustainability of future process performance. Yet, the theoretical SPC and pre-control quality control procedures turned out not completely adequate for high variance processes. A solution for this limitation was identified in data clustering or application of a case specific limit scaling factor. The systematic approach for implementation of innovation and the supply chain integration proposal were not incorporated in the generator and remained limited to theory.

This research addressed the need for repair process design that incorporates future states to enable performance sustainability under expansion and prevent process derailing. It introduced process front end control and identified the importance of return quality in relation to the operational process. Both are combined in a model with programmed interface that is adaptable to business specific requirements and enables repair process design automation. It is recommended to use this research as fundament for sustainable and automated repair process design advancements with a problem prevention rather than recovery mindset. Besides that, further research is recommended in optimization of the return quality controller, extension of the incorporated process parameters of the model and development of the proposed data exchange infrastructure to enhance the applicability of the design method.
# Contents

<table>
<thead>
<tr>
<th>List of Figures</th>
<th>xi</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>xiii</td>
</tr>
<tr>
<td>List of Abbreviations</td>
<td>xv</td>
</tr>
</tbody>
</table>

## 1 Introduction
1.1 Research context ........................................ 1
1.2 Research field ........................................... 1
1.3 Research problem and scope ............................. 3
  1.3.1 Research problem ................................... 3
  1.3.2 Research scope .................................... 4
1.4 Research objective and deliverable ................. 6
  1.4.1 Research objective ................................ 6
  1.4.2 Research deliverable ............................. 6
1.5 Research questions ...................................... 6
1.6 Research methodology .................................. 7
  1.6.1 Research approach ................................. 7
  1.6.2 Data collection ................................... 8

## 2 Repair Process Environment
2.1 Remanufacturing ........................................ 9
  2.1.1 Definition of remanufacturing .................... 9
  2.1.2 Challenges of remanufacturing ................. 11
  2.1.3 Differences from manufacturing ............... 11
2.2 Aviation MRO ........................................... 12
2.3 Engine Services ....................................... 13
2.4 Repair section ....................................... 13
2.5 Conclusion ............................................ 14

## 3 Theory Analysis
3.1 Previous research .................................. 17
  3.1.1 TAT based research ............................. 17
  3.1.2 Quality based research .......................... 18
  3.1.3 Supply chain control research ............... 18
3.2 Operational excellence ................................ 18
  3.2.1 Lean Six Sigma ................................. 19
  3.2.2 Theory of Constraints ......................... 20
  3.2.3 Business Process Re-engineering ............ 21
3.3 Quality management .................................. 22
  3.3.1 Total Quality Management ..................... 22
  3.3.2 Statistical Process Control .................. 23
  3.3.3 Pre-control .................................. 25
3.4 Scalability .......................................... 26
  3.4.1 Definition of scalability ...................... 26
  3.4.2 Design for scalability ........................ 27
3.5 Industry 4.0 ....................................... 28
  3.5.1 Industry 4.0 components ...................... 28
  3.5.2 Industry 4.0 design principles ............... 28
  3.5.3 Industry 4.0 future ........................... 29
3.6 Conclusion .................................................. 29

4 Design Method Model ........................................ 31
  4.1 Model fundam .............................................. 31
  4.2 Process basis with return quality controller - layer 1 ........................................................................ 32
  4.3 Process maturation classification - layer 2 ......................................................................................... 34
  4.4 Upscale strategy - layer 3 ...................................................................................................................... 36
  4.5 Machine capacity arrangement strategy - layer 4 .................................................................................. 40
  4.6 Process innovation strategy - layer 5 ...................................................................................................... 41
  4.7 Supply chain integration ......................................................................................................................... 43
    4.7.1 General integration ............................................ 43
    4.7.2 Advanced data infrastructure .................................. 44
  4.8 Conclusion ...................................................... 46

5 Repair Process Design Generator ................................ 47
  5.1 Generator components ........................................ 47
  5.2 Component mechanisms and in-and output ......................................................................................... 48
    5.2.1 Return quality controller component .................. 49
    5.2.2 Process maturation component .......................... 50
    5.2.3 Upscale strategy component .............................. 50
    5.2.4 Machine capacity arrangement component ....... 51
    5.2.5 Scenario testing component .............................. 52
  5.3 Generator possibilities and limitations ...................................... 53
    5.3.1 Possibilities .................................................. 53
    5.3.2 Limitations ................................................... 53
  5.4 Conclusion ...................................................... 54

6 Model Verification .................................................. 57
  6.1 Model verification design ...................................... 57
  6.2 Return quality controller verification ...................... 58
  6.3 Process flow division verification ........................... 61
  6.4 Upscale strategy verification .................................. 63
  6.5 Model functionality evaluation .............................. 65
  6.6 Conclusion ...................................................... 66

7 Model Validation .................................................... 67
  7.1 Case study description ........................................ 67
  7.2 Case study input ................................................ 67
  7.3 Case study results ............................................. 68
  7.4 Conclusion ...................................................... 70

8 Conclusion & Recommendations .................................. 73
  8.1 Conclusion ...................................................... 73
    8.1.1 Criteria for sustainable initial repair process design ................................................................. 73
    8.1.2 Multi-layer return quality control model .............................................. 74
    8.1.3 Evaluation and main research question .................................... 74
  8.2 Recommendations ............................................ 74
    8.2.1 Recommendations for scientific research .................................. 74
    8.2.2 Recommendations for KLM E&M ES ........................ 75
  8.3 Discussion ....................................................... 75
    8.3.1 Limitations .................................................. 76
    8.3.2 Scientific contribution ....................................... 76

9 Business Implementation ........................................... 77
  9.1 Business current state of development ...................... 77
    9.1.1 Current procedures ......................................... 77
    9.1.2 Present developments ....................................... 78
    9.1.3 Position proposed design method ........................ 78
<table>
<thead>
<tr>
<th>9.2</th>
<th>Implementation requirements</th>
<th>78</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2.1</td>
<td>Data requirements</td>
<td>78</td>
</tr>
<tr>
<td>9.2.2</td>
<td>Process management requirements</td>
<td>79</td>
</tr>
</tbody>
</table>

**Bibliography**

| 81  |

**Appendices**

<table>
<thead>
<tr>
<th>A</th>
<th>Research Paper</th>
<th>87</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Company Profile</td>
<td>97</td>
</tr>
<tr>
<td>C</td>
<td>ES Process Overview</td>
<td>99</td>
</tr>
<tr>
<td>D</td>
<td>Development Strategy KLM E&amp;M ES</td>
<td>101</td>
</tr>
<tr>
<td>E</td>
<td>Regression Analysis Repair Data</td>
<td>103</td>
</tr>
<tr>
<td>F</td>
<td>Model Layers</td>
<td>107</td>
</tr>
<tr>
<td>G</td>
<td>Repair Process Design Generator Interface</td>
<td>111</td>
</tr>
<tr>
<td>H</td>
<td>Repair Process Design Generator Output</td>
<td>113</td>
</tr>
<tr>
<td>I</td>
<td>Model Verification</td>
<td>117</td>
</tr>
<tr>
<td>I.1</td>
<td>Return quality controller verification</td>
<td>117</td>
</tr>
<tr>
<td>I.2</td>
<td>Process flow division verification</td>
<td>118</td>
</tr>
<tr>
<td>I.3</td>
<td>Upscale strategy verification</td>
<td>121</td>
</tr>
</tbody>
</table>

| J   | Model Validation | 123 |
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Organizational chart Air-France-KLM</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Organizational level division</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Engine MRO repair E2E process</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>Research design</td>
<td>8</td>
</tr>
<tr>
<td>2.1</td>
<td>Complementarity of remanufacturing to manufacturing</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Four stages of remanufacturing</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Quality relation defined in the research of S. Stammes</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>Operational Excellence framework</td>
<td>19</td>
</tr>
<tr>
<td>3.3</td>
<td>BPR framework</td>
<td>21</td>
</tr>
<tr>
<td>3.4</td>
<td>Quality Trilogy</td>
<td>22</td>
</tr>
<tr>
<td>3.5</td>
<td>Shewhart individual control chart</td>
<td>24</td>
</tr>
<tr>
<td>3.6</td>
<td>Pre-control chart</td>
<td>25</td>
</tr>
<tr>
<td>3.7</td>
<td>One-sided pre-control chart</td>
<td>26</td>
</tr>
<tr>
<td>3.8</td>
<td>Configurations with different scalability</td>
<td>27</td>
</tr>
<tr>
<td>4.1</td>
<td>Multi-layer return quality control model</td>
<td>32</td>
</tr>
<tr>
<td>4.2</td>
<td>Adapted return quality control charts</td>
<td>34</td>
</tr>
<tr>
<td>4.3</td>
<td>Layer 1 detailed steps</td>
<td>34</td>
</tr>
<tr>
<td>4.4</td>
<td>Coefficient of Variation vs Degree of Freedom</td>
<td>35</td>
</tr>
<tr>
<td>4.5</td>
<td>Layer 2 detailed steps</td>
<td>36</td>
</tr>
<tr>
<td>4.6</td>
<td>Capacity calculation approach</td>
<td>36</td>
</tr>
<tr>
<td>4.7</td>
<td>Utilization vs. cycle time</td>
<td>38</td>
</tr>
<tr>
<td>4.8</td>
<td>Upscale strategy outputs</td>
<td>39</td>
</tr>
<tr>
<td>4.9</td>
<td>Layer 3 detailed steps</td>
<td>39</td>
</tr>
<tr>
<td>4.10</td>
<td>Layer 4 detailed steps</td>
<td>41</td>
</tr>
<tr>
<td>4.11</td>
<td>Categorical framework for Industry 4.0</td>
<td>42</td>
</tr>
<tr>
<td>4.12</td>
<td>Layer 5 detailed steps</td>
<td>43</td>
</tr>
<tr>
<td>4.13</td>
<td>Supply chain connection</td>
<td>43</td>
</tr>
<tr>
<td>4.14</td>
<td>International Definition Modelling languages</td>
<td>44</td>
</tr>
<tr>
<td>4.15</td>
<td>Computation-communication schemes</td>
<td>44</td>
</tr>
<tr>
<td>4.16</td>
<td>ROS based data exchange system</td>
<td>46</td>
</tr>
<tr>
<td>5.1</td>
<td>Generator components</td>
<td>48</td>
</tr>
<tr>
<td>5.2</td>
<td>Primary components relation</td>
<td>48</td>
</tr>
<tr>
<td>5.3</td>
<td>IDEF0 generator visualization</td>
<td>49</td>
</tr>
<tr>
<td>5.4</td>
<td>Amount of repair actions data sets extracted from research field</td>
<td>49</td>
</tr>
<tr>
<td>5.5</td>
<td>Generated amount of repair actions data sets</td>
<td>50</td>
</tr>
<tr>
<td>6.1</td>
<td>Verification elements</td>
<td>57</td>
</tr>
<tr>
<td>6.2</td>
<td>SPC limits vs. data set variance</td>
<td>59</td>
</tr>
<tr>
<td>6.3</td>
<td>SPC limits vs. data set range</td>
<td>59</td>
</tr>
<tr>
<td>6.4</td>
<td>SPC control limit vs. data set variance and range</td>
<td>60</td>
</tr>
<tr>
<td>6.5</td>
<td>Pre-control limits vs. data set variance and range</td>
<td>60</td>
</tr>
<tr>
<td>6.6</td>
<td>Acceptable flow division vs limit tightness</td>
<td>61</td>
</tr>
<tr>
<td>6.7</td>
<td>Warning flow division vs limit tightness</td>
<td>62</td>
</tr>
<tr>
<td>6.8</td>
<td>Bypass flow division vs limit tightness</td>
<td>62</td>
</tr>
</tbody>
</table>
6.9 Filtered data set variance below warning limit vs limit tightness ............... 63
6.10 Amount of upscale and bandwidth calculation value vs limit tightness ........ 64
6.11 First upsales per machine vs limit tightness ...................................... 64
6.12 Upscale strategy sufficiency vs waiting time ...................................... 64
6.13 Influence of different calculation values ............................................. 65

7.1 Histogram and control chart for the 80C & 80E fan mid shaft repair process ............................................................................. 68
7.2 Upscale scenario output for the 80C & 80E fan mid shaft repair process .......... 70

C.1 Overview of KLM E&M ES processes .................................................... 99
D.1 Repair process development strategy of KLM E&M ES ............................ 101
E.1 Regression analysis SAP repair data 2018 .............................................. 103
E.2 Heat shield repair .................................................................................. 104
E.3 Case LPT repair ................................................................................... 104
E.4 Core spinner front repair ...................................................................... 104
E.5 LPT major module repair ..................................................................... 104
E.6 Compressor rear frame assembly repair .............................................. 105
E.7 Mount AFT assembly repair ................................................................ 105
E.8 AGB springloaded seal set repair .......................................................... 105
E.9 Amount of repair actions vs duration standard deviation ....................... 106
F.1 Model layer 1 ....................................................................................... 107
F.2 Model layer 2 ....................................................................................... 108
F.3 Model layer 3 ....................................................................................... 108
F.4 Model layer 4 ....................................................................................... 109
F.5 Model layer 5 ....................................................................................... 109
G.1 Return quality controller generator interface ........................................ 111
G.2 Upscale strategy generator interface ..................................................... 112
G.3 Scenario testing generator interface ..................................................... 112
H.1 Pre-control chart .................................................................................. 113
H.2 Shewhart individual measurement charts ............................................. 113
H.3 Upscale strategy basis graph ................................................................ 114
H.4 Linear market demand upscale strategy .............................................. 114
H.5 Exponential market demand upscale strategy ...................................... 114
H.6 Machine specific upscale actions graph .............................................. 115
H.7 Machine specific upscale actions vs time graph .................................. 115
H.8 Upscale strategy scenario testing graph .............................................. 115
H.9 Flow division depiction ....................................................................... 115
I.1 Generated data sets with reducing variance ....................................... 117
I.2 Application of a limit scaling factor ..................................................... 118
I.3 Fluctuation reduction of limits with smaller data set variance ................. 118
I.4 Flow division vs limit scaling factor 5-75 ............................................. 118
I.5 Flow division vs limit scaling factor 30-50 range ................................ 119
I.6 Variance reduction by application of the control limits ......................... 119
I.7 Data set histograms for flow division calculation .................................. 120
I.8 Scenario for calculated upsales as function of limit tightness ............... 121
I.9 Influence of different bandwidth values for low variance data set .......... 121
J.1 Simulated market demands for design method application .................... 124
J.2 Output of 80C & 80E shafts per week .................................................... 124
# List of Tables

1.1 Theory versus practical oriented research ............................................. 7

2.1 Complicating characteristics for production planning and control in remanufacturing ................................................................. 12

2.2 Differences manufacturing and remanufacturing .................................. 12

4.1 Machine capacity utilization factor division .......................................... 38

4.2 Categorical systematic innovation scheme ............................................. 42

5.1 Input upscale strategy component ......................................................... 51

5.2 Theoretical possibilities of the generator ............................................... 53

5.3 Practical possibilities of the generator .................................................. 53

7.1 80C & 80E fan mid shaft flow division .................................................. 69

E.1 Amount of repair actions standard deviation of repair process cases ........ 106

I.1 Limit scaling factor with respect to limits .............................................. 119

J.1 Machine data 80C & 80E fan mid shaft repair process ............................ 123

J.2 Operational data 80C & 80E fan mid shaft repair process ....................... 123

J.3 Machine occupation data 80C & 80E fan mid shaft repair process .......... 123

J.4 Removed 80C & 80E service orders ...................................................... 124
List of Abbreviations

4Ms  Man, Machine, Material, Method.
80C  General Electric CF6-80C.
80E  General Electric CF6-80E.
AFI  Air France Industries.
AFKLM Air France Koninklijke Luchtvaart Maatschappij.
BPR  Business Process Re-engineering.
CFM  CFM CFM56-7B.
CoV  Coefficient of Variance.
Cpk  Process Capability Index.
CPS  Cyber Physical System.
CS  Component Services.
DMADV Define Measure Analyse Design Verify.
DMAIC Define Measure Analyse Improve Control.
DoF Degree of Freedom.
E&M  Engineering & Maintenance.
EGT  Exhaust Gas Temperature.
ES  Engine Services.
FTE  Fulltime-Equivalent Employee.
GE  General Electric.
GENx General Electric Next Generation.
IDEF International Definition.
IDEF0 International Definition for Functional Modelling.
IDEF1X Integration Definition for Information Modelling.
IoP  Internet of People.
IoS  Internet of Services.
IoT  Internet of Things.
KPI  Key Performance Indicator.
LSS  Lean Six Sigma.
MR   Moving Range.
MRO  Maintenance, Repair and Overhaul.
NDT  Non Destructive Testing.
OE   Operational Excellence.
OEM  Original Equipment Manufacturer.
OTP  On Time Performance.
PDCA Plan Do Check Act.
RMS  Reconfigurable Manufacturing System.
ROS  Robot Operating System.
SPC  Statistical Process Control.
TAT  Turn Around Time.
ToC  Theory of Constraints.
TQM  Total Quality Management.
VSM  Value Stream Mapping.
This chapter serves as introduction to the research conducted for the Delft University of Technology in collaboration with KLM Engineering & Maintenance (E&M). Section 1.1 describes the research context followed by the research field in section 1.2. Subsequently, section 1.3 describes the research problem combined with the research scope. Thereafter, section 1.4 elaborates on the research objective and deliverable. Then, section 1.5 focuses on the main research question and corresponding sub-questions. As last, section 1.6 describes the research methodology to gain insight in the structure of the thesis.

1.1 Research context
A broad-based global economic growth momentum is now in place with a renewed need to prioritize policies that foster new sources of innovation-driven growth [14]. This momentum stimulates the need for research that enables this innovation driven growth. In literature on product related industries this reflects amongst others on increased interest in sustainability of products and processes. This trend is clearly visible in aviation Maintenance, Repair and Overhaul (MRO), which focuses on ensuring aircraft airworthiness and life extension of aircraft parts. A combination of increasing global air travel and the call for a more sustainable world makes development in this industry of significant importance.

An expected global aircraft fleet growth of 3.7% and a monetary increase of 4.0% between 2018-2028 [12] emphasizes this significance for the global aviation MRO market. However, not only this increase in aviation MRO market potential is driving the need for innovation. The rise of Asian MRO providers offering low Turn Around Time (TAT), high quality and low labour costs and the increasing competitive interference of Original Equipment Manufacturers (OEMs) force western third party MRO providers to improve on operational efficiency [79]. KLM Engineering & Maintenance (E&M) is such a western company that recognizes that operational efficiency research and improvements are imperative for future existence. With this interest in research this company forms a suitable base for this research.

KLM E&M is the MRO branch of the airline KLM Royal Dutch Airlines. It comprises three key businesses; Airframe maintenance, Component Services (CS) and Engine Services (ES). Throughout these three branches and in combination with the engineering department innovation accelerated the last few years. With operational excellence as fundament and technology advancements as tools CS and Airframe improved to keep up with the demand and increase in competition. Yet, ES, which is facing an increasingly dynamic environment, remains behind in these innovations. This research is based at ES to practically assist its development alongside the contribution to science.

1.2 Research field
The research is conducted for the Delft University of Technology in cooperation with the Lean Six Sigma Office of KLM E&M, which focuses on Operational Excellence (OE). KLM E&M is part of the KLM Group and together with Air France Industries (AFI) part the Air France Koninklijke Luchtvaart Maatschappij (AFKLM) Group. Combined they provide MRO for the
internal fleet as well as for fleets of external customers. A simplistic organizational chart is shown in Figure 1.1 to provide insight in the AFKLM Group business divisions. A detailed company profile of KLM E&M has been attached in appendix B.

![Organizational chart Air-France-KLM](image)

The KLM E&M divisions and in particular ES are in need of efficiency advancements to sustain in the global MRO market. Organizational adaptations toward a high performance operation have been made in the past few years to maintain the leading market position. Nevertheless, organizational changes only do not suffice to keep up with the developing MRO industry. As mentioned in the section 1.1 the urgency for additional operational and technological developments is recognized too. Although some processes at ES have been improved on the basis of operational excellence, the overall innovation rate stagnated while its market significantly changed. With phasing out of older aircraft and investments in less maintenance sensitive aircraft by the AFKLM group, the demand for internal engine MRO decreased. As result the customer focus of ES shifted from the internal AFKLM fleet towards external airlines. Consequence of this customer shift is a less predictable and more dynamic and competitive market. This intensified the need for performance improvements to maintain a leading position.

ES is considered a future driver for the KLM E&M business. Even though the rate of engine maintenance shop visits for the newer generation engines is decreasing, its market is expected to preserve a 4.9% growth rate on average [12]. Besides that, engines nowadays operate at aggravated circumstances resulting in more extensive shop visits and wider range of required repairs. To preserve adequate service ES established three primary operations:

- Engine Availability
- Engine MRO
- Parts & accessories repair

Engine availability comprises the service to lease engines from an engine spare pool during engine MRO. Considering the nature of this service, it is classified as a planning mechanism. Contrary, the engine MRO and parts and accessories repair are classified as operational mechanisms. An overview of these three services and corresponding operations of ES is attached in appendix C.

To monitor the three services multiple Key Performance Indicators (KPIs) have been defined over the years. The engine availability KPI is the amount of spare engines that can be leased. The operational KPIs are the On Time Performance (OTP), engine quality Exhaust Gas Temperature (EGT), test cell yield and productivity are the main KPIs. Previous graduate students of the Delft University of Technology looked into optimizing the operational processes with
these KPIs as benchmarks. Besides proposing solutions to directly improve the KPIs, some also introduced extra or adapted KPIs to acquire better understanding of the process dynamics. Section 3.1 further elaborates on their findings. Yet, the operational KPIs OTP and productivity still arise in ES score dashboards as significantly below target. So, despite implementation of previously suggested improvements an underlying problem still obstructs the required progression. This persistent under performance in combination with the identified demand and competition growth delineates the essence of research at ES even more.

1.3 Research problem and scope

With the research field defined by current industrial challenges reflected on the organization KLM E&M the research problem is established following a twofold approach. First, a literature survey based on the research field defines not covered areas in science. Subsequently, these literature findings are reflected on the ES environment to incorporate practical context. This procedure results in the research problem as described in subsection 1.3.1 with consequently a research scope description in subsection 1.3.2.

1.3.1 Research problem

Literature survey

In the perspective of MRO processes the term remanufacturing led to two papers that outlined production planning and control state-of-the-art, industry practices and research needs for MRO processes [37],[26]. With respect to general technological development and innovation these papers from 2000 and 2012 could be denoted as dated. Still, both are considered valuable as, supported by on-floor observations, the aviation industry is in general considered conservative. These papers delineated that forecasting, process improvements, process planning and control, reverse logistics and characterization are covered areas in manufacturing and remanufacturing literature. Further search in the area of remanufacturing confirmed that most research related to those topics with some including optimization models and cost management relations [9],[13],[28],[78]. However, it came to attention that these research focus on current process states and recovery, improvement and control on operational level of process phases beyond initial design. From this observation it was noticed that research concerning sustainable initial process design that incorporates future states on operational level is missing. Therefore, research in this area is considered relevant to accelerate repair process development and enhance process future state performance.

Considering design of repair processes, the master thesis of preceding KLM E&M graduate intern S. Stammes [70] stroked with a divergent approach in process fundament definition. Contrary to TAT as process basis in previous graduation research, it introduced product quality. It showed that the relation between repair processes and output quality is substantial and that that relation is a relatively uncovered area of research. Literature survey with the terms quality and remanufacturing combined revealed that return quality, which is the designation of repair process input quality, remarkably influences the process and that it needs research [26],[4],[7]. Recalling the need for sustainable initial process design a continuation on the quality fundament of S. Stammes would be inclusion of the relation of return quality to the operational process. Existing research that concerns return quality did not yet directly address this relation with operational processes [57]. Therefore, this relation is considered a relevant topic for this research.

As last, one reoccurring term in recent literature devoted to innovation is Industry 4.0. Various literature state that a change towards a more digital and integrated industry is impending and that the concept of Industry 4.0 reacts to that [68],[33],[17]. Considering sustainable initial process design and KLM E&M and ES in need for innovation the concept of Industry 4.0 is taken into account in this research. Both [16] and [46] provided an overview of research in Industry 4.0. In [16] it is stated that research is particularly needed in a common definition, validation of Industry 4.0 theories, application potential and approach, case studies of Industry 4.0 and human-machine interaction. The research need for an application approach is considered a relevant subject for this research.
Practical context
As stated before the OTP of ES is significantly below its target. Observations and analyses show that amongst others process integration is lacking and that no clear initial base plan is in place for long-term sustainability of repair processes. The current repair development strategy of KLM E&M ES for initial design of repair developments consists of six phases, shown in appendix D. Phase three and four generate a detailed plan and enable the Man, Machine, Material, Method (4Ms) including quality control respectively. However, reflecting this on the recently improved and prioritized repair process of the fan mid shaft reveals that only definition of the 4Ms is carried out. There is no clear design for process fundament and future expansion. Conventional process management and improvement theories are only applied for recovery rather than prevention of process obstructions. Furthermore, a discussion on machine capacity arrangement is fluctuating continuously. It is clear that sustainable initial process design guidelines are not in place, which aligns with the defined science gap.

Regarding the research area of product and process quality S. Stammes already mentioned that this interest matched the strategy determined by the Vice President of ES, Paul Chûn [70]. It is observed that on-floor product return quality is interpreted binary. The returned product is either considered serviceable or not serviceable. No measurements are performed to quantify the return quality to improve operational performance of processes. Therefore, definition of the return quality relation to operational performance could practically enhance the repair processes.

With respect to innovation and system integration in the perspective of the forthcoming Industry 4.0 revolution ES remains behind. Planning and scheduling is carried out digitally, but changes are often made by hand. Repair process progress is not digitally shown and not communicated throughout stakeholders in the process. As last, the current machines are not integrated and not prepared for an Industry 4.0 change. Some have computer numerical control, but none are connected to an overall network. One could say that KLM E&M is still in the process of Industry 3.0, which consists of computer and automation implementation. So, the need for innovation and integration towards Industry 4.0 is substantial.

Combining the literature research needs and practical observations related to the research field, the research problem is defined as follows.

A method for sustainable initial repair process design is not yet available to sustain operational efficiency with future state expansion in the dynamic MRO market.

1.3.2 Research scope
To address the research problem this research zooms in on the operational level of the repair process of KLM E&M ES with a focus on machinery. The operational level is in management terms often considered as most direct production related level of the general three management decision levels; the strategic, tactical and operational level. In [31] this division is described by the organizational pyramid shown in Figure 1.2. The description in this paper is used as definition for the operational level scope.
1.3. Research problem and scope

Based on this operational perspective Figure 1.3 shows the six operations of which the repair process in general comprises.

In the KLM E&M ES research field disassembly and assembly stage are considered segregated processes with predetermined procedures and hard throughput barriers. Complete disassembly of all parts that require repair is mandatory before forwarding to the repair process. Whether a part originates from a complete engine or is send in as part does not affect the initial design of the repair process or its return quality. Consequently, both stages are considered out of scope for this research. Similarly, the quote process only comprises financial procedures that have no influence on the defined research problem. Cleaning & Non Destructive Testing (NDT), inspection and the repair itself are integral mechanisms of the repair process and are therefore included in this research with a focus on the machinery.

Furthermore, with respect to the OE process approach triangle consisting of quality, TAT and cost optimization this research focuses on quality. In previous research TAT has been accounted for as main driver multiple times and cost optimization relates more to the finance world. S. Stammes [70] started to expand the quality based research field by including the relation of output quality to the operational process. Advancing with quality as approach complements this research range expansion. Contrary, 4Ms establishment and scheduling and planning, often related to process design, are out of the scope of this research as these areas are extensively covered. Research in the industry 4.0 concept is limited to a theoretical implementation strategy with a focus on digitization to achieve paperless operations.

As last, existing and new repair processes at KLM E&M ES are used for practical observations and insight to assist definition of the process environment and proposed problem solution. This implies that the research is inherently scoped to the operational procedures present at KLM E&M ES. With general theory it is attempted to restrain this limitation. Yet, it should be recognized that the research results are influenced and scoped by the defined research field.
1.4 Research objective and deliverable

From the combination of the research problem and scope the research objective and deliverable are delineated in subsection 1.4.1 and subsection 1.4.2 respectively.

1.4.1 Research objective

The research objective rises from the research problem. This research focuses on the development of a method for sustainable initial process design that is adaptable to business specific requirements. Return quality should dominate this method with its relation to the operational process. In addition, it is considered essential to translate the developed method into a programmed repair process design generator to functionalizes the theory.

Accordingly, the following research objective is defined.

- Develop a method for sustainable initial repair process design from a return quality perspective and translate it into a repair process design generator.

1.4.2 Research deliverable

The deliverable specifies the output format of the research objective and thereby implicitly further defines the research scope. The format of the design method is configured as a model with layers of decision and action blocks that represent design strategies. The model is digitized into a repair process design generator with a programmed interface. The decisions and actions remain in a generic level to deliver a comprehensive and widely applicable design method. The summation below indicates which decisions and actions are specifically defined and which are considered as, out of scope, external advice.

- Operational process design actions/decisions included with a focus on machinery.
- Industry 4.0 included as parallel systematic implementation strategy.
- Planning & scheduling actions/decisions defined as external advice.
- Financial actions/decisions defined as external advice.
- Operational excellence exploit/elevate actions defined as external advice.

1.5 Research questions

Based on the research field, problem and scope and the objective and deliverable, the main research question and a set of sub-questions are defined. The main research question is defined as follows.

- What method can be proposed for sustainable initial repair process design from a return quality perspective?

To answer this main research question the following set of sub-questions is defined.

1. What criteria can be identified that influence sustainable initial repair process design?
2. What theories can be used to control the identified criteria?
3. What model can be proposed as design method to collectively control the identified criteria?
4. How can the model be translated into a repair process design generator to verify and validate the model?
5. What is the effect of the theoretical parameters on the procedures of the model and does the model function as intended?
6. How does the output of the proposed model relate to the current state of a repair process at KLM E&M ES?

7. What is the position of the proposed design method with respect to the current state of development of KLM E&M ES and what are requirements for implementation?

1.6 Research methodology

This research is based on the approach described in *Case Study Methodology in Business Research* [18]. Besides a general research approach, which is followed for this introduction, it describes how to determine the orientation of a research and which research procedures fit those orientations. The appropriate research orientation and corresponding research design for this research are described in subsection 1.6.1. Thereafter, subsection 1.6.2 elaborates on the research data collection.

1.6.1 Research approach

**Research orientation**

*Case Study Methodology in Business Research* [18] defines two main research orientations. The first is theory- or practice-based research. A short description of both is shown in Table 1.1. Based on the description of Table 1.1 and the elaboration in [18] this research is defined as theory-based as it aims to contribute to theory development. The underlying intention of this theory-based research is to use the introduced theory to improve practical process performance and development. From this remark the secondary orientation of this research is defined as proposition-building instead of being descriptive as the research aims to propose a progressive design method using known theories. The theory-based, proposition building orientation defines the perspective of research approach.

<table>
<thead>
<tr>
<th>Theory oriented</th>
<th>Practical oriented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory-oriented research is research where the objective is to contribute to theory development. Ultimately, the theory may be useful for practice in general.</td>
<td>Practice-oriented research is research where the objective is to contribute to the knowledge of one or more specified practitioners.</td>
</tr>
</tbody>
</table>

**Research design**

The first step of a theory-building research is exploration of not known concepts and their relations. This is done in subsection 1.3.1 by defining the research problem following a twofold approach with literature survey and practical context reflection based on the research field. Follow-up in this exploration is a theory analysis that guides development of a theory that contributes to knowledge of the defined unknown concept and relations. In this research a sequential approach is chosen to establish guidance for the theory building section. First, chapter 2 describes the process environment to identify criteria that influence sustainable initial repair process design providing the answer to sub-question one. Second, related theories are studied to provide proven concepts that enable development of theory to control these criteria. Chapter 3 describes these theories to answer sub-question two.

With this theory analysis a base is present to facilitate the theory-building part of the research. Chapter 4 continues the research with a description of a multi-layer return quality control model that embodies the design method. This forms the answer to sub-question three. After establishment of the model [18] suggests examination as last step. This examination can be carried out by verifying and validating the developed theory. Chapter 5 first describes how the proposed return quality control model is translated into a repair process design generator to answer sub-question four. Subsequently, chapter 6 and chapter 7 verify and validate the model to answer sub-questions five and six respectively. This approach
enables obtaining a wide range of model insight. After the verification and validation the research is concluded in chapter 8.

In addition to the completed theory-building research strategy of [18], chapter 9 describes how the proposed theory relates to the business state-of-the-art of KLM E&M ES and how it can be implemented to answer sub-question seven.

An overview of the research design is shown in Figure 1.4.

**1.6.2 Data collection**

Data for this research originate from four different sources. The first source is general literature related to the research problem and objective to define influencing parameters and theories for the theoretical design method development. The second source is previous research carried out at KLM E&M to complement the general literature with research environment specific experiences. The third source is repair data from the KLM E&M ES SAP database to obtain practical insight and enable case application of the theory. The fourth source comprises inspection documents of the ES inspection department to provide insight in quality measurements.
The research was introduced with development of a method for sustainable initial repair process design as objective. This means criteria that influence achievement of a sustainable initial repair process design need to be controlled. These criteria need to be identified by acquiring insight in the repair process environment. To obtain this insight, it is of essence to initiate with identifying criteria and continue with downscaling to the relevant process setting. Criteria that arise from this procedure guide the theory review and form the fundament of the model that embodies the design method. A combination of literature and on-floor observations is used to identify the criteria. Four process scale levels are defined to reason towards relevant criteria for sustainable initial repair processes design.

First, section 2.1 describes the general remanufacturing environment, followed by a downscale to aviation MRO in section 2.2. Subsequently, section 2.3 continues with the division ES and section 2.4 with its segment repair. As last, section 2.5 concludes the chapter with an answer to sub-question one.

The following sub-question will be answered in this chapter:

1. What criteria can be identified that influence sustainable initial repair process design?

2.1 Remanufacturing
Subsection 2.1.1 elaborates on the definition of remanufacturing and its main process stages. The challenges of a remanufacturing process are reviewed in subsection 2.1.2. As last, a comparison with manufacturing processes is made in subsection 2.1.3 to delineate differences.

2.1.1 Definition of remanufacturing
Remanufacturing is rising due to increasing attention, necessity for environmental footprint reduction and economic benefits. In [27] this statement is endorsed by stating that remanufacturing rapidly emerges as an important form of waste prevention and environmentally conscious manufacturing. Several definitions of remanufacturing are presented in literature [48],[3],[77],[73]. One definition that comprise most of these is provided in [72] as follows: "Remanufacturing is an industrial process whereby products referred as cores are restored to useful life. During this process the core pass through a number of remanufacturing steps, e.g. inspection, disassembly, part replacement/refurbishment, cleaning, reassembly, and testing to ensure it meets the desired product standards". With this definition in mind, it is stated that remanufacturing complements the manufacturing industry by creating the possibility to extend the life of manufactured products. In [76] this complementary combination is described by a systematic illustration of a hybrid remanufacturing/manufacturing system, which is shown in Figure 2.1.
Accordingly, the conditions for remanufacturing processes and facilities differ from that of manufacturing. A set of conditions to operate a remanufacturing business is described in [71]. First of all, there should be a remanufacturable product and that product should not be based on technologies subject to rapid changes. Furthermore, it should be possible to dismantle and remanufacture the product without damaging it too much. Businesswise an important condition is that the costs of remanufacturing are lower than the value of the remanufactured product and that the value of the remanufactured product is attractively lower than that of a new product. As last, the environmental footprint of the remanufacturing process should be beneficial with respect to scrapping the product and replacing it with a complete new one.

The remanufacturing process is described in various manners in literature. In [40] twelve steps are mentioned for a general remanufacturing process. Yet, [5] merged these steps in the four process stages described below. The first two stages can be interchanged in order depending on the particular product or process.

- **Stage 1 Inspection/Grading**: In this stage the incoming products are cleaned and inspected to determine their return state. Market and waste streams cause a high variation in this return state. This results in varying inspection and cleaning times and diverse inspection tools. The stage ends with a determination whether a product is scrap or remanufacturable. In the first case it is disposed or sold as scrap. In the second case the remanufacturing process is determined with detailed work scopes.

- **Stage 2 Disassembly**: In this stage the product is disassembled into smaller parts if necessary. The disassembly times usually vary less than the inspection times as most products consist of the same parts. However, this still depends on the required level of dismantling. The inspection of stage 1 can again take place on a more detailed level after disassembly and sub parts can still be designated as scrap. As stated before the order of stage 1 and stage 2 can also be interchanged, meaning that the product is first disassembled and afterwards inspected.

- **Stage 3 Reprocessing**: This stage involves the process of restoring the product or parts of the product to a serviceable state, often designated as repair. The amount of required processes and the complexity and time of these processes depend on the return state and consequently work scope of the product. Not restorable sub parts of a product that is considered as overall remanufacturable are replaced by serviceable ones in this stage. The revised and replaced parts are combined into a serviceable product.

- **Stage 4 Reassembly**: This stage consists of the process to reassemble the individual parts to one serviceable product. It is most dependent on the previous stages as any delay in those stages causes this stage to stall. A product can only be completely re-assembled if all of the sub parts are available in the required state.

A visualization of these stages from [5], extended to show the interchangeable order of stage 1 and 2 and the cleaning process, is provided in Figure 2.2. For a visualization and description of the twelve steps one is referred to [40].
2.1.2 Challenges of remanufacturing

The challenges present in the remanufacturing world also implicate its characteristics. In [5] the following seven unique challenges are mentioned as general remanufacturing characteristics.

- Uncertain quality condition of return products
- Variable inspection yields of used products
- Variable disassembly yields of constituent components
- Variable reprocessing efforts of constituent components
- Multiple key remanufacturing stages with inter-dependency between stages
- Multiple types of constituent components
- Matching and reassembly of the same set of constituent components into final products in a customer driven environment

The basis for these seven characteristics is provided in [26]. Moreover, it provided an overview of the remanufacturing characteristics originating from operational challenges in relation to production planning and control activities. Table 2.1 shows this overview.

Regarding repair process design the characteristics that relate to shop floor control are considered of most interest. It is important to retain these characteristics and the seven challenges throughout the downscaling to repair processes for criteria identification.

2.1.3 Differences from manufacturing

Differences between manufacturing and remanufacturing arise from the above described definition and challenges. Primary difference is the unknown condition and stochastic quantities of return products of remanufacturing processes. In manufacturing raw materials or sub-assemblies with a relatively stable, predetermined state and quantity are the system input. In remanufacturing, products in unknown quantities and with unknown conditions need to be disassembled, inspected, repaired and assembled. Consequently, the required repair actions, routes and machine lead times of the remanufacturing processes are stochastic, while for a manufacturing process those are fixed. These stochastic characteristics increase the complexity of capacity design and process expansion possibilities, both essential for process sustainability, of remanufacturing processes compared to manufacturing processes. In addition, in remanufacturing it is often essential that the disassembled parts of a product set
are kept together for assembly while in manufacturing sub parts can be interchanged. These findings are supported and extended by [20]. An overview of differences based on the above findings and descriptions in [20] and [69] is shown in Table 2.2.

Table 2.1 Complicating characteristics for production planning and control in remanufacturing [28]

<table>
<thead>
<tr>
<th>Complicating characteristic</th>
<th>Production planning and control activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecasting</td>
<td>✔</td>
</tr>
<tr>
<td>Logistics</td>
<td>✔</td>
</tr>
<tr>
<td>Shop floor control</td>
<td>✔</td>
</tr>
<tr>
<td>Inventory Control</td>
<td>✔</td>
</tr>
</tbody>
</table>

Table 2.2 Differences manufacturing and remanufacturing [20]

<table>
<thead>
<tr>
<th>Process stage</th>
<th>Manufacturing</th>
<th>Remanufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process input</td>
<td>Design, production, assemble</td>
<td>Disassemble, repair, assemble</td>
</tr>
<tr>
<td>Product input</td>
<td>Fixed quality and quantity</td>
<td>Variable quality and quantity</td>
</tr>
<tr>
<td>Lead times</td>
<td>Low variation</td>
<td>High variation</td>
</tr>
<tr>
<td>Process routes</td>
<td>Fixed</td>
<td>Variable</td>
</tr>
<tr>
<td>Volume - Batch size</td>
<td>High or Low - Large</td>
<td>Low - Small</td>
</tr>
<tr>
<td>Scaling</td>
<td>Uncomplicated</td>
<td>Complicated</td>
</tr>
<tr>
<td>Assemble rules</td>
<td>Parts interchangeable within a set</td>
<td>Parts not interchangeable within sets</td>
</tr>
<tr>
<td>Man vs Machine</td>
<td>Machine driven</td>
<td>Labour intensive</td>
</tr>
</tbody>
</table>

2.2 Aviation MRO

One industry that applies remanufacturing on large scale is the aviation MRO. The MRO-type activities are principally servicing, repair, modification, overhaul, inspection and determination of condition of aircraft [8]. The term remanufacturing in this industry is thus perceived in a broad manner. An important distinction in process mechanism on this scale is made between scheduled and unscheduled maintenance. Scheduled maintenance is of preventive nature with input quantities in general known. Unscheduled maintenance is not predicted and mainly results in input quantity variance. The task packages for both operations are often not specified in advance resulting in variable maintenance routes and operations. These high organizational level variances spill out to the input of lower level processes.

In addition, [79] mentioned that the MRO service world is a relatively unexplored world with the focus mainly on aircraft development and production and not on the aftermarket. In this paper it is mentioned that the MRO industry has strict and precise requirements defined by airworthiness authorities to guarantee safety. Consequently, as substantiated in [19] the aviation industry, including MRO, is considered conservative. This conservative attitude has as effect that the innovation rate in the MRO business is relatively low. Innovations are often reluctantly received with implementations needing extensive guidance. Yet, it also implies considerable opportunities to innovate processes. Therefore, it is important to specify the
2.3. Engine Services

KLM E&M ES serves the aviation MRO with responsibility for MRO of engines and parts from the internal AFKLM fleet and external clients. Currently, ES handles the following four types of engines:

- CFM CFM56-7B (CFM)
- General Electric CF6-80C (80C)
- General Electric CF6-80E (80E)
- General Electric Next Generation (GEnx)

Based on these four engines the input variance, as described in the two previous sections, seems not too extensive for engine MRO. However, one engine usually consists of seven modules, fairly more assy’s and over 10,000 parts. Each of these parts could require service, which is to significant extend not determined before the engine enters the shop. Consequently, return quality and quantity variance appears in the ES division too. The same applies to part repair. Even though the work scope for part repair is more bounded the specific input quality and quantity of parts is not predetermined.

Furthermore, it is recognized that the product volume for ES is relatively low, which is in line with Table 2.2. Yet, the work volume is not low. Because of the amount of parts of one engine and the extensive regulation, the work volume does not correspond with the product volume. This characteristic is important to keep in mind for process automation.

A last notable KLM E&M ES environment observation associates with the two main flows of ES, the engine MRO and parts MRO. The interests for engine MRO differ from that of the part MRO resulting in a different approach in planning and prioritizing. The potential cash flow involved with engine MRO is often higher than that of part MRO. Lastly, the not interchangeable parts characteristic as described in Table 2.2 applies to engine MRO. An engine cannot be finished as long as its set of sub parts is not complete. These factors affect the prioritization of work order for ES. Nevertheless, prioritization particularly relates to planning and control, which is widely covered in literature. Therefore, these factors are considered less significant criteria for initial repair process design.

2.4 Repair section

The last process environment downscale is to the specific repair section of KLM E&M ES. As stated in subsection 1.3.2 the repair section comprises cleaning & NDT, inspection and the repair route in this research. The disassembly and assembly are considered segregated processes. Criteria identified in this process environment level most directly relate to the research objective.

A first complication is process interdependency. Several machines carry out repairs of multiple repair process lines. This mechanism is referred to as flexible resources. The usage of flexible resources is beneficial for capital investments, but complicates the assessment of capacity and availability of machines. A regularly proposed and applied method to optimize flexible resources is cellular manufacturing [51]. However, this mainly improves the internal process flow and is not a remedy for complex assessment of capacity and availability of machines. Accordingly, it remains difficult to expand repair processes and determine allowable quantity in process to sustain efficient operation with increasing demand and competition.

A solution could be a change from flexible to dedicated machines, so that each repair line has its own machines. In [65] it is described how the change from flexible to dedicated machinery could amplify capacity and ease the determination of it. Yet, with extensive variation of...
repairs in this environment it is not feasible to apply dedication for each possible repair. Selection of the most suitable machine arrangement thus is inherently related to the complex determination of expansion possibilities of repair processes. Therefore, the complex definition of process future expansion potential and dependent choice for flexible or dedicated machinery are identified as important criteria that influence preservation of efficiency during expansion and thus process sustainability.

The input quantity and quality variance present throughout the previously discussed processes appears in the repair section too. As previously mentioned higher process level variances spill out to ES. The fluctuations in engines, modules, assy's and parts directly relate to the system input of the repair processes. In [26] high variance in process times is mentioned as result of this input variance. Yet, observed primary result of the quality variance on operational level at KLM E&M ES is variance in required amount of repair actions. Even during operation the amount of repair actions is frequently altered based on new findings. Therefore, return quality and quantity variance remain important criteria with the relation to operational performance identified as influence on either process times or amount of repair actions. A KLM E&M ES data regression analysis, attached in appendix E, substantiates this identified relation.

Furthermore, [74] mentioned low reliability of individual repair stages and a low reproducibility of intended results. For a large share of the repair processes the computer numerical control machine is manually tuned or even completely manually operated. Consequently, the capacity of the machines and operators cannot be used most optimal. This is a factor that should be accounted for in capacity assessment. Therefore, it is not considered as primary criteria for the research objective, but as element of the complex process expansion criteria.

Last observation is the segregation of repair subprocesses. The architecture of the repair section of KLM E&M ES is based on combining similar repair techniques in a cellular manner as described in [51]. For each technique field different teams and managers are assigned, all dependent on each other. This is also indicated as one of the seven remanufacturing challenges described in subsection 2.1.2. Current communication and integration lacks resulting in significant waste of time. Improved integration thus is important for sustainable initial repair process design. This is considered part of the implementation of innovation criteria.

2.5 Conclusion

The chapter focused on identifying criteria that influence sustainable initial repair process design. The remainder of this sections answers sub-question one.

**What criteria can be defined that influence sustainable initial repair process design?**

- First criteria is *return quantity and quality variance*. It appeared that on operational level the quantity variance affects machine available capacity assessment and the quality variance machine lead times or required repair actions, both operational parameters that influence sustainable initial repair process design.

- Second criteria is *classification of process maturation*. Classification of process maturation influences initial design of a repair process as data availability and process state of development determine feasibility of control and innovation methods.

- Third criteria is *definition of process future expansion*. Definition of process future capacity expansion is important to sustain efficient operation and should therefore be part of initial repair process design.

- Fourth criteria is *determination of machine capacity arrangement*. Following from the complex process expansion characteristic the required determination whether to implement flexible or dedicated machinery arose. This arrangement influences the process efficiency during expansion and is therefore considered essential.
• Fifth criteria is *implementation of innovation*. Throughout literature the urgency for innovation is declared and on-floor observations strengthen this need. To enhance sustainability in a fast developing industry, implementation of innovation is important.

To initially control these criteria management and control methods need to be shifted to the input and initial design phase of the repair process. This shift diverges from the conventional approach to apply these methods on phases beyond initial design and output of processes. The criteria facilitate a directed theory study in the next chapter and form the fundament of the design method model.
The identified criteria form the fundament of the design method model. Yet, additional theory is required to explicate this fundament. Therefore, this chapter continues with a theory analysis related to the criteria defined in chapter 2:

- Return quality and quantity variance
- Classification of process maturation
- Definition of process future expansion
- Determination of machine capacity arrangement
- Implementation of innovation

First, section 3.1 describes where this research fits in the chain of preceding graduate interns at KLM E&M ES. Subsequently, section 3.2 to section 3.5 elaborate on theory related to the above criteria. Section 3.2 describes process improvement and design theories that are part of OE. Then, section 3.3 elaborates on theories regarding quality management. Next, section 3.4 presents insight in scalability of manufacturing systems. Thereafter, section 3.5 elaborates on the concept of Industry 4.0. Each theory is evaluated for applicability and allocated to the above criteria. As last, section 3.6 concludes the chapter by answering sub-question two.

The following sub-question will be answered in this chapter:

2. What theories can be used to control the identified criteria?

3.1 Previous research
This sections provides a clear overview of the chain of previous graduation research at KLM E&M ES. It clarifies how this research expands the current chain of knowledge. One recent research not conducted at ES but still relevant is that of A. Lemsom [45]. The research at ES is divided in TAT-based and quality-based.

3.1.1 TAT based research
W. Mogendorff configured a model to measure MRO TAT [54]. As fundament for the model, three main value drivers were defined that determine the TAT of the combustor; components, capacity and capabilities. P. Meijs continued with a research to reduce the TAT of in-house repairs at ES [53]. Three main conclusions resulted from this research. First, the TAT of in-house repairs of ES is influenced by seven factors: inventory, waiting, over processing, re-work, availability of machines, availability of man and batch size. Second, the performance measurements need to be updated to accurately measure TAT and the values of influencing factors. Third, some operational alternatives have to be implemented to reduce the TAT of ES in-house repairs. Subsequently, A. Rozenberg continued on this research by designing a framework to analyze and improve engine MRO processes from an integral perspective. Accordingly, this research developed a seven-step framework based on operational excellence,
process modelling and solution evaluation methodologies. As last, G. Soeters addressed operational excellence by continuous improvement of the integral engine MRO chain [69]. Instead of looking into individual process steps this research analysed the integral chain of engine MRO processes. As outcome the research proposed an integral model and several management decisions to improve the TAT of the integral MRO process chain, which amongst others comprised adjustment of prioritization rules, contract agreements, scheduling and distribution of manpower and process batching.

3.1.2 Quality based research
After these TAT based research the research of S. Stammes used a quality based perspective [70]. It was observed that the only output quality KPI at ES was the EGT margin of the serviced engines. Furthermore, this KPI was binary interpreted as a sufficient or not. As result the main research problem was defined as ES not having enough quality control within the MRO process to match the actual output EGT with the contractual EGT. As solution the research addressed the relation between repair processes and engine output quality. Figure 3.1 shows the general quality marking points on strategic level with the relation defined in this research highlighted. The following abbreviations are present in this figure: Input quality (IQ), Output quality (OQ), Customer quality (CQ) and Operational performance (OP). It can be seen that the relation between sub processes and the input quality is not yet established. This is where this research complements the research of S. Stammes and fits in the established chain of knowledge.

![Figure 3.1: Quality relation defined in the research of S. Stammes](image)

3.1.3 Supply chain control research
The last relevant research is that of A. Lemsom, which focused on controlling of the integrated supply chain from a service level perspective [45]. The research elaborated on various control methods and the impact of those on the service level. In that way a control framework was designed to determine the most suitable control method for certain process characteristics. The research complemented shop floor planning and controlling theory by expanding towards an integrated supply chain. Regarding this research, the research of A. Lemsom could complement the sustainable initial repair process design strategy with a suitable process control theory. After establishment of a sustainable initial repair process design implementation of a suitable current state control strategy is required. The research of A. Lemsom is considered as qualified reference for that purpose.

3.2 Operational excellence
The OE approach is widely applied in businesses, yet a single comprehensive definition still not exists [21]. OE is considered a way of thinking and belief with supporting physical tools. Nevertheless, some models for OE have been developed to establish a theoretical approach. One framework that provides an overview of an OE system is developed by Boston Scientific [22]. Figure 3.2 shows this framework with the elements encircled and continuous improvement direction highlighted that relate to sustainable initial design of repair processes. This illustrates that OE comprises theory relevant for control of the criteria.
3.2. Operational excellence

The sequel of this section elaborates on process improvement and design theories classified as part of OE. Several quality related theories can also be designated as part of OE. However, as return quality determination is defined as one of the objectives of this research the related theories are separately discussed in the next section. This section continues with the following theories:

- Lean Six Sigma (LSS)
- Theory of Constraints (ToC)
- Business Process Re-engineering (BPR)

### 3.2.1 Lean Six Sigma

LSS combines the principles of Lean and Six Sigma in a method to improve customer satisfaction as well as company results. The two main targets of Lean and Six Sigma, reduce process steps and improve process predictability respectively, complement each other in this method. Both approaches are independently reviewed before the combination is discussed.

**Lean**

The lean philosophy originated from Toyota Production Systems and was in preliminary form introduced by M. Porter[62]. Yet, definition of the general principles and knowledge became generally known after publication of "The Machine That Changed the World"[82]. Three main objectives are identified in the lean philosophy: improving flow, apply only value adding time and steps into the organization and eliminate all waste[11]. These objectives were translated into the following five key principles for lean management:

- Identify value
- Map value stream
- Create flow
- Establish pull
- Continuously improve

These five principles can be used to improve a process towards a standardized, just-in-time, pull system where customer demand is determinative. Although the main focus of lean theory is improvement of existing processes, the principles are valuable to establish the relation of return quality to the repair process.

**Six Sigma**

The Six Sigma concept was introduced by two engineers of Motorola to standardize the way defects were counted and reduce statistical significance of defects using the data set standard deviation, $\sigma$. This initial idea was translated into six steps in the Motorola University Design for Manufacturing training program[56]:

![Figure 3.2: OE framework with relevant components encircled [22]](image-url)

Figure 3.2: OE framework with relevant components encircled [22]
• Identify the product created or the service provided.
• Identify the customer for the product or service and its demands.
• Identify your needs in order to provide the product or service.
• Define the process for doing your work.
• Mistake proof the process and eliminate defects and waste.
• Ensure continuous improvement.

From these first steps the Six Sigma concept developed to a theory to improve output quality by identifying and removing defects and minimizing the variability in the process. Based on the six steps of the Motorola University, the Define Measure Analyse Improve Control (DMAIC) and Define Measure Analyse Design Verify (DMADV) methodology were developed to implement the Six Sigma theory. Similar to Lean theory, Six Sigma mainly aims for process improvements and not design. But again, for initial design of repair processes the six steps of Six Sigma could be useful for process basis determination. With variance previously defined in chapter 2 as important process influencing factor the Six Sigma steps could help anticipate this variance during initial process design.

**Lean Six Sigma**

The question "What specific improvements should be executed and in what order" led to the combination of Lean and Six Sigma as both theories separately did not, but together did, provide a satisfactory answer. Lean cannot bring a process under statistical control and Six Sigma cannot significantly improve process speed or reduce invested capital [23]. In the same research a definition of the principle of LSS is provided as follows: "The activities that cause the customer’s critical to quality issues and create the longest time delays in any process offer the greatest opportunity for improvement in Cost, Quality, Capital, and Lead time”. These activities should be excluded as much as possible during initial repair process design, which makes the philosophy of LSS valuable to keep in mind.

### 3.2.2 Theory of Constraints

The ToC is a management philosophy that aims to identify the bottleneck in a chain of processes and then improve that bottleneck. The theory was first introduced in 1984 by E. Goldratt [24]. The theory distinguished itself by looking at the integral process chain and not at processes independently. The Value Stream Mapping (VSM) tool is regularly mentioned as useful in conjunction with the ToC for this purpose. The VSM defines the gates of the sub processes and includes process data. The combination encourages to identify the bottleneck of the process chain and determine its relation to the other sub processes. To measure organizational performance [24] identified the following three specific determinants:

• **Throughput**: In what rate generates the organization cash through sales
• **Inventory**: Cash spend to buy products that are to be sold later
• **Operating Expenses**: Cash spend to turn inventory into throughput

To improve on these determinants Goldratt defined five steps as ToC procedure:

• Identify the bottleneck
• Exploit the constraint
• Subordinate and synchronise to the exploited constraint
• Elevate performance of the constraint
• Repeat the process
3.2. Operational excellence

With these determinants and five steps to improve the integral process, the ToC can be considered as more than an improvement theory only. In [29] a demonstration showed that the ToC also proves viable for operation management. It implied that the ToC is applicable in a broader perspective than only as improvement theory. Continuing this perspective it is identified that in a reversed manner the ToC could be a method to determine a process upscale strategy with allowable quantity in process. Reversed signifies in this case that bottlenecks are calculated in advance to determine potential capacity limitations and upscaling steps to sustain efficient operation with increasing quantity in process. Furthermore, it could enable a systematic approach to determine whether to operate machines in a flexible or dedicated arrangement. With these application possibilities, the ToC is considered useful for sustainable initial repair process design. Yet, to apply the ToC as front end upscale calculation it is imperative to define reasonable process and parameter ranges. Consequently, it is recognized that a complementary method to establish process input bandwidth is required.

3.2.3 Business Process Re-engineering

BPR is a management strategy introduced by M. Hammer with the perception to rather eliminate non-value-adding processes than automate with new technology [32]. BPR seeks to let organizations fundamentally rethink and change their processes to improve performance. In this approach, information technology is considered as valuable enabler for these changes. This is in line with the described Industry 4.0 revolution with data exchange as main driver. In essence, the BPR approach has overlap with sustainable initial repair process design. Figure 3.3 illustrates BPR configured into a framework.

![Figure 3.3: BPR framework](image)

The phases of this BPR framework fit the design of this research and stages one to four are applicable for sustainable initial repair process design. A primary BPR modelling tool that guides the definition of these stages is the swimlane diagram. This diagram enables visual depiction of business process models, such that these can be defined, analysed and integrated. Therefore, part of the BPR framework and the swimlane diagram are considered valuable assets for the development of the design method model. Further elaboration on the framework can be consulted in [30].
3.3 Quality management

This section continues with quality management theory. With return quality determination identified as fundamental in this research these theories are considered relevant. First, subsection 3.3.1 discusses the Total Quality Management (TQM) with its main influencers. Subsequently, subsection 3.3.2 and subsection 3.3.3 elaborate on the quality control Statistical Process Control (SPC) and pre-control theories.

3.3.1 Total Quality Management

TQM is a collection of methods, ideas and approaches to improve the quality of products or processes. An overview of principles and contributors of TQM is provided in [59] and [6]. For the purpose of this research the three main TQM contributors are discussed; Deming, Juran and Crosby.

**Deming**

Deming is considered an important contributor to TQM with the Plan Do Check Act (PDCA) cycle, fourteen points and seven deadly diseases as useful tools. The PDCA cycle serves as tool for quality management. It helps to establish hypotheses about required changes and then test those with a continuous feedback loop. The PDCA cycle supports improvement of products or processes by breaking those up in smaller parts. The fourteen points of Deming were also developed to assist companies to obtain quality improvements. These fourteen points can be found in detail in [15]. In the same paper Deming also mentioned the seven deadly diseases, each being a barrier to effective implementation of his principles. The PDCA cycle, fourteen steps and seven diseases are kept in mind during the development of the model as those contain information for effective application of quality related theory.

**Juran**

Juran contributed to TQM with the quality trilogy [38]. According to Juran three quality-orientated processes form the framework for improving quality:

- Quality planning
- Quality control
- Quality improvement

The paper described the three processes as follows. Quality planning comprises creating a process that is able to meet established goals and do so under operating conditions. Due to deficiencies in the original planning waste is inherent with the process. Therefore, quality control is necessary to keep that waste from getting out of control. Meanwhile, the chronic waste should be reduced by quality improvement. Figure 3.4 illustrates the quality trilogy.

![Figure 3.4: Quality Trilogy [38]](image)

The quality control process relates most to the quality variance criteria. Therefore, its steps are provided below. For detailed steps of all three processes [38] can be consulted.
3.3. Quality management

- Choose control subject - What to control
- Choose units of measurement
- Establish measurements
- Establish standards of performance
- Measure actual performance
- Interpret difference (actual versus standard)
- Take action on the difference

These quality control steps suit for return quality variance control and are considered convenient guidelines.

Crosby
Crosby introduced the zero defects concept with the interpretation that efficient quality management must be based on prevention-based systems with the so-called first time right principle [59]. Crosby described four absolutes that characterized his TQM vision that increased quality does not imply increased costs by definition:

- Quality means conformance to requirements, not goodness.
- Quality is achieved by prevention, not appraisal.
- Quality has a performance standard of zero defects, not acceptable quality levels.
- Quality is measured by the price of nonconformance, not indexes.

To implement his vision Crosby defined fourteen steps, which can be consulted in [59]. Yet, the vision of Crosby is particularly for output quality of the products and does not suite for the return quality variance criteria. The concept is more of value for the connection of sub processes to the process output quality, which is covered in the research of S. Stammes [70].

3.3.2 Statistical Process Control
SPC is an approach to control quality with statistical methods. The aim of SPC is to reduce variability in the process and consequently enhance efficiency. In [60] SPC is described as a method of TQM that can be used for problem solving and process improvement or to stop producing chaos. Over the years several statistical tools have been developed for SPC with the Shewhart individual control chart as most technically sophisticated [55]. This twofold chart uses control limits to define an allowable process data range. The Shewhart individual control chart is in particular applicable to slow processes with singular inspections and impracticality to use rational subgroups, such as remanufacturing processes [55]. Moreover, it does not require normally distributed data. Therefore, it is chosen to further elaborate on the Shewhart individual control chart.

Shewhart created the basis for this control chart for individual units after which it developed to a common tool for SPC [67]. The chart consists of two parts: one with individual measurements and one with the Moving Range (MR). The MR is used to estimate the process variability and is defined by Equation 3.1:

\[ MR_i = |X_i - X_{i-1}| \]  

(3.1)

The MR shows the difference between two subsequent measurements and forms the basis for the control limits of both charts. For the MR chart Equation 3.2 to Equation 3.4 define the mean and upper and lower control limits with m individual values.

\[ MR = \frac{\sum_{i=2}^{m} MR_i}{m-1} \]  

(3.2)
\begin{align*}
UCL_r &= D_4 \times \overline{MR} \quad (3.3) \\
LCL_r &= D_3 \times \overline{MR} \quad (3.4)
\end{align*}

In these equations \( D_4 \) and \( D_3 \) are sample size specific anti-bias constants for \( n = 2 \) observations, which can be found in the appendix VI table of [55]. The values are 3.267 and 0 respectively. In the case of a normally distributed data set \( \overline{MR} \) can be estimated using \( \sigma \) with Equation 3.5.

\[
\overline{MR} = \frac{2 \times \sigma}{\pi} \quad (3.5)
\]

For the individual measurements chart Equation 3.6 to Equation 3.8 define the mean and upper and lower control limits.

\[
\bar{X} = \frac{\sum_{i=2}^{m} X_i}{m-1} \quad (3.6)
\]

\[
UCL = \bar{X} + 3 \times \frac{\overline{MR}}{d_2} \quad (3.7)
\]

\[
LCL = \bar{X} - 3 \times \frac{\overline{MR}}{d_2} \quad (3.8)
\]

In these equations \( d_2 \) is again the sample size specific anti-biasing constant for moving range samples \( n = 2 \) observations, which can be found in the appendix VI table of [55]. For \( n = 2 \) observations \( d_2 \) is 1.128. In addition a warning limit can be added by using the same formulas but with \( \frac{2}{d_2} \). Measurements outside the determined limits of these charts indicate that the process is not operating as intended. Figure 3.5 illustrates both charts with upper and lower control limits.

![Figure 3.5: Shewhart individual control chart [35]](image)

SPC can be implemented according the following steps defined in [49]:

- Identify processes
- Identify measurable attributes of the process
- Characterize natural variation of attributes
- Track process variation
• If the process is in control, continue to track

• If the process is not in control
  – Identify assignable cause
  – Remove assignable cause
  – Return to ‘Track process variation’

With these steps and charts, the SPC approach provides a method to design a return quality controller to reduce the return quality variance with allowable input limits. These limits enable definition of a process input bandwidth, which was identified as required to apply ToC as upscale strategy. In addition, it provides a base for maturation classification as for SPC application significant data are required. However, current SPC commonly focuses on output quality instead of return quality. Besides that, the description of the concept above elaborates on a two-sided distribution with an upper and lower limit. Repair work often consists of restoring materials that experienced material wear. This means that only an one-sided chart is suitable. In general the method remains the same, but modifications are required for remanufacturing process applicability.

### 3.3.3 Pre-control

In [75] pre-control is described as technique that helps operators to control the process to prevent production of defective parts. Pre-control is capable of providing feedback about the process from its initiation making it highly responsive to process signals. It aims to adjust the process in its early stages based on small or no measurement sample data. Pre-control uses the pre-control chart as statistical tool. The chart uses a division in a green, yellow and red zone. The middle part of the chart is the green zone defined by a lower pre-control limit and upper pre-control limit. The yellow zone is the zone between the control limits and tolerance limits. The part of the chart outside the tolerance limits is red. Figure 3.6 illustrates the pre-control chart with an assumed Process Capability Index (Cpk) of 1 and a tolerance mean that coincides with the process mean. The percentages in the figure show the percentage of the sample data in a particular zone.

![Figure 3.6: Pre-control chart](image)

To qualify the quality with no or insignificant data five sequent units from the process are taken for measurement. The initial tolerance is based on the product or process specifications or six times the standard deviation of an available small data set [75]. If all five of the units fall in the green zone the initial process design is accepted to run. Henceforth, the tolerance is based on six times the $\sigma$ of the green run data set. The probability of five consequent units in the green zone drops with lower Cpk. The relation between this probability and the Cpk is shown in [75]. If one of the units falls in the yellow zone the counting is restarted. If two sequent units fall in the yellow zone or one unit in the red zone the process needs adjustments. As soon as the process is qualified, it is important to keep measuring two
sequent samples at periodic intervals. In [44] the following steps are described to remain sufficient quality control of the process:

- If at least one of the units falls in the green zone and none in the red continue the process.
- If both units fall in the yellow zone the process is stopped and adjustments need to be made. After adjustments the initiating sequence starts again with five consequent unit measurements.
- If sequent units fall in both the opposite yellow zones it is likely that the variability increased. The process need to be stopped to determine and solve the causes of the variability.
- If one unit falls in the red zone the process need to be stopped and investigated thoroughly to solve the misalignment.

For repair processes with hardly or no historical data available, the pre-control method could provide an option to design and manage the return quality control. In the case of no data availability, a downside is that at least five items have to be accepted based on process product specification boundaries to establish the first pre-control limits. Moreover, the pre-control concept has relatively low accuracy. The three zones represent three quality levels, with the units in these levels considered as equally good. In an advanced state of the process, where more accurate work scope planning is desirable, the concept lacks as measurements are not distinguished individually. Similar to the SPC method only an one-sided graph is required. In [75] two cases are described with one-sided control charts. Case one of those two suits the situation with material wear. Figure 3.7 illustrates this one-sided control chart.

![Figure 3.7: One-sided pre-control chart [75]](image)

3.4 Scalability

ToC was already identified as convenient for the complex upscale and flexible or dedicated machine arrangement criteria defined in chapter 2. Yet, literature is available devoted to scalability of manufacturing systems, which relates to proces future expansion. Both [63] and [42] provide insight in the concept and applicability of scalability theory. Based on these papers, this section presents a general description in subsection 3.4.1 and design for scalability approach in subsection 3.4.2 to research its applicability for remanufacturing systems.

3.4.1 Definition of scalability

Scalability expresses the volume flexibility and is defined as the ability to change the system capacity to produce different product volumes [42]. This definition is extended in [63] by stating that a system that is scalable is able to expand its operations using the same methods and without disturbing its performance. It distinguished two main scalability implementation principles:
3.4. Scalability

- **First principle:** Several identical elements of the architecture may be linked together to provide scaled performance or functionality

- **Second principle:** A single element of the architecture may be scaled by up/downsizing its characteristic parameter

The first principle can be interpreted in two ways. A system can be scaled by linking replications of machines into a more extensive network with increased capacity or by improving communication infrastructure. Integration of machinery can be achieved with improved data exchange. Section 3.5 further elaborates on system integration. Furthermore, the definition of scalability and its two principles is often related to the parameters adaptability, changeability and robustness. For an elaboration on their particular relation [63] can be consulted.

3.4.2 Design for scalability

Scalability models for manufacturing systems are mainly developed for Reconfigurable Manufacturing System (RMS). In [42] ideal system scalability is quantified. This quantification, without influencing factors such as queuing, latency, different process times is defined by Equation 3.9:

\[
System \ scalability = 100\% - Smallest \ incremental \ capacity \ in \ % \quad (3.9)
\]

The smallest increment implies the minimal percentage of the production line that needs to be added to adjust to the new demand. Figure 3.8 shows five configurations to exemplify the formula. For configuration (a) the increment is 100% as the complete line need to be duplicated to expand capacity, which means that the scalability of the system is 0%. For configuration (b) the increment is 50% resulting in a system scalability of 50%. Applying the formula for configuration (c), (d) and (e) results in 67%, 84% and 84% respectively.

Using Equation 3.9 and these configuration models combined with system rebalancing, a choice can be made how to scale up a RMS when the demand increases as shown in [43]. In addition, the paper stated the following design-for-scalability-principles:

- The architecture of manufacturing systems must be reconfigurable to enable the integration of additional production resources, when needed.
- The RMS capacity must be designed at the outset to be scalable in optimal increments.
- To be rapidly scalable, the RMS requires additional investment in its initial infrastructure.
- To be economically scalable, the RMS contains a mix of flexible and reconfigurable equipment.
- To minimise the number of additional machines needed to scale-up the system capacity, reconfiguration planning and system rebalancing must be performed simultaneously.
The second to fourth principle are less suitable for the repair environment. Due to the high return quantity and quality variance remanufacturing system capacities are not designed at outset. Furthermore, the initial infrastructure of repair process is most of the times pre-defined and based on existing machinery. As last, the flexibility and reconfigurability of the machines and processes is low. Manufacturing facilities often attempt to change from a dedicated setting to a flexible one, while remanufacturing facilities often attempt to change in the opposite direction. Therefore, it is declared that the scalability theory does not suit for sustainable initial repair process design. The fundamental definition and Equation 3.1 are applicable, but the ToC is considered more feasible for an upscale strategy.

3.5 Industry 4.0
The principles of Industry 4.0 are taken into account for implementation of innovation. Industry 4.0 follows up the mechanization, mass production and computer and automation revolutions. In [33] Industry 4.0 is described as the convergence of industrial production, information and communication technologies. A general understanding of the concept is provided in this section. Subsection 3.5.1 discusses the components of Industry 4.0. Subsequently, subsection 3.5.2 presents design principles for Industry 4.0. As last, subsection 3.5.3 points out the challenges and status of Industry 4.0.

3.5.1 Industry 4.0 components
The concept Industry 4.0 consists of three main components, each key enablers for its revolution [33]. These key enablers allow decentralized control and system components with capabilities that can interact with each other and humans.

Internet of Things and Internet of Services
The Internet of Things (IoT) allows physical system components to communicate and cooperate with each other. It aims to connect systems beyond the standard connected items like computers and phones. Using the IoT machines are able to interact and exchange process data allowing remote control, cooperation and process monitoring. The Internet of Services (IoS) has a similar approach but focuses on integrated offering of services via the internet. This integration of services allows a new way of dynamic variation of the distribution of individual value chain activities [61]. Integration with external stakeholders can be empowered by applying both concepts. In the context of this research this could assist reducing the return quality and quantity variance.

Cyber-physical systems
The Cyber Physical System (CPS) provides the fusion between the physical and virtual world. It integrates the computation and physical processes in one system. Embedded systems monitor and control the physical processes with feedback loops so that both affect each other. According to [66] most CPSs nowadays are heterogeneous entities that need to combine discrete and continuous dynamics. It stated that CPSs need to be adaptive to function in dynamic environments and able to operate with humans. The required combination of the above described characteristics creates the design challenge of dependable, secure and high performance CPSs. The same paper can be consulted for CPS design features to meet these characteristics.

Smart factory
A smart factory combines the previous two components. It is defined as a factory that context-aware assists people and machines in execution of their tasks. Background systems, the CPSs, with tasks based on data from the physical and virtual world make sure this is achieved. The data exchange in these factories is carried out with the IoT and IoS. The combination of CPS with IoT and IoS facilitates the change towards paperless processes and stakeholder integration.

3.5.2 Industry 4.0 design principles
To guide concept development and practical implementation of Industry 4.0 [33] identified four design principles. These four principles are interconnection, information transparency,
decentralized decisions and technical assistance.

**Interconnection**
Connectivity of objects and humans is essential for Industry 4.0. Wireless connections via the IoT allow paperless data exchange, which is key for integrated, automated and collaborating networks. Three types of connections have been defined: human-human, machine-human, machine-machine. As previously stated standardization is important to enable these connections. Consequence of the rising number of interconnections is increased need for cyber security.

**Information Transparency**
With the increasing interconnectivity of objects and humans, the information transparency also increases. To analyse the physical world its physical data should be integrated in higher level computational decision making systems. The decision data obtained in these systems should be made available for the physical systems to be carried out. The availability and transparency of information throughout the connected network levels is of major importance.

**Decentralized Decisions**
The decentralized decision principle arises with interconnection and information transparency. The combination of decentralized decisions with interconnections and data transparency enables integrated utilization of local and global data for better decision making and increasing productivity [50].

**Technical Assistance - Human Interaction**
Applying Industry 4.0 implies a shift towards autonomous, decentralized systems. Consequently, the role of the human operator shifts from machine operator towards strategic decision maker and problem solver. To assist humans in this complex role and enable them to work with the systems, technical assistance is required. This technical assistance can be interpreted as aggregated and visualized information that supports humans in decision making. Both [80] and [25] can be consulted for further elaboration on human interactions with the so-called Internet of People (IoP).

As the objective of this research includes Industry 4.0 preparation, the four principles are taken into account for control of the implementation of innovation criteria.

### 3.5.3 Industry 4.0 future

The advanced techniques of Industry 4.0 introduce challenges that stall its development. These challenges, described in [39], are discussed below. A first challenge is the requirement for a more systematic approach to innovation and development. A broad systematic approach with the elemental principles serves best to overcome this challenge in the future. The second challenge relates to the human aspect of factories. The integration of machines and humans requires new and interactive interfaces and training that ease the operation of the complex Industry 4.0 systems and tools. Moreover, acceptance of the concept in the industry is of essence for development. A clear and practical concept structure and extensive security measures could enhance the positive perception of Industry 4.0. Following and last challenge is more thorough data security. To assure privacy and data protection enhanced cyber security is necessary. This research could contribute in particular to a systematic implementation approach to enhance the Industry 4.0 perception and application.

### 3.6 Conclusion

This chapter continued with a theory analysis related to the identified criteria. The remainder of this section answers sub-question two with allocation of applicable theory to the criteria.

What theories can be used to control the identified criteria?

- Return quality and quantity variance
  
The SPC and pre-control theory suit for control of return quality variance if modified to front end applicability and the remanufacturing environment. Both enable definition
of process input bandwidth that is required for process front end application of the ToC. The principles of Lean and Six Sigma are kept in mind for establishment of the process basis and complement the quality control steps defined by Juran for quality quantification. As last, the ToC suits for control of quantity variance by determination of allowable quantities in process.

• Classification of process maturation
The SPC theory suits to classify products based on the required amount of samples for accurate application of the Shewhart individual measurements chart.

• Definition of process future expansion
The ToC suits for definition of future expansion by calculation of potential bottlenecks with defined capacity upscale scenarios. The process input bandwidth defined by the quality control theory provides directions for this calculation.

• Determination of machine capacity arrangement
The ToC also suits as guidance for systematic determination of machine capacity arrangement on the basis of the process front end bottleneck calculation.

• Implementation of innovation
The Industry 4.0 theory suits for implementation of innovation. In particular the design principles are considered useful for development of a systematic implementation approach.

Not directly related to the specific criteria, but more as overarching theory the BPR framework is considered as useful guidance for development of the model. As last, the scalability theory proved infeasible for the remanufacturing environment and consequently control of the criteria. With the theory allocated a base is provided for the development of the design method model in the next chapter.
Design Method Model

With the criteria identified and theory analysed a model that embodies the method for sustainable initial repair process design from a return quality perspective can be designed. The criteria function as fundament and the applicable theories as guidance to outline the details. In that way the model can be designed according to the recognized front end process management and control approach. The chapter is build up based on the criteria identified in chapter 2.

First, section 4.1 defines the fundament of the design method model. Subsequently, section 4.2 to section 4.6 elaborate on this fundament with the appropriate theories. The required data and assumptions for the theory application are indicated in these sections. With the model defined, section 4.7 discusses how its outcome can be integrated in the organizational supply chain. As last, section 4.8 concludes the chapter with an answer to sub-question three.

The following sub-question will be answered in this chapter:

3. What model can be proposed as design method to collectively control the identified criteria?

4.1 Model fundament

The fundament of the model emanates from the five identified criteria:

- Return quality and quantity variance
- Classification of process maturation
- Definition of process future expansion
- Determination of machine capacity arrangement
- Implementation of innovation

The model is designed by definition of layers that each address a criteria. As process input bandwidth was defined imperative, the first layer focuses on a process basis with a return quality controller that controls the quality variance. This controller is established using the SPC or pre-control theory. To determine which theory is applicable the layer integrates with the second layer that controls the classification of process maturation. Based on the maturation classification the SPC or pre-control chart is chosen as control method. With the process input bandwidth then defined by the return quality controller an upscale and machine capacity arrangement strategy based on the ToC form the third and fourth layer to control the corresponding criteria. Besides that, the upscale strategy layer controls the return quantity variance by ToC-based bottleneck calculation. The fifth layer defines a strategy for innovation implementation as follow-up on the third and fourth layer and to control the implementation of innovation criteria. As last, it is important to recognize that a repair
process is part of a larger system and that integration is part of its design. Therefore, to enhance implementation and functionality of the designed repair process the relation to the organizational supply chain need to be defined.

Based on the above description it is declared that the design method model primarily depends on the return quality control in the first layer. The return quality controller of layer one enables control of the subsequent criteria with a defined process input bandwidth. Therefore, the model is denoted as multi-layer return quality control model. Figure 4.1 illustrates the model with corresponding criteria as described above.

4.2 Process basis with return quality controller - layer 1
The first layer concerns the basis of the initial process design with a return quality controller. Chapter 3 defined SPC and pre-control as methods to control output quality with established limits. To use these methods as return quality controller modification of the procedures and quality quantification is necessary. First, it is determined how return quality of the process input is quantified. Output quality quantification has been addressed in literature several times, but return quality research is limited [57]. Research that elaborates on return quality quantification only described the relation with cost optimization. This research aims to use the return quality controller to reduce the return quality variance and hence improve operational performance. Therefore, quantification need to be established based on operational process parameters.

The relation between return quality variance and disparate lead times and amount of repair actions came forward in chapter 2. Therefore, it is chosen to quantify the return quality using those two operational parameters. Accordingly, either a single product feature or the amount of repair actions is used to quantify the return quality. This distinction depends on whether the repair process TAT primarily varies due to disparate machine lead times or amount of
required repair actions respectively. In the first case the amount of repair actions is constant and the lead times variable and in the second case vice versa. The following approach, based on Lean principles, six Six Sigma steps and Juran quality control steps, is used to realize this type of quantification:

1. Identify product and service provided.
2. Define required basis processes with a VSM using common prescribed guidelines.
3. Determine the primary TAT influencing factor of the operational process.
4. For single product feature quality quantification translate the main value adding process to a measurable feature. For amount of repair actions quality quantification use the total amount of required repair actions as measurement.
5. Establish the measurement feature for the return quality controller.

After establishment of quality quantification, it should be decided whether to use the SPC Shewhart individual control chart or the pre-control chart. Based on the process matura-
tion classification in layer two a decision is made between both charts. Pre-control is used for class I and class II processes and SPC for a class III, which are described in the next section. As stated in section 3.3 both methods need modified procedures to be applicable as return quality controller. These modified procedures are described below:

1. SPC

   • **Repair actions quantification**: The historical amount of repair actions data is used to establish the limits of the Shewhart individual measurement chart. The moving range chart is calculated following the procedures described in subsection 3.3.2. The individual measurement chart is altered to a positive one-sided interval with the data set average and upper warning and control limits. The calculation of the average and both limits follows the procedure as described in subsection 3.3.2.

   • **Single product feature quantification**: The calculation procedure of the limits is similar to that of the amount of repair actions quantification, but with a data set that contains historical data of the defined single product feature and an one-sided chart with lower limits.

2. Pre-control

   • **Repair actions quantification**: The one-sided upper limit pre-control chart described in subsection 3.3.3 is used to establish the coloured zones. To determine the tolerance a division is made between the class I and II classification. In the case of class I no guidelines are present to define the initial tolerance. It is proposed to set the initial yellow zone limit at 1.25 times the basis amount of repair actions prescribed by the OEM and the green zone limit at the mid value of both. Analysis of several KLM E&M ES cases, attached in appendix E, resulted in an average relative deviation of 23%. The factor 1.25 includes 25% extra repair actions and is therefore suggested. After five consecutive green zone runs or availability of at least a sample size of five (Class II), the conventional pre-control procedure replaces these initial limits.

   • **Single product feature quantification**: The procedure is the same as for the repair actions quantification, but with a lower limit one-sided chart. For a class I process the initial yellow zone limit is set at the minimal remaining product feature value prescribed by the OEM and the green zone limit at half the difference between the serviceable value and the yellow zone limit.

The limits should be interpreted differently. The warning or green zone limit mean revision of the standard contractual agreement to allow more leeway in the scheduling and planning of the returned product. Surpassing the control or yellow zone limit mean that the product should not be accepted or send to a bypass process. Figure 4.2 illustrates both one-sided control charts.
With the return quality controller instituted the basis of the process is set up. Next step is to further design the process with the conventional 4Ms method and define the process scheduling and planning strategy. These strategies could be combined with the SPC method to more accurately define required repair actions and lead time estimation. As this is not part of the scope of this research, further research is recommended to substantiate this statement. Likewise, further process basis design with 4Ms and scheduling and planning of the process are out of the scope of this research.

The proposed adaptations enable establishment of a process basis with a return quality controller. The controller defines a process input bandwidth to reduce the return quality variance. With periodic revision the control limits are more accurately defined over time as the data set increases. The detailed steps of layer one are summarized in Figure 4.3 with rectangles as actions and hexagons as decisions.

**4.3 Process maturation classification - layer 2**

The second layer of the model classifies process maturation. As determined in subsection 3.3.2 mature processes with significant historical data allow quality control with the SPC Shewhart individual control chart and processes with insignificant or no historical data with the pre-control chart. Therefore, three categories are defined in layer two of the model:
4.3. Process maturation classification - layer 2

- Mature process
- Immature process
- New process

The categorization is based on available historical data for the quality quantification determined in layer one. With no historical data the process belongs to the category new process. The division between mature and immature processes is made with a statistical method described by [52] using the Degree of Freedom (DoF) and Coefficient of Variance (CoV) of a data set. The relation between these two enables calculation of the amount of data required to calculate accurate limits for the SPC Shewhart individual control chart. The DoF is the number of independent values that is used in a statistical analysis, which is a measure for how useful data are. How larger the DoF, the less uncertainty present in the data. The CoV is a measure for data variance describing the amount of variability relative to the data mean. According to [52] Equation 4.1 and Equation 4.2 define the DoF and CoV with sample size n and constant 'a'.

\[ \text{DoF} = a(n-1) \quad (4.1) \]

\[ \text{CoV} = \frac{1}{\sqrt{2\text{DoF}}} \quad (4.2) \]

Rearranging both equations results in Equation 4.3:

\[ n = \frac{1}{2a \cdot \text{CoV}^2} + 1 \quad (4.3) \]

In [81] constant 'a' is defined as 0.62 to calculate the effective DoF. This 0.62 is specific for individual measurement control charts with no rational subgroups where the average moving range is used for calculation of limits. The Shewhart individual control chart is such an individual measurement chart that uses the average moving range. Yet, for deviant scenarios [81] can be consulted for a method to define constant 'a' using an extensive mathematical procedure.

The allowable CoV is necessary to determine the required sample size. According to [52] the CoV is typically chosen to be between 15% and 20% as it then approaches steady-state. This is illustrated by Figure 4.4 with constant 'a' being 0.62. Yet, with the inherent high variance of return quality of repair processes it is chosen to restrict the CoV to a maximum of 10% in this research. If the available sample size exceeds the determined n, the process is categorized as mature, else as immature.

Using the above equations layer two defines a threefold classification of process maturation. The detailed steps of layer two are summarized in Figure 4.5.

![CoV vs DoF](image-url)
4.4 Upscale strategy - layer 3

This layer comprises an upscale strategy that defines a stepwise approach to control the complex future expansion potential and return quantity variance by applying bottleneck calculation. The ToC proved applicable for this purpose. Instead of using the theory in the regular way to improve processes it is now applied at the design phase of the process. The conventional steps of the ToC remain mostly the same, but the required data differ and are based on assumptions, standardization and the bandwidth established by the return quality controller. Besides that, the exploit, subordinate and elevate step are combined into a singular future action decision. As result a strategy is outlined to sustain efficient operation with expanded future demands.

First, the required machines for the process concerned are defined by the VSM and 4Ms. For each of these machines the average weekly available processing capacity, \( T_{\text{avg}} \), is determined. Processing minutes per week is used as capacity measuring unit as on-floor observations show that planning uses at maximum a week as forecast and machine processing data is logged in minutes. Figure 4.6 illustrates the approach to determine the \( T_{\text{avg}} \). The operational restrictions in this approach comprise workdays per week, shifts per day, effective work hours per shift and operator availability. The historical machine occupation data of a process is excluded from the data set if the process already existed.
For this stepwise approach the following data and assumptions are essential:

- **Required Data**
  - Theoretical machine availability
  - Operational restriction data
  - Actual machine occupation

- **Assumptions**
  - No rework is carried out.
  - No unforeseen machine downtime is present.
  - Machine occupation based on average of weekly occupation of preceding year is considered representative.
  - Operator availability is based on average per week.

With the $T_{av}$ determined the ToC calculation is initiated. First, the required processing time per week per product quantity in process, $Q$, need to be calculated for each machine $i$, denoted as, $T_{req,i,Q}$. This is done with $Q$, the average lead time per machine per week per quantity, $LT_i$, and a design margin $S$ combined into Equation 4.4:

$$T_{req,i,Q} = Q \times LT_i \times S \quad (4.4)$$

$LT_i$ is the machine $i$ process time ($PT_i$) times the amount of repairs per $Q$ per week on that machine ($AoR_j$) as presented by Equation 4.5:

$$LT_i = PT_i \times AoR_i \quad (4.5)$$

The input bandwidth is incorporated by definition of this equation. With the relation between return quality and operational parameters not previously defined in literature, it is proposed to base the $PT_i$ or $AoR_j$ in this equation on the quality quantification and bandwidth of the return quality controller. This is done by using the mid value of the desired or average value and the control limit. The mid value is considered appropriate as it corresponds to the average of the most demanding part of process inputs. Correspondingly, Equation 4.5 is based on the bandwidth of the return quality controller as follows:

- **Product feature quality quantification:** The $PT_i$ is variable and the $AoR_j$ is constant. For $PT_i$ the process time that corresponds to the mid value is used. For $AoR_j$ the constant amount of repairs per week is used.

- **Amount of repair action quality quantification:** The $PT_i$ is constant and the $AoR_j$ is variable. For $AoR_j$ the amount of repairs that corresponds to the mid value divided by the contractual TAT weeks is used. So, if the mid value is 50 repair actions with on average 12 on machine $i$ and a contractual TAT of 4 weeks, $AoR_j$ is 3.

The design margin $S$ inversely relates to the maximum machine capacity utilization and business strategy. In general it is stated that too high machine utilization induces significant increase in cycle times and work in progress. Figure 4.7 illustrates this relation with $V = 1$ as a process with high variability and $V = 0.25$ as a process with low variability. For a detailed description of the graph [34] can be consulted. As remanufacturing processes deal with significant input variance the $V = 1$ line is considered applicable. Based on this line 80% utilization is considered as maximum utilization. To incorporate different business strategies in the design margin $S$, a distinction is made between maximizing the OTP or product volume. A company with a high OTP strategy should use a lower machine utilization than one with a strategy to maximize product quantity. Based on the $V = 1$ line of Figure 4.7 a threefold division for $S$ is suggested as shown in Table 4.1. This threefold definition of $S$ is a guideline that can be adapted case specific.
With Equation 4.4 and the suggested values for $S$ the bottleneck is calculated by incrementation of $Q$ till the following bottleneck condition is attained for the first machine.

$$\text{Machine}_i = \begin{cases} \text{Bottleneck}, & \text{if } T_{req,i} \geq T_{ava,i} \\ \text{Not a Bottleneck}, & \text{Otherwise} \end{cases}$$

To use Equation 4.4 and the bottleneck condition the following data and assumptions are required:

- **Required Data**
  - Design margin factor $S$
  - Lead time assessment based on return quality controller bandwidth
  - Available machine processing time

- **Assumptions**
  - A repair action is carried out at once and not divided over multiple weeks.
  - Repair actions can be planned flexible and independent within a workweek.
  - The amount of repair actions on a machine is evenly distributed over the TAT weeks.
  - The mid value represents a suitable value for strategy calculation.

Next step is determination of the action to upscale the process capacity of the bottleneck. The ToC mentions either exploitation or elevation. In the perspective of this proposed calculation, exploitation and elevation correspond to capacity expansion by maximizing utilization and productivity and resource investments respectively. The calculation pairs these actions into a capacity upscale action. First, the upscale potential of bottleneck exploitation is determined. If that potential is insufficient with regards to market potential, elevation by changing the machine capacity arrangement or implementing potential innovation is required. **For this elevation integration the fourth layer is required as that layer defines machine capacity arrangement. Integration with layer five can be done parallel to show the potential of innovations defined for the bottleneck machines.**
After the upscale decision the calculation process iterates with incrementation of \( Q \) till the maximum market potential. For each subsequent iteration the increased capacity is taken into account for calculation of available processing times per machine. This procedure leads to upscale strategies with required machine capacity as function of allowable quantity in process per week as illustrated by Figure 4.8a. Incorporating market demand enables generation of a similar graph as function of time as illustrated by Figure 4.8b. Ultimately, the machine strategies are combined into a process overarching upscale strategy with allowable quantity in process per week as function of time.

Using the described approach, process and machine specific upscale strategies are incorporated in the initial process design to sustain operational performance with process expansion. Besides that, the approach delineates when and if insource capabilities can be extended. Periodic revision of the calculation is essential as the market potential and process environment are subject to change. The detailed steps of layer three are summarized in Figure 4.9.

Figure 4.8: Upscale strategy outputs

Figure 4.9: Layer 3 detailed steps
4.5 Machine capacity arrangement strategy - layer 4

This layer forms a decision strategy that is integrated with the upscale strategy to determine required machine capacity elevation rearrangement. If $T_{ava}$ is not sufficient to meet the market demand after bottleneck exploitation machine capacity rearrangement becomes required. This machine capacity rearrangement comprises the decision to invest in a dedicated or flexible machine. Dedicated means that the capacity of the machine is assigned to a singular repair line and flexible that the capacity is assigned to various repair lines. As mentioned in subsection 3.4.2 manufacturing facilities generally attempt to change from dedicated to shared resources and remanufacturing facilities vice versa. This has as effect that repair processes in general are first implemented in the existing flexible machine arrangement before changing to a dedicated machine arrangement. **This layer provides a strategy to determine whether investment and change from flexible to dedicated machinery is a suitable elevation action in the upscale strategy of layer 3.** The advice can either be to continue with the existing arrangement, invest in an additional machine but keep it flexible or invest in an additional machine that becomes dedicated. The strategy only includes arrangement decisions related to the upscale strategy and not decisions concerning new machinery for the 4Ms in layer one.

In [65] it is stated that the decision to use dedicated or flexible capacities depends on the variety of products, their demand volumes and economic factors. Based on these three factors, it presents an integer optimization model for making capacity acquisition decisions specific for manufacturing systems. This research uses its findings and on-floor observations to propose a generic and accessible machine capacity arrangement strategy for a remanufacturing environment.

The first step determines whether machine investment is required after exploitation. The ToC and previous E&M graduation research can be consulted for exploitation procedures. The exploited capacity, $T_{ava,EX}$, is compared with the $T_{req,MAXdemand}$. If the $T_{ava,EX}$ exceeds the $T_{req,MAXdemand}$ bottleneck exploitation is sufficient and no further action is required, if not elevation is required. Subsequently, it is determined whether resources as capital, space and operators are available for machine investments. If not, investment is not a possibility. If resources are available, the sequent step is to determine the feasibility of investment in an additional machine, $machine_{2}$, based on thresholds.

The feasibility of machine investment is assessed by financial advice and required capacity at the end of the company specific payback period, $T_{req,MAXpBP}$. The conditions below show the proposed twofold threshold for machine investment feasibility:

$$Machine_{2} \text{Investment} = \begin{cases} Yes, & \text{if Positive Financial Advice } & \text{& } T_{req,MAXpBP} \geq T_{ava,EX} \\ No, & \text{Otherwise} \end{cases}$$

If the investment is considered feasible, the last step is to determine whether $machine_{2}$ should be implemented as dedicated or flexible resource. The chosen utilization percentage from Table 4.1 in layer 3 is used for comparison with the potential utilization percentage of the new machine, $Utilization_{machine2}$. $Utilization_{machine2}$ is determined with the available capacity of the new machine, $T_{ava,machine2}$, $T_{req,MAXpBP}$ and Equation 4.6:

$$Utilization_{machine2} = \frac{T_{ava,machine2}}{T_{req,MAXpBP}} \times 100\% \quad (4.6)$$

With $Utilization_{machine2}$ defined, a comparison is made to the chosen utilization of Table 4.1. If the capacity of $machine_{2}$ can be used to its full extend, it is implemented as dedicated resource and if not as shared resource:

$$Machine_{2} = \begin{cases} Dedicated, & \text{if } Utilization_{machine2} \geq Utilization_{chosen} \\ Shared, & \text{Otherwise} \end{cases}$$
4.6 Process innovation strategy - layer 5

To use Equation 4.5 and the above conditions the following data and assumptions are required:

- **Required Data**
  - Machine capacity data
  - Financial advice for machine investments
  - Demand forecast and payback period

- **Assumptions**
  - Operations from old machinery can completely be transferred to new machinery.

With these data requirements and assumptions the machine capacity arrangement strategy is finalized. Again periodic revision is necessary to adapt to financial and market potential fluctuations. The detailed steps of layer four are summarized in Figure 4.10.

![Figure 4.10: Layer 4 detailed steps](image)

**4.6 Process innovation strategy - layer 5**

Industry 4.0 innovations are extensively divergent and research in practical implementation is limited. Consequently, an universal decision strategy to control the innovation need for each case is not feasible. Therefore, the fifth layer limits to a systematic strategy to determine possibilities and enhance innovation implementation from a digitization perspective. In the current state of industry this strategy can be considered as parallel demonstration, but with the forthcoming change towards Industry 4.0 it could become a valuable asset for development.

The categorical framework defined in [64], shown in Figure 4.11, provides a suitable basis for systematic implementation of Industry 4.0. The framework enables categorical allocation of innovations. This provides the fundament for a manageable Industry 4.0 implementation strategy that enhances understanding and development of the concept.
The systematic strategy aims to identify a development plan from category I to category IX for each machine $i$ of the process concerned. First step is to classify machine $i$ as new or existing. For new machines advanced technological hard- and software needs to be explored to acquire state-of-the-art capabilities. In the case of an existing machine, innovation should be sought in attainable soft- and hardware adaptations. If the innovation stagnates due to obsolete capabilities, it should be indicated in which category the current machine is not sufficient anymore. So, with the classification of new or existing machine an iterative process defines a development plan to advance from category I to IX.

The iterative process initiates in category I. For each iteration for Machine $i$ (I), except the first, the requirements to progress to a subsequent category are defined with a description of required progress actions. It should be determined what changes are necessary for these progress actions. This is done by defining the four Industry 4.0 design principles required per category. Comparing the principles of two consecutive categories delineates the changes required to achieve the progress actions. It is important to keep the paperless perspective, as mentioned in section 3.5, in mind. Especially for interconnectivity the focus should be on changing towards paperless processes with a standardized data infrastructure. As last, the human interaction and the potential Machine $i$ capacity expansion are defined. The human interaction description can be based on findings described in [80] and [25]. Table 4.2 presents a scheme that illustrates the described iterations.

Table 4.2  Categorical systematic innovation scheme

<table>
<thead>
<tr>
<th>I</th>
<th>PC</th>
<th>CC</th>
<th>Required Actions</th>
<th>Design Principles</th>
<th>Human Interaction</th>
<th>Capacity Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interconnection</td>
<td>Transparency</td>
<td>Decentralized</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Decisions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Completing the iterations delineates a fundamental plan for Industry 4.0 implementation towards an automated, integrated and digitized factory. Important during the iterations is standardization to end up with consistent strategies that can be merged into one smart factory. In subsection 4.7.2 a data infrastructure is proposed that suits this standardization. The detailed steps of layer four are summarized in Figure 4.12.
4.7 Supply chain integration

To strengthen implementation and functionality of the sustainable initial repair process design supply chain integration is essential. Subsection 4.7.1 describes how this integration can be established using process visualization tools and subsection 4.7.2 elaborates on an additional advanced data infrastructure proposal to anticipate the Industry 4.0 revolution.

4.7.1 General integration

The swimlane diagram and VSM are suitable process visualization tools. The swimlane diagram organizes activities into separate categories to illustrate different function capabilities [10]. In [36] it is indicated that the swimlane actors depend on the process and level at which the VSM is defined. Data and product flows and process time dimensions connect the actors. Therefore, a combination of a swimlane diagram on organizational level with a detailed process VSM suits to situate the designed process in the integral supply chain. This combination delineates the responsibilities and relations of the process with respect to the other actors in the supply chain. Figure 4.13 illustrates the swimlane-VSM concept. Example actors are described with blocks, the sequential data flow with thin arrows and the parallel data flow with arched thin arrows.

Figure 4.12: Layer 5 detailed steps

Figure 4.13: Supply chain connection
4.7.2 Advanced data infrastructure

For Industry 4.0, visual illustration with operational excellence tools only is insufficient. Industry 4.0 requires an advanced data infrastructure with standardization that allows automation to achieve organizational integrality. This section elaborates on standardized process visualization in combination with a data infrastructure proposal that enables process, but also organizational integration.

**Standardized process visualization**

The International Definition (IDEF) concept suits for standardization of process visualization. IDEF refers to a series of modelling languages that can be used for process engineering. The International Definition for Functional Modelling (IDEF0) language is designed for standardized functional modelling of processes. It presents processes in a scheme with in- and output, control information and process mechanisms. Using this modelling language for actor and flow depiction in the swimlane and VSM enables standardized data formats. To define the data formats the Integration Definition for Information Modelling (IDEF1X) language is suggested. IDEF1X generates a graphical information model with process data that matches the flows defined by IDEF0 method. Figure 4.14 illustrates the IDEF0 and IDEF1X schemes.

![Figure 4.14: International Definition Modelling languages](image)

The IDEF combination can be used to integrate the designed process with the swimlane-VSM concept in the supply chain and automate the provision of data. Using this combination the required data exchange can be delineated in advance. During operation the data set can be changed based on process deviations. These data set changes require frequent updates of the IDEF0 control information. This aligns with the aim of Industry 4.0 to integrate and digitize control with self-learning, adaptive and autonomous machinery. Yet, to functionalize this visualized data infrastructure a physical data exchange system is required too.

**Data exchange system**

To determine the required data exchange mechanism for Industry 4.0 a classification is established using the computation-communication scheme provided by [58] and the data push and pull principle, which are shown in Figure 4.15.

![Figure 4.15: Computation-communication schemes](image)
A first distinction is made between static or dynamic control. For static control single iteration data push is sufficient and no data pull is required as actual performance data are not accounted for. Contrary, for dynamic control multiple iterations are required to adapt to actual performance deviations. This means performance data need to be frequently pushed and pulled for control updates. The second distinction comprises process integration and is based on local and (semi-)global objective definition. The local objective accounts for individual machine process optimization, where serial and synchronous communication is suitable. The semi-global objective is defined as the objective of a process chain, which requires serial and asynchronous communication. The global objective accounts for process overarching goals, which requires parallel and asynchronous communication.

The Industry 4.0 concept aims for an integrated organization with autonomous and dynamic control where local and semi-global objective are combined to achieve the global objective. The following data exchange mechanisms are required to attain these demands:

- Data push and data pull
- Asynchronous data exchange
- Parallel data exchange
- Multiple iterations

A communication software framework that suits these demands is the Robot Operating System (ROS) concept. The ROS consists of following components:

- **Database**: In the database required process data are stored. In practice the database functions as a message board.
- **Agent**: An agent is an autonomous calculation program of a process. This ranges from machine control to planning unit programs.
- **Master**: The master is a program that coordinates a subset of agents and their data exchange in a larger system.

The database is the fundament of the data exchange system and consists of data organized in topics. Data are published to and retrieved from these topics after registration of agents via their assigned masters. The masters coordinate the data flows of agent chains and the agents regulate the control of the singular processes. As publisher an agent provides data that is stored via its master in the registered topic. As subscriber the agent retrieves data via the master from the relevant topic. Every agent is uniquely identified as network node, which enables to master to direct the data flows. Important feature of this setting is the ability to allow parallel data exchange at various frequencies without complex procedures. This enhances data exchange flexibility and modularity, both essential for process scaling. Moreover, the master can be used to combine multilevel objectives to enhance integration of process strategic and on-floor decisions. Figure 4.16 illustrates the general arrangement as described above.

To define the elements of this ROS data exchange system, the combination with the IDEF based swimlane-VSM concept proves effective. The swimlane-VSM combination delineates which data topics, agents and masters are required and how these are related. The IDEF modelling language provides the information for determination of the required topics and their data formats, subscription or publishing registrations and agent identifiers. This standardized communication language in combination with the ROS data exchange system enables application of Industry 4.0 and integration of external process stakeholder. Integration of external process stakeholders provides the opportunity to gather return product data from the customer before its repair process is initiated.

The application of the ROS communication infrastructure in combination with the VSM and swimlane thus enables advanced integrality of the organization. It facilitates the change towards an Industry 4.0 proof data network. The scalable characteristic of this data exchange system allows segmented implementation, but eventually complete revision of the organizational data infrastructure is required.
4.8 Conclusion

Using the identified criteria of chapter 2 and theory of chapter 3 this chapter defined a model that represents the method for sustainable initial design of a repair process. The remainder of this section answers sub-question three.

*What model can be proposed as design method to collectively control the identified criteria?*

The five criteria resulted in the multi-layer return quality control model shown in Figure 4.1. The first layer addresses the repair process basis with a return quality controller. Using the SPC or pre-control theory return quality limits are established that define an allowable process input bandwidth. To be able to use the appropriate theory layer two classifies the process maturation.

Layer three delineates an upscale strategy to control process future expansion. Using the ToC, bottlenecks are calculated in advance. The defined input bandwidth is used to make these bottleneck calculations reasonable. Layer four and five focus on machine capacity arrangement and innovation respectively. Layer four suggests a decision strategy for machine investment in either a dedicated or flexible arrangement. Layer five provides a parallel strategy for systematic implementation of innovation to prepare for Industry 4.0.

Last part is integration of the model output in the organizational supply chain. For existing network integration a combination of the visual swimlane and VSM operational excellence tools is proposed. For Industry 4.0 integration an advanced data infrastructure is added to meet the Industry 4.0 requirements. This data infrastructure combines the swimlane-VSM concept with the standardized IDEF language and ROS-based data exchange system.

The proposed multi-layer return quality control model enables sustainable initial repair process design with theory application shifted to the input and design phase of the repair process. The next chapter describes the translation of the theory into a repair process design generator to verify and validate the model.
To verify and validate the multi-layer return quality control model, the theoretical model is translated into a repair process design generator that functionalizes its procedures. Using this generator the functioning and outcome of the proposed model is demonstrated. Based on the IDEF language of subsection 4.7.2 this chapter elaborates on the translation into a MATLAB®-based generator with interface.

First, section 5.1 describes the generic outlines of theory to generator translation. Subsequently, section 5.2 elaborates on the generator mechanisms and in- and outputs using the IDEF language. Thereafter, section 5.3 describes the possibilities and limitations of the generator. As last, section 5.4 concludes the chapter with an answer to sub-question four.

The following sub-question will be answered in this chapter:

4. How can the model be translated into a repair process design generator to verify and validate the model?

5.1 Generator components

The generator comprises four of the five layers of the multi-layer return quality control model and an additional scenario testing component. The innovation layer and advanced data infrastructure are intended as contribution to Industry 4.0 concept understanding and are not yet researched thoroughly enough. Therefore, those parts of the theory are not incorporated in the generator.

The layers are translated into primary and facilitating generator components based on the integrations described in chapter 4. The process basis with return quality controller layer is designated as first primary component with the classification of maturation layer as facilitating component. This primary component only embodies the return quality controller as the additional procedures of layer one are considered less relevant for the research objective. The upscale strategy layer represents the second primary component with the machine capacity arrangement strategy layer as facilitating component. The primary components are construed as calculation procedures, while the facilitating components remain calculation input parameters or elementary calculations.

The relation between the primary components is the bandwidth based $LT_i$ for machine$_i$. As described in section 4.2 the input bandwidth can either be based on the amount of repair actions or product feature quality quantification. With the amount of repair actions denoted specific for the defined research field and data sets available that provide insight, the generator is based on this component relation. Consequently, the product feature quantification remains theory for further research in an appropriate research field.
The scenario testing component comprises a secondary data set with similar conditions as the return quality controller input data set. Using this data set, the application of the return quality controller limits and upscale strategy sufficiency are tested. The limit application is tested by division of the secondary data set in an acceptable, warning and bypass flow based on the defined limits. The upscale strategy sufficiency is tested by comparison of the processing time demands of randomized data samples from the secondary data set to the available processing time of the calculated upscale strategy.

Figure 5.1 visualizes the generator components and relations and Figure 5.2 the two relations between the return quality controller and upscale calculation.

5.2 Component mechanisms and in- and output
This section elaborates on the generator components on the basis of the IDEF0 flows shown in Figure 5.3. For each component the calculation input, consisting of the input and control data, the mechanism and output are discussed. The generator interface can be consulted in appendix G for insight in the translation of the model into the generator on the basis of IDEF0.
5.2. Component mechanisms and in- and output

5.2.1 Return quality controller component

**Input**
The input comprises actual KLM E&M ES repair process data or a generated data set and a process classification from the second maturation classification component. The data set contains the number of repair actions for a certain product. Figure 5.4 shows two loaded data sets and appendix E can be consulted for a more extensive selection. Due to notable inconsistency in KLM SAP data the option to generate data is built in as well. Moreover, with generated data it is possible to cover an extended range of model behaviour and analyse how it responds to parameter adaptations. Data generation is established with definition of the upper boundary, lower boundary and sample variation of the data set. The generated data set distribution is able to approach an uniform distribution with high variance as well as a truncated normal distribution with reduced variance around the average of the defined upper and lower boundary. Figure 5.5a shows a generated data set that approaches an uniform distribution and Figure 5.5b a truncated normal distribution.

Besides the input data set, a limit tightness factor for SPC and tolerance tightness and division factor for pre-control are incorporated as input. This enables adaptation of the conventional theory to tighten the calculated limits. In the case of a class I process the proposed factor 1.25 is used as limit calculation factor.

---

**Figure 5.4: Amount of repair actions data sets extracted from research field**

(a) Low pressure turbine case repair  
(b) Heat shield repair
Mechanism
Based on the process classification either the SPC and pre-control theory is selected for the return quality controller. Following the procedures of subsection 3.3.2 or subsection 3.3.3 the limits and corresponding bandwidth are calculated. The tightness of the limits can be influenced using the limit tightness factor as described in the previous section.

Output
The output of this component for the classification of process maturation is the sample size of the input data set. For the upscale and scenario testing component the output is the process input bandwidth with quality limits. The input process bandwidth with quality limits are visualized in charts attached in appendix H.

The corresponding generator interface in relation to the IDEF0 component of Figure 5.3 is attached in appendix G.

5.2.2 Process maturation component

Input
The input is the sample size of the data set and the CoV. This CoV is proposed as 10% in the developed theory, but is variable as input of the generator.

Mechanism
The applied mechanism is described in section 4.3 and uses the DoF and CoV to calculate a significant sample size n for SPC method application. Constant value ‘a’ is programmed as 0.62 based on [81].

Output
The output is the process classification to which the generator is dynamically adapted. The influence of sample size and CoV is directly reflected by the determined classification. The classification is shown by use of either the Shewhart individual control chart or the pre-control chart.

The corresponding generator interface in relation to the IDEF0 component of Figure 5.3 is attached in appendix G.

5.2.3 Upscale strategy component

Input
The calculation input consists of the bandwidth of the return quality controller and component control parameters. These parameters are divided in theoretical input based on model assumptions, practical input based on on-floor operations and machine capacity expansions scenarios. The scenario input is used to enable different upscale scenarios. Table 5.1 delineates the input parameters.
Table 5.1 Input upscale strategy component

<table>
<thead>
<tr>
<th>Input Classification</th>
<th>Parameter description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical input</td>
<td>Total amount of repair actions calculation value taken from the defined bandwidth</td>
</tr>
<tr>
<td></td>
<td>Repair actions per machine division based on historical data set</td>
</tr>
<tr>
<td></td>
<td>Allowable machine utilization factor S</td>
</tr>
<tr>
<td>Practical input</td>
<td>Machine process times</td>
</tr>
<tr>
<td></td>
<td>Working days per week</td>
</tr>
<tr>
<td></td>
<td>Working shifts per day</td>
</tr>
<tr>
<td></td>
<td>Work hours per shift</td>
</tr>
<tr>
<td></td>
<td>Scheduled maintenance per week</td>
</tr>
<tr>
<td></td>
<td>Machine occupation percentage</td>
</tr>
<tr>
<td></td>
<td>Available work time of a Fulltime-Equivalent Employee (FTE) per week</td>
</tr>
<tr>
<td>Scenario input</td>
<td>Machine upscale percentages</td>
</tr>
<tr>
<td></td>
<td>Market demand</td>
</tr>
</tbody>
</table>

**Mechanism**

Using the equations of section 4.4 as mechanism, $T_{req}$ is calculated based on the theoretical input parameters and $T_{ava}$ based on the practical parameters with 100% operator coverage assumed. Based on the input parameters the upscale calculation increments the quantity in process $Q$ till the bottleneck condition of $T_{req,i} \geq T_{ava,i}$ is reached. The calculation continues with an upscale percentage for the bottleneck machine. This upscale percentage is obtained via the machine capacity arrangement component. The entered percentage is multiplied by the practical process time and the result added to the $T_{ava,i}$ of the bottleneck machine for the next incrementation of $Q$. After definition of the upscale strategy the calculated quantities are linked to market demand scenarios to calculate a time-based strategy.

**Output**

The output for the machine capacity arrangement component is a defined bottleneck machine that requires a capacity upscale. The output for the scenario testing component is the determined upscale strategy. This upscale strategy is embodied by the following graphs:

- **Q vs Upscale actions**: Shows allowable quantity in process per week, $Q$, as function of upscale actions including net required FTEs.
- **Q vs T**: Shows allowable quantity in process per week, $Q$, as function of time including machine upscale percentages.
- **$T_{ava}$ vs T**: Shows $T_{ava}$ as function of time including upscale percentage for each machine.
- **$T_{ava}$ vs $Q$ per week**: Shows $T_{ava}$ and $T_{req}$ as function of the allowable quantity in process per week, $Q$, including net required FTEs.

These output graphs are attached in appendix H.

The corresponding generator interface in relation to the IDEF0 component of Figure 5.3 is attached in appendix G.

**5.2.4 Machine capacity arrangement component**

**Input**

The machine capacity arrangement strategy is limited to an upscale percentage input. This input can be realized passive or active. Passive input refers to predefined sequent upscale percentages that are used to perform $T_{ava}$ upscaling. Active input refers to defining the upscale percentage during the calculation. This dynamic method relates more to the strategy as defined in section 4.5. For active input the following information is shown when a bottleneck is calculated:

- The bottleneck machine
• The bottleneck quantity in process with respect to the maximum market demand
• The required upscale percentage to achieve maximum market demand

Using the active input the machine capacity arrangement strategy can be calculated more accurately while passive input suits for parameter influence examination.

**Mechanism**
The only present mechanism in this component is the active input procedure, which enables dynamic upscale strategy calculation.

**Output**
The output of this component is included in the graphs of the upscale strategy component. The percentages used to upscale are included in these graphs. Thereby, the influence of model parameters on the required amount and percentage of upscales is directly visible.

The corresponding generator interface in relation to the IDEF0 component of Figure 5.3 is attached in appendix G.

### 5.2.5 Scenario testing component

**Input**
The primary input of the scenario testing component comprises a secondary data set with similar conditions as the return quality controller input data set. In addition, a waiting time percentage is requested to incorporate stochastic or build-in process manoeuvre time in processing time calculations. As last, a selection need to be made which return quality controller limit is used for data sampling of the generated or loaded data set.

**Mechanism**
The scenario testing consists of two mechanisms, a flow division and an upscale strategy comparison. For the flow division the scenario data set is divided by the following conditions:

• Acceptable flow - Below warning limit
• Warning flow - Above warning limit & below control limit
• Bypass flow - Above control limit

The upscale strategy is tested by comparing the calculated available processing time of the upscale strategy, $T_{req,i}$, with the required processing time of a test scenario, $T_{req,sc}$. Equation 5.1 to Equation 5.3 outline the calculation procedure for $T_{req,sc}$ with $i$ as machine denotation and $j$ as sample taken for $Q$ in process per week.

\[
PT_i = PT_i + (WT\% \times PT_i)
\]  
\[
LT_{t,j} = PT_i \times \frac{Actions_{sample,i}}{Actions_{strategy}} \times \frac{Actions_{strategy}}{Actions_{strategy,i}}
\]  
\[
T_{req,sc} = \sum_{Q=1}^{Q} LT_{t,Q}
\]

First, the waiting time (WT) percentage is included in the machine, $PT_i$. Subsequently, this process time is multiplied by the corresponding machine, $PT_i$, repair actions. The repair actions per machine, $i$, for the scenario data set are calculated by multiplying by the ratio of the total amount of repair actions of the upscale strategy to the scenario data set. As last, the $T_{req,sc}$ is calculated as function of $Q$ by adding the $LT_i$ of each sample till the maximum market demand for $Q$ is reached.

**Output**
As flow division output the absolute amount of samples and percentages are calculated. This depiction shows the direct influence of return quality controller limit on the three product
flows in the designed process. The output of the upscale strategy testing is a graph with the $T_{ava}$ of the upscale strategy and the random sampled $T_{reqsc}$ for each machine. The sufficiency of the upscale strategy is reflected by comparison of both lines. The output graphs are attached in appendix H.

The corresponding generator interface in relation to the IDEF0 component of Figure 5.3 is attached in appendix G.

5.3 Generator possibilities and limitations

This section discusses the possibilities and limitations of the repair process design generator with respect to the developed multi-layer return quality control model. Subsection 5.3.1 describes the possibilities and subsection 5.3.2 the limitations.

5.3.1 Possibilities

A division is made in theoretical and practical model possibilities. The theoretical possibilities relate to proposed relations in the model and the practical possibilities to operational conditions. The theoretical possibilities are summed in Table 5.2 and the practical in Table 5.3.

<table>
<thead>
<tr>
<th>Theoretical Possibility</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical data set variance</td>
<td>Shows influence of the historical data set distribution on the controller limits and upscale strategy.</td>
</tr>
<tr>
<td>Historical data set boundaries</td>
<td>Shows the influence of the range of the amount of repair actions on the controller limits and upscale strategy.</td>
</tr>
<tr>
<td>Limit calculation factor variation</td>
<td>Shows influence of theoretical limit calculation method adaptation on limits and upscale strategy.</td>
</tr>
<tr>
<td>Controller method variation</td>
<td>Shows influence of using the SPC or pre-control method on limits and upscale strategy.</td>
</tr>
<tr>
<td>Total repair actions variation</td>
<td>Shows influence of the bandwidth calculation value on upscale strategy.</td>
</tr>
<tr>
<td>Scenario data set</td>
<td>Shows flow division and sufficiency of upscale strategy for similar process conditions.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Practical Possibility</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine process time variation</td>
<td>Shows influence of the machine process times on the upscale strategy and net required FTEs.</td>
</tr>
<tr>
<td>Operational restrictions variation</td>
<td>Shows influence of the working days per week, shifts per day, hours work per shift and scheduled maintenance on the available machine capacity, upscale strategy and net required FTEs.</td>
</tr>
<tr>
<td>Machine occupation variation</td>
<td>Shows influence of the machine occupation on the upscale strategy.</td>
</tr>
<tr>
<td>Design margin S variation</td>
<td>Shows influence of capacity design strategies on the upscale strategy.</td>
</tr>
<tr>
<td>Market demand variation</td>
<td>Shows influence of different market demand prospects on the upscale strategy as function of time.</td>
</tr>
<tr>
<td>Waiting time variation</td>
<td>Shows influence of stochastic or build-in manoeuvre space on required process time and consequently upscale strategy sufficiency.</td>
</tr>
</tbody>
</table>

5.3.2 Limitations

The limitations described in this section refer to the deviations of the generator from the theoretical model. The limitations are discussed per layer of the model.
Process basis - layer 1
Layer one comprises design of a process with the return quality controller, 4Ms and scheduling and planning included. The generator only includes the return quality controller. As 4Ms and scheduling and planning are out of the scope of this research the exclusion of the 4Ms and scheduling and planning mechanisms does not create relevant discrepancy. Furthermore, the generator is limited to the amount of repair actions quality quantification. The generator does not account for the effect of product feature quality quantification. As last, the generated data sets have an equal amount of samples on each side of the average and with reduction of variance the data set upper and lower boundary also reduce.

Process maturation classification - layer 2
The generator does not differ from the procedures described in layer 2. Only constant ‘a’ is programmed as 0.62 and cannot be adapted. This 0.62 aligns with theory proposal, but in the theory consultation of [81] is added for case specific calculation of the factor if the conventional conditions are not met.

Upscale strategy - layer 3
The upscale strategy calculation of the generator follows the ToC procedure as described in section 4.4. Yet, the repair actions division is manually set contrary to the proposed historical average divisions in the model theory. Furthermore, the strategy can only be calculated for a maximum of six machines and four predefined market demand behaviours. As last, 100% operator availability is assumed in the programmed generator. This differs from the calculation of available practical process time in the model. However, operator availability inclusion can be approached by reducing the effective work hours per shift.

Machine capacity arrangement strategy - layer 4
The capacity arrangement strategy is limited to upscale percentage input. Discrepancy exists in the fact that these percentages do not link to exploitation or machine investment based on the threshold set in the model. Moreover, the flexible or dedicated capacity arrangement decision is absent in the generator. However, it is possible to approach exploitation, elevation and dedicated or flexible machine arrangement with upscale percentage variation. The active model input procedure approaches the developed theory with insight in allowable quantity in process per week and percentage process time left to achieve maximum market demand, but does not provide upscale directions based on that information.

Process innovation strategy - layer 5
The implementation of innovation layer is excluded from the generator. Capacity expansion due to innovation can be incorporated by upscale percentage input, but this is done without guidance of the established theory.

5.4 Conclusion
Based on the developed model this chapter elaborated on a repair process design generator to functionalize and evaluate the proposed theory. The remainder of this section answers sub-question four.

How can the model be translated into a repair process design generator to verify and validate the model?
The proposed generator comprises the first four layers of the multi-layer return quality control model and a scenario testing component. The innovation strategy of layer five and supply chain integration procedures remain theory. The four remaining layers are divided in two primary and two facilitating components. The return quality controller of layer one and the upscale strategy of layer three form the primary components and the process maturation classification and machine capacity arrangement the facilitating. Furthermore, it is chosen to only incorporate the amount of repair actions as quality quantification and thus relation between the primary components.

In addition, a scenario testing component loads or generates a secondary data set with similar conditions and potential waiting time included. This enables definition of a flow division and testing of the calculated upscale strategy for various repair process scenarios.
5.4. Conclusion

The generator provides the possibility to functionalize and evaluate the proposed multi-layer return quality control model. This enables verification and validation of the model in the next two chapters. The programmed interface can be considered as first preliminary sustainable repair process design generator tool.
Model Verification

To verify that the proposed multi-layer return quality control model functions as intended the theory need to be quantified. One method for such verification is examination of output with parameter adjustment. As mentioned in chapter 5 the possibilities of the generator cover an extensive range. Yet, for the purpose of this research the verification is limited to parameters directly related to the theoretical possibilities described in Table 5.2.

First, section 6.1 describes the design of the verification. Subsequently, section 6.2 to section 6.4 continue with verification of the primary procedures and relations of the multi-layer return quality control model. Thereafter, section 6.5 evaluates the multi-layer return quality control model on its functionality. As last, section 6.6 concludes the chapter with an answer to sub-question five.

The following sub-question will be answered in this chapter:

5. What is the effect of the theoretical parameters on the procedures of the model and does the model function as intended?

6.1 Model verification design

The model is verified with generated data sets that represent total amount of repair actions distributions. These generated data sets enable artificial changes of the upper and lower boundary and variance around the average of those boundaries to extend the model verification and circumvent inaccurate KLM E&M ES SAP data.

The verification is divided in three segments that together represent the elementary behaviour of the proposed model. Figure 6.1 illustrates this division.

The upscale strategy calculation and flow division are dependent on return quality controller output. With behaviour definition of the controller limit calculation the link to the upscale
strategy and flow division is made by adjusting the limits and parameters that follow from these limits. In that way the defined theoretical possibilities described in Table 5.2 are each addressed.

Parameter adjustment is applied by iteration of calculations with the parameter selected from a bounded range. The results are shown and evaluated as function of the changed parameter. Distributions of the generated data sets only vary if the standard deviation or range need to be changed or in the case of random scenario data set sampling. It is chosen to iterate parameter adjustment 100 times to obtain significant exemplification of the model behaviour. The choice for 100 iterations is based on the approach defined by precedent graduate A. Lemson [45]. Aisha stated, based on [47], that sufficient large samples are often data sets from 100 samples and subsequently demonstrated that statement as satisfactory in the KLM E&M environment. Yet, the 100 samples are used to define a representative behaviour distribution and not a model output bandwidth.

As the proposed model and corresponding generator comprise procedures based on non-randomized related calculations the model behaviour is similar for each input data set. This substantiates the statement to examine parameter influence by changing the parameters and keeping the input data set the same except for data set variance or range changes or random scenario data set sampling. Moreover, this implies that the results are explanatory for the generic behaviour. The following statement summarizes these declarations and should be kept in mind for understanding of the performed verification:

**The result of the model is specific for each input case, yet the behaviour similar.**

### 6.2 Return quality controller verification

The limit calculation follows the procedures shown in section 3.3 and depends on the historical data set in the case of a class II and class III process classification. For a class I process the calculation is not influenced by a historical data set as prescribed product or process specifications are used. To show the influence of the input data set variance and range and the limit calculation method, historical data sets are generated, as shown in appendix I, with either changing the standard deviation, range or sample size. The data set standard deviation with respect to the data set average is used as measure for variance. This definition is maintained in the remainder of this chapter. Regression analyses are included as the data set distributions change with variance or range adaptation. The following relations are verified in this section:

- The influence of the data set variance and range on the warning and control limit calculation.
- The difference between the SPC and pre-control calculation.

**Results**

As first result Figure 6.2 shows the influence of data set variance on the SPC warning and control limit calculation for a fixed data set range. The limits are measured with the difference from the data set average as percentage of the data set average. Changing variance is defined by relative standard deviations from a 3%-30% range with the input data set regenerated for each standard deviation.
Both limit calculations behave exponentially towards a steady state with decreasing ratio for reduction of data set variance. Linear and exponential regression results in an average R-squared of 0.641 and 0.869 respectively. This aligns with the SPC calculation procedure using the moving range. With less variance the samples scatter and absolute differences reduce. This results in double influence on the moving range and thus limit calculation. Furthermore, it can be noticed that the limits lie above the upper boundary for high variance data sets. These limits do not affect data sets with similar or lower upper boundaries. This implies that for high variance data sets a scaling factor need to be applied to the limit calculation or data set clustering is required to obtain useful limits. A graph with applied scaling factors is attached in appendix I. Scaling factor application enables useful limits with slight reduction of the exponential R-squared. Yet, as the data set range, as shown below, and variance both influence the limit calculation the required scaling factor can only be determined case specific. Therefore, further research to define an optimization model or procedure for determination of the scaling factor is recommended. It should be noted that variance reduction goes together with reduction of the data set maximum in the data set generation, while in practice outliers are still present. As consequence the shown lines would shift slightly upwards. This does not influence the elementary behaviour.

Next, Figure 6.3 shows the influence of the data set range on the SPC warning and control limit for a fixed variance. The changing range parameter is defined by upper and lower boundaries from ranges 40-70 and 10-30 respectively.

It can be seen that the limits behave linearly towards the data set average with fluctuations. Linear regression resulted in an average R-squared of 0.780 for both limits together. The linear behaviour aligns with the moving range calculation procedure as in this case only the
absolute difference between samples reduces and not its scatter. The fluctuations occur due to the regeneration of data sets with different upper and lower boundaries for each range change. The fixed 29% relative variance of the regenerated data sets amplifies these fluctuations. Appendix I can be consulted for a similar graph with less relative variance and correspondingly less extensive fluctuations. Again limits are calculated that lie above the upper boundary of the data set for high data set variance.

To crosslink both graphs Figure 6.3 shows the calculated SPC warning limit as function of data set variance for fixed 70, 50 and 30 data set ranges. The variance is defined by standard deviations from a 3%-30% range.

The figure shows that for smaller data set ranges the limits lie closer to the data set average. This corresponds to the shown linear influence of range reduction in Figure 6.3 that is now incorporated. Besides that, the maximum achievable reduction of difference between the limit and data set average as function of the variance reduces for smaller range data sets. This corresponds to faster achievement of the steady state as can be seen in the figure.

As last, a comparison is made between the limit calculation of the SPC and pre-control methods. This comparison demonstrates the difference in accuracy. The behaviour of the pre-control limits with respect to data set variance and range is similar to that of the SPC limits.

It is observed that the pre-control method is less accurate than the SPC method as result of the standard deviation used in the tolerance calculation. The limits lie for a higher range of data set variance above the data set upper boundary. This again implies that the limits are not applicable for process data sets with a similar or lower upper boundaries. Similar as for the SPC method a scaling factor or data clustering is required to obtain useful limits in those cases. For the pre-control method it is possible to change the tolerance factor as
scaling factor. General theory used six times the standard deviation as tolerance, which can be reduced to obtain applicable limits. The application of this scaling factor has the same effect as shown for a SPC limit calculation in appendix I.

6.3 Process flow division verification
For the flow division the acceptable, warning and bypass flow division is used. To define the flow division the return quality controller component is combined with the scenario testing component. The data set of the scenario testing corresponds to the data set range and standard deviation used for the return quality controller, but with a different distribution of values. Identical conditions are used as in general process conditions remain the same. Yet, different distributions within these conditions are used as the future process is not a copy of the historical process.

The scenario data set samples are divided over the three flows based on calculated SPC limits. The limits are artificially scaled by application of a 1-0.01 scaling factor to show the effect of tighter limits. The relation of the scaling factor to the limit difference from the data set average is shown in appendix I. This limit scaling procedure is iterated for different data set variances and ranges. Histograms of the data set combinations are attached in appendix I. Furthermore, it is shown how application of the limits influences the return quality variance. Pre-control application results in similar behaviour, but with higher limit to data set average differences as shown in section 6.2. The following relations are verified in this section:

- Flow division of the scenario data set in % as function of the difference of SPC limits from the data set average defined by the scaling factors 1-0.01.
- Standard deviation of the filtered scenario data set as function of the difference of SPC limits from the data set average defined by the scaling factors 1-0.01.

Results
Figure 6.6 to Figure 6.8 show the behaviour of the three flows as function of the scaling factor for a data set with 29% and 6% standard deviation with respect to the range. The flow shares are percentages of the 150 samples of the scenario data set for scaling factors ranging from 1 to 0.01.

![Figure 6.6: Acceptable flow division vs limit tightness](image)
Figure 6.6 shows that the percentage of acceptable flow reduces with tighter limits towards 50%. The 50% is the minimum acceptable flow for this calculation as the limits approach the data set average and the data sets are generated with about equal amount of samples on each side of that average. For non-equal scatter of amount of samples on each side of the average the flow divisions are affected faster or slower, but the behaviour remains the same. Maintaining 100% acceptable flow for the 29% variance data set for scaling factor interval 1-0.7 corresponds to the previous graphs showing that the limits lie above the upper boundary for high variance data sets. The data set with 6% standard deviation as percentage of range shows that for data sets with less scattered samples the effect approaches a step behaviour due to accumulation of samples. Again, it should be noticed that less variance goes together with a reducing data set maximum. Inclusion of outliers would result in a small reduction of the acceptable flow and increase of the warning and control flow in practice. This does not influence the general behaviour.

Figure 6.7 shows that the warning flow increases as soon as the acceptable flow decreases till the control flow, shown in Figure 6.8, starts to increase. Due to decrease in ratio between the warning and control limit the warning flow percentage starts to decrease as soon as the control limit has influence. Similar behaviour as for the acceptable flow occurs in opposite direction for the control flow. For a data set with less variance the warning and bypass flow are affected faster by the determined limits. This aligns with Figure 6.2. The behaviour of all three flows combined for data set ranges 5-75 and 30-50 is shown in appendix I.

As result of these flow changes due to limit application the variance of the filtered scenario data set changes. Figure 6.9 shows the variance of the filtered scenario data set in the case of warning limit application. A similar graph with application of the control limit is attached in appendix I.
6.4 Upscale strategy verification

The upscale strategy verification is split in two. First, the influence of the limits on an upscale strategy calculation for a six-machine process is provided. This is demonstrated by the total required amount of upscales and the quantity in process per week for which a machine needs its first upscale. Fixed practical parameters are used for the calculation, which are attached appendix I. As upscale scenarios 25%, 50% and 50% are used. These scenarios represent machine exploitation followed by shared and subsequently dedicated extra machine capacity in practice.

Second, the influence of the limit tightening and bandwidth calculation value on the strategy sufficiency is outlined. This is done by comparing multiple calculated strategies for a singular machine with the capacity demands of a corresponding process scenario with various incorporated waiting times. The following relations are verified in this section:

- Total amount of upscales and passed through bandwidth calculation value as function of the limit scaling factor.

- The first quantity in process per week for which a machine needs an upscale as function of the limit scaling factor.

- Amount of sufficient upscale strategy calculations for a singular machine as function of incorporated 0%-200% waiting times for a large and small variance data set.

- Amount of sufficient upscale strategy calculations for a singular machine as function of incorporated 0%-200% waiting times for different bandwidth calculation values.

**Results**

Figure 6.10 and Figure 6.11 show the amount of upscales and bandwidth calculation value for six machines. The amount of upscales is the sum of upscales for the six machines and the total amount of repair actions the bandwidth calculation value. Both are shown as function of 1-0.01 scaling factors.
Figure 6.10 shows that tighter limits stepwise reduce the total amount of upscalings calculated. This aligns with the calculation procedure that is based on the mid value of the data set average and upper control limit. The total amount of repair actions line represents the used bandwidth calculation mid value. Figure 6.11 shows that with tighter limits the strategy allows more quantity in process per week before it calculates a machine as bottleneck. With less variance the strategy allows more quantity in process per week.

Next, Figure 6.12 shows the influence of limit tightness on the sufficiency of the strategy with application of the warning limit. The sufficiency is expressed in sufficient strategies out of 100 comparisons to a random sampled scenario process with 0%-200% waiting time incorporated in the calculated $T_{req}$. 

Figure 6.10: Amount of upscale and bandwidth calculation value vs limit tightness

Figure 6.11: First upscalings per machine vs limit tightness

Figure 6.12: Upscaling strategy sufficiency vs waiting time
Comparing the lines of both data sets it can be seen that for a high variance data set more stochastic is allowed before the strategy turns out insufficient. This aligns with incorporation of more process leeway in the case of a high variance process. Furthermore, the influence of limit tightening for a high and low variance data set differ. For a high variance data set limit tightening allows less process stochastic while for a small variance data set limit tightening allows more stochastic. This is a result of the reducing bandwidth calculation value. For small variance the effect of refusing more samples with tighter limits is stronger than the effect of the reducing difference between the bandwidth calculation value and the data set samples and vice versa for high variance. Yet, the differences due to limit tightening remain small, which implies that the upscale calculation value scales properly with limit tightening.

In addition, it can be seen that the allowed stochastic approaches a minimum, in this case 25%. This asymptotic approach relates to the used factor $S$ in the $T_{req}$ calculation, which is 1.25 for the 80% utilization in this case. Again outliers are not accounted in the case of the low variance data set due to the data generation method. Inclusion of those outliers could result in a small shift of the lines to the left. For understanding of the behaviour this does not have significant effect.

As last, the return quality controller bandwidth calculation value used for the upscale strategy is examined. Figure 6.13 shows the effect of using different bandwidth calculation values on the allowable process stochastic. The mid value, proposed in section 4.4, is the blue line in this graph.

It is observed that for lower bandwidth calculation values the amount of sufficient runs with similar limits reduces. This is due to the reduced leeway in the upscale strategy calculation with respect to the data set range. Higher bandwidth calculation values result in similar lines shifted to the right. The allowable stochastic in this graph is dependent on the incorporated maximum utilization, in this case 80%, and the data set variance, in this case 29%. In appendix I a similar graph is attached for a data set with less variance. Lowering or raising the allowable design utilization results in a shift to the right and left respectively. Whether the bandwidth calculation value suffice depends on the specific process parameters and business strategy. It can either be chosen to apply a different utilization factor or a different bandwidth calculation value to fit the process to the operating circumstances.

### 6.5 Model functionality evaluation

This section evaluates the functionality of the model based on the described verification. Functionality is depicted as the ability to provide control for each of the identified criteria.

Application of the return quality controller limits reduced the quality variance of the process input and provided the required process input bandwidth. The limit calculation verification did however show that the proposed conventional SPC and pre-control calculation procedures did not suffice for high variance data sets. Data set clustering or a limit scaling factor
is required to solve this deficiency. The quantity variance is controlled by definition of the allowable quantity in process. This method functions as intended with the possibility incorporated to adjust to specific business conditions. The threefold classification of layer three did function as intended and suffice for process maturation classification.

The process upscale complexity is controlled by definition of an upscale strategy that calculates future bottlenecks and required upscales. Verification showed that the proposed procedures functioned as intended with the possibility to adapt to business specific conditions. The determination of the machine capacity arrangement is controlled by using a financial and capacity based decision tree related to the bottleneck order of the upscale strategy. However, as this part of the model is only incorporated in the generator as upscale scenario percentages the functionality is declared with reservation. Similarly, the implementation of innovation layer and supply chain integration proposal remained limited to theory. Their functionality is only substantiated by theory and therefore also declared with reservation.

6.6 Conclusion

This chapter verified the the multi-layer return quality control model on the basis of theory quantification by parameter adjustments. The remainder of this section answers sub-question five.

What is the effect of the theoretical parameters on the procedures of the model and does the model function as intended?

The variance and range of the historical data set have a positive exponential and linear influence on the limit calculation respectively. Observation is the need for data set clustering or application of a scaling factor in the limit calculation for high variance data sets to obtain adequate limits. Tightening of the limits results in linear reduction of the acceptable flow, parabolic increase and decrease of the warning flow, linear increase of the bypass flow and reduction of return quality variance. Likewise, limit tightening reduces the required amount of upscales, allows more quantity in process before a bottleneck is calculated and has an either positive or negative influence on the allowable process stochastic depending on the process variance. As last, bandwidth values lower than the mid value allow significantly less stochastic in the process and vice versa.

Based on the findings of this chapter the functionality of the multi-layer return quality control model is verified with a remark for high variance processes. The functionality of the machine capacity arrangement determination and innovation implementation and supply chain integration procedures is declared with reservation as these procedures remain limited to generator input and theory respectively. The next chapter complements the verification with a case study model validation.
Model Validation

With the verification in place the theory is further quantified by validation. Validation determines to what extent the model represent the real system. One method for validation is comparison of the model results to the conditions of the real system that it represents. Correspondingly, validation of the theory is established by a case study and comparison of the model results to the current system state of that case.

First, section 7.1 describes the KLM E&M ES case used for this validation. Subsequently, section 7.2 elaborates on the data gathering and preparation for the case application. Thereafter, section 7.3 outlines the results of the case study with a comparison to the actual case state. As last, section 7.4 concludes the chapter with an answer to sub-question six.

The following sub-question will be answered in this chapter:

6. How does the output of the proposed model relate to the current state of a repair process at KLM E&M ES?

7.1 Case study description

The 80C and 80E fan mid shaft engine part repair is chosen as repair case. This engine part connects the fan and booster with the low pressure turbine of a jet engine. The repair is currently under the loop ES department managing board. It is pronounced KLM E&M ES wants to become global leader in provision of the 80E & 80C and GEnx fan mid shaft repair with extensive capabilities and significant quantity growth. Yet, the repair process of the fan mid shafts currently lacks resulting in TATs of almost twice the contractual agreements of four weeks. The managing board tried to improve the TAT by prioritizing fan mid shaft repairs over all other repairs. As result the TAT reduced, but at the expense of performance of the other repairs. Consequently, the prioritization was revised resulting in a setback to former lacking performance. A current process control development at KLM E&M ES, further described in subsection 9.1.2, focuses on recovery, stabilization and control of the current state of the fan mid shaft repair process. However, with the aim to perform according to customer agreements and enable significant quantity growth, sustainable initial design is required too. This substantiates the importance of application of the proposed model and the reason for this KLM E&M ES case. The GEnx is not taken into account as that repair is relatively new, has hardly data available and does not align with the work scopes of the 80C and 80E.

7.2 Case study input

To apply the model, the theoretical and practical parameters need to be defined using SAP data and input from KLM E&M ES mechanics. The return quality controller calculations are based on the historical 80C and 80E SAP data set from March 2016 till April 2019. Eight orders are filtered from this data set due to significant disparity. Description of these outlying orders is attached in appendix J. The subsequent calculation of the upscale strategy deviates from the real process as the generator allows six machines while the 80C and 80C
repair process comprises up to fifteen machines. It is chosen to calculate the upscale strategy for the following six most occurring operations:

- Machine 1: Painting
- Machine 2: Grinding
- Machine 3: Masking
- Machine 4: Shotpeening
- Machine 5: HVOF spraying
- Machine 6: Oven

The processing times of these machines for the shafts are obtained from mechanics and the average weekly occupations from the SAP data. The amount of repair actions per machine is deduced from repairs that have a similar total amount of repair actions as the mid value of the calculated return quality controller bandwidth. The utilization percentage is chosen to be 70%. KLM E&M ES is market leader and ahead of competition in the provision of 80C and 80E shaft repairs but also classifies OTP as important business value. Therefore, the middle value of Table 4.1, 70%, is used in the calculations. As last, the current global stock of remanufacturable fan mid shafts could provide up to three shafts per week, which means a maximum of twelve in process with a TAT of four weeks. Moreover, AFI currently has 35 scrapped shafts in stock with the desire to restore as soon as possible. Aligning with these demand the following two market demand scenarios are used:

- A linear increasing market demand that ranges from 0 to 12 shafts in process per week in two years representing gradual expansion to the global market demand with room for machine investment procedures.

- An exponential increasing market demand that ranges from 0 to 12 shafts in process per week in one year representing fast process expansion to accommodate the AFI demands.

An overview of the practical input data, market demands, machines occupations and performed data processing steps to attain more reasonable input data is attached in appendix J.

### 7.3 Case study results

The model initiates with return quality controller limit calculation. With 90 samples and a CoV of 10% the process attains a class III classification resulting in SPC application. Figure 7.1 shows the corresponding histogram and calculated quality control chart.

![Figure 7.1: Histogram and control chart for the 80C & 80E fan mid shaft repair process](image)
With a minimum of five and maximum of ninety-two repair actions the process has a high relative variance of 26%. As previously noticed in section 6.2, the upper control limit lies above upper boundary of the set due to this high variance. The limits can be enhanced by data set clustering as shown by the dotted circles in Figure 7.1 or by applying a limit scaling factor. The following three modifications align with these proposals:

- **Modification 1:** Clustering 5-35 range: Control limit; 31 & warning limit: 27
- **Modification 2:** Clustering 35-92 range; Control limit: 87 & warning limit: 79
- **Modification 3:** Scaling factor 0.7, 5-92 range: Control Limit: 83 & warning limit 69

Table 7.1 shows the corresponding average flow division for application of these limits to 100 different scenario testing data set distributions with similar variance and range as the 80C and 80E process. The percentages relate to 100 samples per data set.

<table>
<thead>
<tr>
<th>Modification</th>
<th>Acceptable flow</th>
<th>Warning Flow</th>
<th>Bypass Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>78%</td>
<td>17%</td>
<td>5%</td>
</tr>
<tr>
<td>2</td>
<td>78%</td>
<td>19%</td>
<td>3%</td>
</tr>
<tr>
<td>3</td>
<td>74%</td>
<td>16%</td>
<td>10%</td>
</tr>
</tbody>
</table>

The limits and flow divisions could be further adjusted based on desired business strategies. The case application continues with modification three as currently no clustering is performed at KLM E&M ES.

The upscale strategy calculation is carried out using the active scenario input function of the generator. This means that input scenarios are requested as soon as the calculation encounters a bottleneck. Based on the limits of modification 3 the input bandwidth mid value is 62 repair actions. Correspondingly, the amount of repair actions per machine is based on completed repair orders with similar total amount of repair actions carried out. Table J.2 in appendix J shows the corresponding amount of repair actions per machine.

For the dynamic input it is chosen to first exploit a machine with 25% and then elevate it with dedicated or shared investment. The resulting upscale scenarios are the following:

- Painting becomes a bottleneck at 4 of the 12 shafts per week with 41% extra capacity required for the market demand. Upscale action: Exploitation of the machine with 25% extra capacity.
- Grinding becomes a bottleneck at 5 of the 12 shafts per week with 69% extra capacity required for the market demand. Upscale action: Exploitation of the machine with 25% extra capacity.
- Shotpeening becomes a bottleneck at 6 of the 12 shafts per week with 38% extra capacity required for the market demand. Upscale action: Exploitation of the machine with 25% extra capacity.
- Grinding becomes a bottleneck at 8 of the 12 shafts per week with 44% extra capacity required for the market demand. Upscale action: Machine investment with shared resources capacity arrangement with 50% extra capacity.
- Painting becomes a bottleneck at 10 of the 12 shafts per week with 16% extra capacity required for the market demand. Upscale action: Machine investment with shared resources capacity arrangement with 20% extra capacity.
- Shotpeening becomes a bottleneck at 11 of the 12 shafts per week with 13% extra capacity required for the market demand. Upscale action: Machine investment with shared resources capacity arrangement with 20% extra capacity.
Figure 7.2a and Figure 7.2b illustrate the corresponding upscale strategy output for the linear and exponential market demand.

It can be seen that a first maximum of four shafts in process per week is calculated, which equals an averaged output of one shaft per week. The current output is on average two shafts with often one and some weeks three of four shafts, as shown in appendix J. However, the average TAT for those shafts is twice the contractual agreement and 3 or 4 shafts output is only accomplished with small work scope repairs present. Furthermore, the fan mid shaft project manager initiated a procedure to put an unused painting cabin into operation and is researching possibilities for the shotpeen machine as both came forward in practice as process flow bottleneck. The strategy calculated painting, grinding and shotpeening as bottlenecks, which except for the grinding machine thus aligns with the actual bottlenecks. As last, the strategy calculated four net required FTEs. The current dedicated fan mid shaft team consists of four mechanics. These mechanics carry out eleven of the on average fifteen required operations, but at the moment with twice the contractual TAT. Extrapolating these numbers, it is stated with reservation that the calculated net FTEs correspond to the actual situation.

Overall the outcome of the combination of the return quality controller and upscale strategy aligns with the actual process setting to a significant degree. The calculated future states can only be compared over time and are therefore presumed appropriate based on the above model validation. Using the return quality controller limits and calculated upscale strategy the process can be stabilized and made sustainable for future expansion. In addition, a machine investment plan can be made based on the assessed upscale weeks.

7.4 Conclusion

This chapter validated the multi-layer return quality control model on the basis of quantification by case application of the theory. The remainder of this section answers sub-question six.

*How does the output of the proposed model relate to the current state of a repair process at KLM E&M ES?*

The return quality controller limits were in line with the actual 80C and 80E shafts data set and the calculated upscale strategy showed output related to the current process situation. The average actual output flow is twice the calculated flow, but the current process TAT is also twice the contractual TAT used in the case application. Furthermore, two of the three calculated bottlenecks are identified as bottlenecks in the real process. As last, the
7.4. Conclusion

calculated amount of net required FTEs aligns with the dedicated fan mid shaft team of KLM E&M ES. The dedicated fan mid shaft team currently operates eleven machines, but at twice the contractual agreement. Extrapolating these numbers, it is stated with reservation that the calculated net FTEs corresponds to the actual situation. Validation of the calculated future states is attainable, but over time, as those states do not yet exist in the real system. Still, based on the current state similarities the model is considered validated.

With the model verified and validated the Case Study Methodology in Business Research [18] research cycle is completed. Therefore, the next chapter finalizes the research with an overall conclusion and recommendations. Afterwards, chapter 9 provides an additional description of implementation requirements for KLM E&M ES.
Conclusion & Recommendations

This chapter provides the conclusions, recommendations and discussion. Section 8.1 concludes the research with the answer to the main research question. Section 8.2 elaborates on the recommendations for further research and KLM E&M ES. As last, section 8.3 discusses the limitations and scientific contribution of this research.

8.1 Conclusion
The conclusion completes the circle of research that was initiated with identification of the research problem. It answers the following main research question: *What method can be proposed for sustainable initial repair process design from a return quality perspective?* The answer to this main research question is established by describing the following aspects:

- Criteria that need to be controlled for sustainable initial repair process design.
- Design of a multi-layer return quality control model that embodies a method for sustainable initial repair process design.
- Evaluation of the model and answer to the main research question.

8.1.1 Criteria for sustainable initial repair process design
To develop a method for sustainable initial repair process design criteria that affect this aim need to be identified. The following criteria are identified using literature and on-floor observations:

- Return quality and quantity variance
- Classification of process maturation
- Definition of process future expansion
- Determination of machine capacity arrangement
- Implementation of innovation

To enable initial control of these criteria, management and control methods need to be applied at the front end of the process. This requires theory application that deviates from the conventional application to recover, improve and control operational processes.
8.1.2 Multi-layer return quality control model
The criteria facilitated the design of a multi-layer return quality control model that represents a method for sustainable initial repair process design from a return quality perspective. The designed model consists of five layers that address the identified criteria.

The first layer defines the repair process basis with a return quality controller. On the basis of quality quantification a warning and control limit are calculated using either SPC or pre-control theory. The second layer classifies the process maturation to determine which of the two theories suits the available process data set. By definition of the limits a return quality input bandwidth is established.

Based on the bandwidth layer three defines a ToC-based upscale strategy for machine capacity. Part of this strategy is definition of the capacity arrangement of the machines, which is obtained by integration with layer four. This fourth layer includes a procedure that facilitates determination of machine investment feasibility and dedicated or shared capacity arrangement. Layer five constitutes a systematic approach for implementation of the Industry 4.0 concept with a focus on digitization for paperless operations. The last part of the model is integration of its outcome in the organizational supply chain. This is facilitated by combining IDEF-based swimlane and VSM diagrams with a ROS-based data infrastructure.

8.1.3 Evaluation and main research question
The multi-layer return quality control model is considered serving its intended purpose to enable sustainable initial repair process design. Criteria that require control for this purpose are identified and proven theories are applied following the recognized process front end approach to facilitate that control. On the basis of these findings a mindset change is initiated to incorporate process return quality management and future state calculation to prevent instead of recover operational process obstructions. The design method with defined model is applicable for KLM E&M ES repair cases, but is generically designed to extend its application range. Besides that, the procedures are designed to be adaptable to specific business requirements. As last, the programmed model interface provides a preliminary repair process design generator tool to support the movement towards automation.

The answer to the main research question is as follows:

As design method a multi-layer return quality control model is proposed that enables control of criteria that influence sustainable initial repair process design. The first layer concerns a return quality controller that uses SPC or pre-control theory to establish control limits based on process maturation classification determined in the second layer. These control limits define a process input bandwidth for product return quality. The third layer continues with a bottleneck calculation based on the defined bandwidth to delineate an upscale strategy. This upscale strategy is combined with machine capacity arrangement determination and systematic innovation implementation procedures in the fourth and fifth layer respectively. Last part of the model is integration of its output in the supply chain by combining IDEF-based swimlane and VSM diagrams with a ROS-based data infrastructure.

8.2 Recommendations
This section describes the scientific recommendations in subsection 8.2.1 and practical recommendations for KLM E&M ES in subsection 8.2.2.

8.2.1 Recommendations for scientific research
The design method in this research is developed with the intention to maintain a generic level to extend the range of applicability and provide a foundation for a new direction of research. Yet, observations from the research field and the singular case application still partly confine its applicability declaration to the aviation MRO repair environment. Therefore, it is recommended to reflect the developed design method on a wider range of remanufacturing facilities in different industry fields. In addition, it is recommended to extend the design method to the manufacturing industry as its primary purpose suits that industry too. The
definition of reasonable ToC calculation input and the return quality controller require a different approach for the manufacturing industry, but the concept and objective could prove valuable. As last on generic level, it is recommended to extend the model validation by keeping track of its application result over time. This extended model validation with process future state comparison invigorates its utility substantiation.

Furthermore, on a more detailed level three recommendations emerged during the research. As first, it is recommended to extend the research on the return quality controller. The current theoretical quality control methods turned out convenient, but with a limitation with respect to the data set variance. The solution was identified in data set clustering or application of a limit scaling factor in the limit calculation. It is recommended to further research the return quality controller and scaling factor application to enable limit calculation for a wider range of process conditions.

As second, it is recommended to extend the research on the upscale and machine capacity arrangement strategies. This research included a considerable, but still limited, range of parameters in the upscale and machine arrangement strategy calculation. It is suggested to extend the parameter range of the upscale strategy with a link to operation scheduling and planning and of the machine capacity arrangement strategy with financial parameters.

As third, it is recommended to extend the research on the proposed systematic approach for Industry 4.0 implementation. It is recognized that Industry 4.0 is changing the industry perception, but intelligible implementation guidelines remain unavailable. The systematic implementation approach defined in this research provides a base for research in this direction.

8.2.2 Recommendations for KLM E&M ES
It is recommended to implement the proposed design method in combination with the current Process Excellence movement in the six-phase repair development strategy. To use the combination to its full utility it is imminent to conform to limits on return quality and quantity and change the mind set from problem recovery to problem prevention. This research provides the fundament to guide this change of perception. Further development and application of the design method in combination with planning and scheduling of the direct support division is suggested as starting point.

On an operational level the following changes in data measurements are recommended to enhance the design method accuracy and applicability:

- Cluster data on the basis of light, middle and heavy maintenance work scopes.
- Include measurements of product feature quality.
- Measure actual machine occupation and processing times at the work floor.
- Improve the accuracy of repair action logging.

As last, it is recommended to accelerate digitization and revise the organizational data structure to incorporate the process innovation strategy and advanced data infrastructure of the design method. This contributes to the data accuracy of the facility and integration of machinery, which enhances the functionality and veracity of the design method. It is suggested to initiate with digitization of process progress, performance and data availability using the guiding procedures of this research.

8.3 Discussion
This section presents the discussion of this research with the research limitations in subsection 8.3.1 and scientific contribution in subsection 8.3.2.
8.3.1 Limitations
The data used to obtain insight in the functioning of repair processes and for the case application are not completely reliable. The KLM E&M ES data sets contain deficiencies with duplicate, missing or unrealistic data due to inaccurate logging, multiple data systems and manual adaptations. Data processing is applied to enhance accuracy, but 100% reliable data is not attainable.

Furthermore, the MATLAB® model has three limitations.

• Variance reduction of the generated data sets goes at the expense of data set minimum increase and maximum decrease resulting in exclusion of outliers.

• The data sets are generated with about equal amount of samples on both sides of the average resulting in an average that is the middle of the upper and lower boundary.

• The generator includes a rounding error for iterative calculations of repair actions per machine for changing limits due to non-integer ratio multiplication.

These limitations introduce deviations from reality in the absolute results, but not in design method behaviour demonstration. The differences resulting from these limitations were explainable and described in the verification of the model. The limitations did not affect the validation as for that case application an actual KLM E&M ES data set was used without artificial changes and calculation iterations.

8.3.2 Scientific contribution
The scientific contribution relates to the research gaps defined in subsection 1.3.1.

The primary scientific contribution of the research is the introduction of a repair process design method with process front end management and control from a return quality perspective. Instead of conventional application of proven theories for process recovery and output control, the proposed design method enables process front end theory application. This enhances the sustainability and foundation of repair processes. Consequently, it contributes to the perception to direct research towards automated process design. Furthermore, the base of the design method was defined by a multi-layer return quality control model that relates return quality to the operational process. To the knowledge of the author this relation was not yet addressed in previous research. This perspective extended the range of research in the relatively uncovered subject of remanufacturing process return quality and encourages follow-up research.

A secondary contribution to science is the addressed Industry 4.0 implementation research need. The proposed systematic implementation approach provides a generic procedure to simplify the implementation of the broad concept of Industry 4.0. The additional suggested combination of standardized visual process integration tools with an advanced data infrastructure facilitates this approach. Besides that, the advanced data infrastructure provides a preliminary data exchange structure that can be used for research in paperless and automated production facilities.
Business Implementation

Definition of the link between theory and practice is essential for contribution to both fields. Although input from the practical research field is incorporated in the proposed multi-layer return quality control model and a case application showed the outcome in a practical context, it is still developed as generic procedure to extend the range of applicability. As consequence, the relation to the current state of development of KLM E&M ES and implementation requirements need further elaboration. This chapter discusses how the design method with multi-layer return quality control model relates to the current state of development of KLM E&M ES and how it could be implemented.

First, section 9.1 outlines its position with respect to the currently available initial process design procedures and present developments. Thereafter, section 9.2 elaborates on the implementation requirements and related recommendations for practical functionality. As last, section 9.3 concludes the chapter with an answer to sub-question seven.

The following sub-question will be answered in this chapter:

7. What is the position of the proposed design method with respect to the current state of development of KLM E&M ES and what are requirements for implementation?

9.1 Business current state of development

This section describes the position of the proposed design method with respect to current procedures and present developments in repair process design at KLM E&M ES. Subsection 9.1.1 describes the current procedures and subsection 9.1.2 the current developments. Subsection 9.1.3 defines the position of proposed design method in relation to both.

9.1.1 Current procedures

The repair development department of KLM E&M ES uses a six-phase process design procedure, which runs from selecting market opportunities to project handover to the work floor. The complete procedure is attached in appendix D. The proposed model fits best in the plan and execute phases of this procedure.

Plan phase

The plan phase starts after approval of the business case. A planning is made to provide a repair process implementation timeline till the handover to the work floor. The required team for the new repair is gathered ranging from mechanics to sales. Furthermore, the process critical path is made visible and internal and external stakeholders are identified. The phase ends with identifying and obtaining required work packages and skills and starting a risk management analysis.

Execute phase

The plan of the previous phase is executed during this phase. The 4Ms are put in place as process basis. Dry-runs are done to verify the process requirements and 4Ms are met and to obtain insight in demand-supply balancing. This balancing focuses on workforce planning in
relation to current demand. Meanwhile, project monitoring and control is carried out to make sure the implementation is executed according to the plan. This directs at the overall project and not at the operational repair process itself. Quality control is defined and tested in this phase, but only to control delivered output quality and make sure the required serviceable level is met.

9.1.2 Present developments
The KLM E&M Lean Six Sigma office identified the need for current state process control in process design and started the Process Excellence movement. Process Excellence has its base in operational excellence theories, with particular interest in the ToC. The fundament finds itself in the twofold approach to first stabilize and then control a process. Directed by identification of uncontrolled waiting times in the integral process it intends to stabilize the process by reducing and curbing these waiting time and creating process specific cadence. Based on this cadence process control is established that fits in an integrated network of processes.

9.1.3 Position proposed design method
It is recognized that current state process control and sustainable future state design are both not included in the existing process design procedure. The Process Excellence development accommodates the need for current state process control, but sustainable design with future states remains excluded. This implies that established control methods still not anticipate potential demand expansions. As result the robustness in terms of adaptiveness is not established most optimal. Out of control action plans could preserve this robustness on short term, but with significant demand expansions these turn out inadequate. Correspondingly, the inclusion of long term robustness is where the proposed design method positions itself. Contribution in practice is maximized if it is combined with process stabilization and control. Application of the return quality controller concept can assist this stabilization of repair processes by reduction of input variance.

Based on these observations it is stated that the proposed design method suits the business current state of development and that its utility can be maximized if it is merged with the process excellence approach in the existing initial design procedures.

9.2 Implementation requirements
Delineation of implementation requirements is also essential for successful integration. As the implementation concerns integration of a method for repair process design this comprises process data and management requirements. Subsection 9.2.1 elaborates on the data requirements and subsection 9.2.2 on the process management requirements. Recommendations that follow from these requirements are included.

9.2.1 Data requirements
To apply the model of the design method data gathering needs to be extended. The required data measurements and corresponding recommendations for KLM E&M ES are as follows:

- To enable functionality of the return quality controller the amount of repair actions or product feature quality need to be measured.
  - The amount of repair actions is extractable from KLM E&M ES SAP data, but the current data are inconsistent due to incorrect logged repair actions. Besides that, large variance in amount of repair actions for a singular product results in inapplicability of determined limits. It is recommended to improve the systematic logging of executed repair actions to enhance accuracy of the return quality controller and cluster repair work scopes on light, middle or heavy maintenance bandwidths to curb the work scope variance.
  - Product feature quality measurements are sporadically carried out and most of the times logged on paper. The current perception is that the amount of repair actions
9.3. Conclusion

is of primary influence to the operational performance and not the product feature quality. It is recommended to apply and digitize product feature quality measurements to examine this perception and enhance definition of the added product value.

- To enable functionality of the upscale strategy the machine repair actions or process time division and machine occupation need to be measured.
  - Machine repair action division can be measured by connecting SAP repair actions data to the corresponding machine. This can be done based on the corresponding technique and equipment code. Again it is recommended to cluster repairs on light, middle or heavy maintenance work scope bandwidths and enhance repair actions logging.
  - Machine process time variation is not measured and process time is only present in SAP data as constant predefined duration. To enhance the calculation of the upscale strategy the actual machine process times need to be added to the data logging. It is recommended to examine the perception that process time variation does not influence operational performance using the model.
  - Machine occupation can be measured by connecting the SAP repair actions predefined duration to corresponding technique codes. But actual on floor process time measurements enhance accuracy. It is recommended to gather machine occupation percentage averages with time spans of a week and day. This provides an accurate average weekly occupation with insight in potential daily variation.

9.2.2 Process management requirements

For implementation of the design method in process management the requirements and recommendations are as follows:

- Acceptance as part of the Process Excellence movement is required for full utility. Insertion of the combination in the six-phase process design procedure is recommended.

- The perception of process management needs revision. The focus should not only be on output quality control and operational problem solving, but also on return quality control and operational problem prevention. Inclusion of the model in process management decisions is required for this change. It is recommended to apply the warning limit of the return quality controller as threshold for inclusion of extra TAT leeway in the contractual agreement and the control limit as threshold for segregating the product to a bypass procedure. Furthermore, it is recommended to maintain the defined allowable quantity in process and machine capacity arrangement of the design method output.

- Periodic revision of the design method output is required to anticipate market demand and process environment changes.

- Revision of the data exchange infrastructure is required for incorporation of the innovation strategy and ROS-based data infrastructure. To initiate this revision digitization of process performance, progress and data availability is required. Development of the ROS-based data infrastructure can be done in parallel.

9.3 Conclusion

This chapter complemented the theoretical orientation of this research by establishing a link between the developed theory and practice of KLM E&M ES. The remainder of this section answers sub-question seven.

What is the position of the proposed design method with respect to the current state of development of KLM E&M ES and what are requirements for implementation?

The current procedure for repair process design at KLM E&M ES does not incorporate current state process control or sustainable design with future states. A recently initiated movement
called Process Excellence targets current state process control, but not sustainable design with future states incorporated. This is where the proposed repair process design method of this research is positioned.

To implement the proposed design method in that position the following requirements with corresponding recommendations are identified:

- **Data related**
  - Cluster SAP data on light, middle and heavy maintenance work scopes and improve repair action tracking and logging accuracy.
  - Institute measurement of product feature quality.
  - Institute measurement of process time variation of machines.
  - Institute measurement of machine occupation with weekly and daily time spans at the work floor.

- **Process management related**
  - Incorporate the proposed design method combined with Process Excellence in the six-phase process design procedure of KLM E&M ES.
  - Change singular focus on output control and operational problem solving to one that incorporates return quality control and operational problem prevention.
  - Revise the design method output periodically.
  - Initiate with facility digitization and development of the proposed data infrastructure.
Bibliography


A

Research Paper
I. INTRODUCTION

A broad-based global economic growth momentum is now in place with a renewed need to prioritize policies that foster new sources of innovation-driven growth [2]. This reflects on the dynamic and increasingly competitive aviation Maintenance, Repair and Overhaul (MRO)-industry with western third party MRO providers seeking for process efficiency enhancement and process sustainability.

MRO in aviation comprises services that ensure continues airworthiness of aircraft. In general, these services are divided in airframe maintenance, engine services and component services. KLM Engineering & Maintenance (E&M) is a western third party MRO provider that offers these three services. This research is performed at the Engine Services (ES) division of KLM E&M. ES provides engine availability, engine MRO and parts & accessories repair. Currently, the performance of engine MRO and parts & accessories repair processes remains behind despite implementation of suggested adjustments of previous research. An underlying problem still obstructs progression in process performance emphasizing the need for research.

Present research focus on current process states and recovery, improvement and control on operational level of process phases beyond initial design. Research concerning sustainable initial process design that incorporates future states on operational level is lacking. Besides that, return quality is repeatedly mentioned as having significant influence on remanufacturing process performance [5],[1], but research that target return quality in relation to the operational processes is not available. As last, Industry 4.0 reoccurred in relation to innovation and process development. Industry 4.0 comprises the predicted industry revolution towards a more digital and integrated industry. Yet, research in a systematic approach to implement Industry 4.0 lacks, while it becomes increasingly important for process development [7]. With a reflection of these findings on the practical environment of KLM E&M ES environment it was recognized that a method for sustainable initial repair process design is not yet available to sustain operational efficiency with future state expansion.

From this observation the objective of this research to answer the following question emerged: What method can be proposed for sustainable initial repair process design from a return quality control perspective? To define this method guiding actions and decisions are configured into a layered model. The focus of this model is on the operational process level as defined by [6] and excludes scheduling & planning, financial procedures and 4Ms establishment.

A. Research Orientation

The research follows the methodology defined in Case Study Methodology in Business Research [3]. Accordingly, the orientation of the research is defined as theory-based, proposition building as it aims to propose a progressive design method based on proven theory.

B. Research Design

The research initiates with theory exploration by a twofold approach. First, the repair process environment is researched to identify criteria that influence sustainable initial process design. Second, theory is analysed that enable control of those criteria. The criteria define the model fundament and corresponding theory enable exemplification of that fundament. Follow-up is the theory-building section where the model that embodies the design method is designed. Thereafter, the model is
translated into a programmed repair process design generator with calculation mechanisms and in- and outputs defined. This enables theory examination with model verification and validation. The research is completed with a conclusion, recommendations and discussion.

II. THEORY EXPLORATION

The theory exploration comprises a theory analysis that identifies criteria that influence sustainable initial repair process design and theory that enables control of those criteria.

A. Criteria for sustainable initial repair process design

To identify the criteria insight in the repair process environment is acquired by downscaling from general remanufacturing to the repair division of KLM E&M ES. A combination of on-floor observations and literature resulted in identification of the following criteria:

i. Return quality and quantity variance

ii. Classification of process maturation

iii. Definition of process future expansion

iv. Determination of machine capacity arrangement

v. Implementation of innovation

It emanated that, to initially control these criteria, management and control methods need to be shifted to the input and initial design phase of the repair process. This shift diverges from the conventional application procedures. Consequently, it required reassessment of applicability and modification of theory. The five criteria function as fundament for the design of the model.

B. Theory to control the criteria

To acquire theory to exemplify the model fundament operational excellence, quality control, scalability and Industry 4.0 theory were studied. Lean Six Sigma, the Theory of Constraints (ToC) and Business Process Reengineering (BPR) were considered relevant as operational excellence theory. Total Quality Management (TQM) contributors Juran, Crosby and Deming and Statistical Process Control (SPC) and pre-control were considered relevant as quality control theory. Scalability and Industry 4.0 theory do not comprise a collection of concepts and were included as singular theory. Allocated to the criteria the following theory turned out suitable:

i. SPC and pre-control theory suit for return quality variance if modified to the front end application and remanufacturing environment. Both enable definition of process input bandwidth by application of the Shewhart individual measurement or pre-control chart respectively. The quality control steps defined by Juran provide guidance for definition of quality quantification. The principles of Lean and Six Sigma are kept in mind for definition of the process basis and quantity quantification. As last, the ToC suits to determine allowable quantities in process addressing the return quantity variance.

ii. SPC theory suits to classify the maturation of a process based on the required amount of samples for accurate application of the Shewhart individual measurements chart.

iii. The ToC suits for definition of future expansion by calculation of potential bottlenecks with defined capacity upscale scenarios. The process input bandwidth defined by the quality control theory is required to enable reasonable process front end calculations.

iv. The ToC suits as guidance for the machine capacity arrangement determination. Bottleneck calculation enables systematic determination of machine capacity arrangements.

v. The Industry 4.0 theory suits for control of implementation of innovation. The design principles [7] are convenient for development of a systematic implementation approach.

The BPR framework defined in [10] is considered convenient guidance for development of the model. The scalability theory proved infeasible for the remanufacturing environment.

III. THEORY BUILDING

The theory building comprises definition of the model fundament with subsequent elaboration on its elements.

A. Model Fundament

The model is designed by definition of layers that each address a criteria. As process input bandwidth is imperative for application of the ToC, the first layer defines that bandwidth with a return quality controller. This controller is based on SPC or pre-control quality control charts. The second layer classifies the process maturation to determine whether the SPC or pre-control theory suits for the controller. Based on the defined bandwidth the third layer comprises a machine capacity upscale strategy that is combined with a machine capacity arrangement strategy as fourth layer. The fifth layer defines a parallel strategy for implementation of innovation as follow-up on the third and fourth layer. As last, definition of the model output in relation to the organizational supply chain is incorporated to enhance implementation and functionality.
As the model primarily depends on the return quality control in the first layer it is denoted as multi-layer return quality control model. Figure 1 illustrates the model with corresponding criteria.

Figure 1. Multi-layer return quality control model

B. Process basis with return quality controller

First, return quality is quantified by the amount of required repair actions of a product or a specific measurable product feature. This distinction depends on whether the repair process Turn Around Time (TAT) primarily varies due to amount of required repair actions or disparate machine processing times respectively. Subsequently, the process maturation is classified in layer two based on the sample size of available historical process data that corresponds to the quality quantification. A class I & class II classification results in application of the pre-control control chart based on product or process predefined specifications or a small historical data set respectively. A class III classification results in application of the Shewhart individual measurement chart based on a historical data set. The charts comprise a data set average and warning and control limit that define the process input bandwidth. Calculation procedures for the Shewhart and pre-control chart can be consulted in [9] and [12].

C. Process Maturation Classification

Process maturation is classified following a method described in [8] that defines a minimal sample size for SPC application. Based on equations for the data set Degrees of Freedom (DoF) and Coefficient of Variance (CoV) this minimal sample size is defined by Equation 1 with constant ‘a’ as 0.62 [13]:

$$n = \frac{1}{2a \cdot COV^2} + 1 \quad (1)$$

A process with no data is classified as class I, a process with a smaller sample size than n as class II and a process with a larger sample size than n as class III.

D. Upscale Strategy

The upscale strategy is defined using ToC procedures [4] to calculate potential machine capacity bottlenecks by incrementing the allowable quantity in process per week, Q. The machine required and available processing time is compared for each incrementation of Q. The available processing time is based on operational process parameters and the required processing time on operational process parameters and the defined bandwidth. A bottleneck is calculated by the following condition:

$$\text{Machine}_i = \begin{cases} \text{Bottleneck}, & \text{if } T_{req} \geq T_{ava} \\ \text{Not a Bottleneck}, & \text{Otherwise} \end{cases}$$

After calculation of a bottleneck potential exploitation and, if required, elevation is defined by feasible artificial bottleneck capacity expansion. For capacity elevation the machine capacity arrangement strategy of layer four is consulted. The incrementation continues till the potential maximum market demand for Q is reached. Combining the incrementation outcome with a market prospect results in an allowable Q as function of time with machine upscale actions defined as illustrated in Figure 2.

Figure 2. Upscale Strategy: Q as function of time

E. Machine capacity arrangement strategy

The capacity arrangement strategy comprises a procedure that defines suitable elevation of a bottleneck. It determines if machine investment is advisable and whether it should be implemented as dedicated or shared resource. Investment feasibility is based on financial advice and machine capacity shortcoming after bottleneck exploitation. The choice for machine dedication or sharing is based on the potential utilization (U) of the new machine compared to a predetermined maximum design utilization as delineated by the following condition:

$$\text{Machine}_{i2} = \begin{cases} \text{Dedicated}, & \text{if } U_{\text{machine}_{i2}} \geq U_{\text{design}} \\ \text{Shared}, & \text{Otherwise} \end{cases}$$
F. Process innovation strategy

A systematic approach to advance on innovation implementation is defined based on the categorical Industry 4.0 framework described in [11]. This framework classifies Industry 4.0 progress in categories I to IX by three levels of intelligence and automation. The systematic approach defines a development plan to progress from I to IX based on Industry 4.0 design principles. The approach is standardized to obtain consistent machine strategies that can be merged into one smart factory.

G. Supply chain integration

Last part of the model is integration of its output in the organizational supply chain. For existing network integration a combination of the visual swimlane and Value Stream Mapping (VSM) diagrams is proposed. This combination delineates responsibilities and relations of the designed repair process with respect to the other actors in the supply chain. For Industry 4.0 integration it is proposed to apply the International Definition (IDEF) languages IDEF0 and IDEF1X to the visual tools combined with a Robot Operating System (ROS)-based data infrastructure. The standardized VSM and swimlane in combination with the ROS data infrastructure enables operational integrality and automation of the organization.

IV. THEORY EXAMINATION

The theory examination comprises translation of the model into a programmed repair process design generator and theory quantification by verification and validation of the model. Verification is obtained by analysing and evaluating the elementary behaviour and functionality of the model and validation by a case study.

A. Repair process design generator

The repair process design generator functionalizes the proposed multi-layer return quality control model to facilitate the verification and validation of the model. The generator comprises four of the five layers of the multi-layer return quality control model and scenario testing. The process innovation strategy layer and supply chain integration proposal are excluded. The four layers are divided in two primary and two facilitating generator components. The return quality controller of layer one and the upscale strategy of layer three form the primary components and the process maturation classification and machine capacity arrangement the facilitating. The amount of repair actions quality quantification and thus bandwidth relation between the primary components is used in the model as that quantification suits the research field conditions. A scenario testing component is added to define a process flow division based on controller limits and test the sufficiency of the upscale strategy. Figure 3 illustrates the translation of the multi-layer return quality control model of Figure 1 into the generator basis.

B. Model verification

Verification is obtained by elementary behaviour and functionality analysis using theoretical parameter adjustments. The data sets for the return quality controller and scenario testing component are artificially generated to extend the range of model behaviour and circumvent inaccurate KLM data. The verification is divided in verification of the return quality controller, flow division and upscale strategy followed by a functionality evaluation.

Figure 4 illustrates the elementary behaviour of the return quality controller limit calculation as function of data set variance and range.

The variance and range of the historical data set have a positive exponential and linear influence on the return quality controller limit calculation respectively. Observation is the need for data set clustering or application of a scaling factor in the limit calculation for high variance data sets to obtain adequate limits below the data set upper boundary (dotted lines). The scaling factor can only be determined case specific. The SPC or pre-control warning limit has a similar response but with less difference from the data set average. The pre-control control limit has a similar response, but with increased deviation from the data set average.

Figure 5 and Figure 6 illustrate the elementary behaviour of the flow division and variance of the process as function of limit tightening.
Limit tightening results in linear reduction of the basis flow (below warning limit), parabolic increase and decrease of the warning flow (between warning and control limit), linear increase of the bypass flow (above control limit) and reduction of return quality variance. Maintaining 100% basis flow for the 29% variance data set for scaling factor interval 1-0.7 corresponds to limits above the data set upper boundary as illustrated in Figure 4. The parabolic behaviour of the warning flow aligns with limit ratio reduction as consequence of the limit calculation procedures. For high variance data sets a faster and larger reduction in variance can be achieved by limit application. Yet, variance reduction goes at the expense of the percentage basis flow. The appropriate consideration of these parameters depends on the business strategy.

Figure 7 and Figure 8 illustrate the elementary behaviour and sufficiency of the upscale strategy calculation as function of limit tightening.

C. Model validation

Validation is obtained by a case study that compares the model outcome to the current state of a KLM E&M ES repair process. For this purpose the 80C & 80E fan mid shaft repair process is elected.

Figure 9 illustrates the SPC limits of the return quality controller based on the historical data set comprising the total amount of repair actions of completed orders.

Limit tightening reduces the total required upscales and allows more quantity in process. This aligns with the calculation that is based on the defined bandwidth. Besides that, limit tightening has an either positive or negative influence on the allowable process stochastic depending on the process variance. The differences remain small, which implies that the upscale calculation is properly based on the controller bandwidth. As last, the upscale strategy for high variance processes allows more waiting time. This aligns with the intention to incorporate additional processing leeway in the case of a high variance process.

The functionality of the multi-layer return quality control model is verified with a remark for high variance processes. These processes need data clustering or limit scaling factor application. The functionality of the machine capacity arrangement determination, implementation of innovation strategy and supply chain integration proposal is declared with reservation as these procedures remain limited to generator component input and theory.
The control limit is calculated beyond the data set upper boundary. Following the verification findings a scaling factor of 0.7 is applied in the limit calculation resulting in the limits and flow division as depicted in Table I.

<table>
<thead>
<tr>
<th>Control Limit</th>
<th>Warning Limit</th>
<th>Basis Flow</th>
<th>Warning Flow</th>
<th>Bypass Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>69</td>
<td>74%</td>
<td>16%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Based on the bandwidth defined by the controller and operational process parameters the upscale strategy calculation resulted in the outcome of Figure 10.

Figure 10. Upscale strategy for linear market scenario

The actual case average output flow is twice the calculated flow, but the current actual process TAT is also twice the contractual TAT used in the calculation. Besides that, two of the three calculated bottlenecks are identified as bottlenecks in the real process. As last, the calculated amount of net required FTEs aligns with the fan mid shaft team of KLM E&M ES. These alignments validate the model in comparison to the actual state of the 80C & 80E fan mid shaft repair process. Validation of the calculated future states is attainable, but over time as those states do not yet exist in the real system.

V. THEORY COMPLETION

The theory completion comprises the research conclusion, recommendations and discussion.

A. Conclusion

As method for sustainable initial repair process design a multi-layer return quality control model is proposed. This model enables control of identified criteria that influence sustainable initial repair process design. The first layer concerns definition of a process basis with a return quality controller to establish return quality control limits. The applicable control theory for these limits is based on process maturation classification determined in layer two. The limits define a process input bandwidth that enables calculation of an upscale strategy for process future expansion in layer three. This upscale strategy is combined with a machine capacity arrangement strategy and systematic process innovation strategy in layer four and five respectively. Last part of the model is integration of the model output in the supply chain. This integration is facilitated by a combination of an IDEF-based swimlane and VSM diagram with a ROS-based data infrastructure.

B. Recommendations

It is recommended to reflect the model on a wider range of remanufacturing industry fields, extend the application range towards the manufacturing industry and enhance its utility substantiation by keeping track of its application result over time. Furthermore, it is recommended to extend research on the return quality controller, the included parameter range of the upscale strategy and the systematic approach for Industry 4.0 implementation proposed in this research.

C. Discussion

The KLM data are not completely reliable. Data processing enhanced accuracy, but 100% reliable data is not attainable. The generator has three limitations. Variance reduction of the generated data sets results in exclusion of outliers. Data sets are generated with about equal amount of samples on both sides of the data set average. The generator includes a rounding error for iterative upscale strategy calculations. These limitations introduce deviations from reality in absolute results, but do not influence the verification and validation.

Primary contribution of this research is the introduction of a repair process design model with front end management and control from a return quality perspective. It contributes to the perception to direct research towards sustainable and automated process design with a problem prevention rather than recover mind set. Thereby, the model relates return quality to the operational process, a relation, to the author’s knowledge, not yet addressed in previous research. A secondary contribution is the systematic implementation approach that simplifies the implementation of the broad concept of Industry 4.0. The standardized visual process integration tools with an advanced data infrastructure facilitates this approach. Besides that, the advanced data infrastructure provides a data exchange structure suitable as foundation for research in paperless production facilities.

ACKNOWLEDGMENTS

I wish to express my gratitude to my direct supervisor W.W.A. Beelaerts van Blokland and to my graduation committee chair D.L. Schott for the cooperation, research directions, suggestions and challenging discussions.


Company Profile

This research is conducted in corporation with KLM E&M at the Engine Services division. This appendix provides an organizational overview with background information of the organization KLM and KLM E&M.

The Koninklijke Luchtvaart Maatschappij (KLM) was founded in 1919 with aviation pioneer Albert Plesman as administrator and first director. In 1920 the first scheduled flight between Amsterdam and London took place. In 2004 KLM merged with Air France to the Air-France KLM (AFKLM) Group. This resulted in an operational expansion from 345 passengers and 25,000 kilos airfreight for KLM that first year [41] to currently over 100 million passengers and 1.1 million tonnes cargo for the AFKLM Group [2].

Air-France KLM Group
Air-France and KLM merged to maintain a competitive global position with an expanded network and aircraft fleet. Currently, the combination is the leading group in intercontinental departures from Europe and a major global competitor in airfreight transport [2]. Together the group owned 548 aircraft and served 348 destinations in 118 different countries in 2018 [2]. As additional benefit of the fusion KLM joined the Skyteam alliance, one of the three worldwide airline alliances. The key businesses of the group are passenger transport, cargo transport and engineering and maintenance. For the engineering and maintenance business the divisions of both airlines, KLM E&M and AFI, joined forces.

KLM Engineering & Maintenance
KLM E&M together with Air-France Industries provides MRO for the internal fleet of AFKLM Group as well as for external clients. In 2017 the combination served 200 international customers and supported nearly 2000 aircraft with 600,000 parts in stock and a combined workforce of 14,000 employees [1]. The KLM E&M part of the group consists of three primary divisions: Airframe, Component Services and Engine Services. This research is conducted at the Engine Services division.

Airframe
Airframe takes care of line and base maintenance of aircraft and fleet management support for AFKLM as well as external customers. A wide range of capabilities and detailed insight obtained over the years due to the combination of an airline with MRO department resulted in an established global market position. Currently, the facility in Amsterdam facilitates the following airframe maintenance operations:

- Light maintenance - A to C checks
- Heavy maintenance - C and D checks
- Aircraft on ground support
- Airframe maintenance engineering
- Cabin and avionics modifications
Component Services
Components at KLM E&M comprise rotables, repairables or expendables of an extensive range of aircraft families. Beside repair and overhaul of components, logistics, warranty management, pooling, loan & lease, procurement and financing, up to the development of ad hoc solutions are services offered in the component market [1]. The component services division at KLM E&M is currently under operational revision to adapt to a more dynamic and technically advanced facility. Under the project name CS 2.0 technological developments are tested and implemented to improve the logistics and capabilities. In this way it is attempted to maintain a leading global market position.

Engine Services
With over 80 years combined experience with AFI in the engine MRO market broad capabilities have been developed on General Electric (GE) and CFMI engines. Continuous expansion and exchange of knowledge is used to keep up with the engine evolution. The main businesses of the engine division are engine availability, parts & accessories repair and engine MRO. Engine availability relates to an engine spare pool from which engines can be exchanged during service. Parts repair comprises repairs of singular engine parts send in by Air-France or KLM or external customers. For engine MRO services are offered from basic engine inspection to complete engine overhaul for Air-France or KLM as well as external customers. Additional services offered by AFI and KLM E&M with respect to aircraft engines are engine performance monitoring and in-shop engineering. Both services aim to advance the operations on technical level. The engine shop in Amsterdam is currently presented by the AFKLM Group as state-of-the-art with sophisticated and advanced equipment.
This appendix shows an overview of the processes of KLM E&M ES in Figure C.1 as defined by P. Meijs [53]. This research is scoped to the stage 2 repair process, which is part of the 'provide engine MRO' division.

Figure C.1: Overview of KLM E&M ES processes [53]
This appendix shows the current development strategy of KLM E&M ES in Figure D.1. The strategy consists of six phases that result in a repair process design and implementation. It is noticed that no sustainability plan is available on operational level in this strategy. This substantiates the identified inadequacy of research in sustainable initial repair process design.

Figure D.1: Repair process development strategy of KLM E&M ES
Regression Analysis
Repair Data

This appendix shows regression analyses of repairs at KLM E&M ES to support the statement that increased amount of repair actions relates to increased process duration and duration variation. Figure E.1 shows the regression analysis of amount of repair actions and process duration of all KLM E&M ES SAP repair data of 2018 with a $r^2$ of 0.58 for a sample size of 10,331 repairs. Figure E.2 to Figure E.7 show the same analysis on a case specific detail level. Figure E.8 shows a repair case regression that does not support the statement. This specific repair process has a sign out procedure of a combined package of tasks which is presented in the data as one repair action. Therefore, the total duration of those combined tasks is extensive with respect to the other singular signed out repair actions. Compared to other repairs with conventional singular task sign out it is stated that this repair does not represent a common scenario. Figure E.9 shows the regression analysis of the relation between the amount of repairs and the standard deviation of the total duration of the in detail analysed repairs. This analysis shows a positive correlation between the amount of repairs and standard deviation of the total process time. Besides the regression analysis, the included histograms show the division of total amount of repair actions to obtain insight for definition of the generator input. Lastly, Table E.1 shows the standard deviation of the amount of repair actions with respect to the data set range of 15 KLM E&M ES repair processes, which functioned as basis for the limit calculation factor 1.25 described in section 4.2.
Figure E.2: Heat shield repair

Figure E.3: Case LPT repair

Figure E.4: Core spinner front repair

Figure E.5: LPT major module repair
Figure E.6: Compressor rear frame assembly repair

Figure E.7: Mount AFT assembly repair

Figure E.8: AGB springloaded seal set repair
Figure E.9: Amount of repair actions vs standard deviation total repair process duration

Table E.1 Amount of repair actions standard deviation (STD) of repair process cases

<table>
<thead>
<tr>
<th>Repair case</th>
<th>Range amount of repair actions</th>
<th>STD amount of repair actions</th>
<th>Relative STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Shield Assembly</td>
<td>31</td>
<td>8</td>
<td>26%</td>
</tr>
<tr>
<td>Case LPT</td>
<td>68</td>
<td>19</td>
<td>28%</td>
</tr>
<tr>
<td>Combustor Chamber</td>
<td>143</td>
<td>33</td>
<td>23%</td>
</tr>
<tr>
<td>Core Spinner Front</td>
<td>25</td>
<td>4</td>
<td>16%</td>
</tr>
<tr>
<td>LPT Major Module</td>
<td>70</td>
<td>11</td>
<td>16%</td>
</tr>
<tr>
<td>QEC Power Plant</td>
<td>22</td>
<td>4</td>
<td>18%</td>
</tr>
<tr>
<td>HPT Stage 2 Nozzle</td>
<td>26</td>
<td>4</td>
<td>15%</td>
</tr>
<tr>
<td>Housing TRF</td>
<td>44</td>
<td>14</td>
<td>32%</td>
</tr>
<tr>
<td>Rear Frame Assembly</td>
<td>88</td>
<td>14</td>
<td>16%</td>
</tr>
<tr>
<td>Springloaded Seals</td>
<td>5</td>
<td>2</td>
<td>40%</td>
</tr>
<tr>
<td>Dome Combustor Chamber</td>
<td>58</td>
<td>18</td>
<td>31%</td>
</tr>
<tr>
<td>Fan Rotor Assembly</td>
<td>24</td>
<td>4</td>
<td>17%</td>
</tr>
<tr>
<td>Mount AFT Assembly</td>
<td>16</td>
<td>3</td>
<td>19%</td>
</tr>
<tr>
<td>Mount FWD Assy</td>
<td>25</td>
<td>6</td>
<td>24%</td>
</tr>
<tr>
<td>Power Plant</td>
<td>22</td>
<td>4</td>
<td>18%</td>
</tr>
<tr>
<td>HPT Rotor Shaft Front</td>
<td>51</td>
<td>12</td>
<td>24%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>23%</strong></td>
</tr>
</tbody>
</table>
This appendix shows the layers of the multi-layer return quality control model in chapter 4. Figure F.1 to Figure F.5 show each layer separately.

Figure F.1: Model layer 1
Process Maturation Classification

- Measurement Feature - Layer 1
  - Historical Data Available
    - Yes
      - Determine Required Cov
      - Determine Constant
      - Determine n
      - Historical Data Sample Size > n
        - Yes
          - Class II: Mature Process
        - No
          - Class II: Immature Process
    - No
      - Class I: New Process

Figure F.2: Model layer 2

Upscale Strategy

- Determine Required Machines
- Determine T_m (set Machine and Set Q)
  - Determine T_hi as Function of Q
  - Machine with T_high = T_hi
    - Yes
    - Increment Q
    - No
- Determine Action for Capacity Expansion
  - Maximum Market Potential Reached
    - Yes
    - Define Q-based Scalability Approach
    - Define Scalability Time Based Action Plan
  - No

Figure F.3: Model layer 3
Figure F.4: Model layer 4

Figure F.5: Model layer 5
This appendix shows the developed repair process design generator interface in relation to the defined IDEF0 generator basis. Using the interface the established design method is evaluated and the output visualized. Based on this visualization additional insight is provided in the translation of the design method into the generator on the basis of the IDEF0 model. Figure G.1 shows the return quality controller interface, Figure G.2 the upscale strategy interface and Figure G.3 the scenario testing interface. The three interfaces combined can be considered as first preliminary sustainable repair process design generator tool.

Figure G.1: Return quality controller generator interface
Figure G.2: Upscale strategy generator interface

Figure G.3: Scenario testing generator interface
This appendix shows the output of the generator as described in chapter 5, which approaches the output of the developed design method model. The values displayed in appendix G are used to generate this output. A secondary sample size of 50 is used to generate a pre-control chart. Figure H.1 and Figure H.2 show the pre-control and SPC output charts respectively. Figure H.3 to Figure H.7 show the output of the upscale strategy for a linear and exponential market demand. As last, Figure H.8 and Figure H.9 show the output of the scenario testing with an upscale strategy sufficiency comparison and flow division.

![Pre-control Limit Graph](image1.png)

Figure H.1: Pre-control chart

![Moving Range Limit Product Feature](image2.png)

![Individual Control Limit Product Feature](image3.png)

Figure H.2: Shewhart individual measurement charts
Figure H.3: Upscale strategy basis graph

Figure H.4: Linear market demand upscale strategy

Figure H.5: Exponential market demand upscale strategy
Figure H.6: Machine specific upscale actions graph

Figure H.7: Machine specific upscale actions vs time graph

Figure H.8: Upscale strategy scenario testing graph

Figure H.9: Flow division depiction
I Model Verification

This appendix shows additional data descriptions and graphs that support the verification in chapter 6.

I.1 Return quality controller verification

Figure I.1 shows six examples of generated data sets with reducing variance. Figure I.2 shows the application of a scaling factor. Figure I.3 shows the reduction in fluctuations for smaller range data sets.

![Generated data sets with reducing variance](image)

Figure I.1: Generated data sets with reducing variance
I.2 Process flow division verification

Figure I.4 and Figure I.5 show the behaviour of the flow division as function of the limit scaling factor for a return quality controller input data set and scenario testing data set with similar variance for the range 5-75 and 30-50 respectively. Figure I.6 shows the reduction of variance of a filtered scenario testing data set with application of the control limit. Table I.1 shows the relation of the limit scaling factor with respect to the warning and control limit difference from the data set average as percentage of the average. It also shows that the ratio between the limits reduces, which means that the absolute difference between both reduces. Figure I.7 shows the distributions of the used data sets for flow division.
I.2. Process flow division verification

Figure I.5: Flow division vs limit scaling factor 30-50 range

Figure I.6: Variance reduction by application of the control limits

Table I.1 Limit scaling factor with respect to limit from average difference and limit ratio; 5-75 data set range

<table>
<thead>
<tr>
<th>Limit Factor</th>
<th>Scaling Factor</th>
<th>WL difference from average [%]</th>
<th>CL difference from average [%]</th>
<th>Ratio WL and CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>118</td>
<td>175</td>
<td></td>
<td>1.26</td>
</tr>
<tr>
<td>0.9</td>
<td>105</td>
<td>158</td>
<td></td>
<td>1.26</td>
</tr>
<tr>
<td>0.8</td>
<td>93</td>
<td>140</td>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td>0.7</td>
<td>83</td>
<td>123</td>
<td></td>
<td>1.22</td>
</tr>
<tr>
<td>0.6</td>
<td>70</td>
<td>105</td>
<td></td>
<td>1.21</td>
</tr>
<tr>
<td>0.5</td>
<td>58</td>
<td>88</td>
<td></td>
<td>1.19</td>
</tr>
<tr>
<td>0.4</td>
<td>48</td>
<td>70</td>
<td></td>
<td>1.15</td>
</tr>
<tr>
<td>0.3</td>
<td>35</td>
<td>53</td>
<td></td>
<td>1.13</td>
</tr>
<tr>
<td>0.2</td>
<td>23</td>
<td>35</td>
<td></td>
<td>1.10</td>
</tr>
<tr>
<td>0.1</td>
<td>13</td>
<td>18</td>
<td></td>
<td>1.04</td>
</tr>
</tbody>
</table>
Figure I.7: Data set histograms for flow division calculation

- RQC input variance = 29.2%
- Scenario input = 29.3%
- Range 75-5

- RQC input variance = 6.1%
- Scenario input = 6.1%
- Range 75-5

- RQC input variance = 30.0%
- Scenario input = 29.9%
- Range 30-50
I.3 Upscale strategy verification

Figure I.8 shows the practical parameters used for the upscale strategy calculation as function of the limit tightness. Figure I.9 shows the influence of the bandwidth calculation value reduction for a low variance data set.

Figure I.8: Scenario for calculated upscales as function of limit tightness

Figure I.9: Influence of different bandwidth values for low variance data set
Model Validation

Table J.1 to Table J.3 show the practical input data used for application of the model on the 80E and 80C shaft repair process. These tables relate to the interface input fields shown in Figure G.2. Figure J.1 shows the linear and exponential market demand scenarios. Figure J.2 shows the output of 80C and 80E shafts per week for the SAP data set from 2016 till 2018. As last, the data processing steps to attain more reasonable data are described. In addition, Table J.4 shows the outlying orders removed from the 80C & 80E data set.

**Table J.1 Machine data 80C & 80E fan mid shaft repair process**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Processing time per quantity [min]</th>
<th>Average amount of repair actions per quantity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Painting</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td>Grinding</td>
<td>90</td>
<td>7</td>
</tr>
<tr>
<td>Masking</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Shotpeening</td>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>HVOF Spraying</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>Oven</td>
<td>40</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table J.2 Operational Data 80C & 80E fan mid shaft repair process**

<table>
<thead>
<tr>
<th>Operational Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working days per week</td>
<td>5</td>
</tr>
<tr>
<td>Shifts per day</td>
<td>2</td>
</tr>
<tr>
<td>Effective hours work per shift</td>
<td>5.1 (Standard KLM E&amp;M calculation value)</td>
</tr>
<tr>
<td>Scheduled maintenance per week</td>
<td>5%</td>
</tr>
<tr>
<td>Allowable machine capacity utilization</td>
<td>70%</td>
</tr>
<tr>
<td>Practical process time</td>
<td>2907 minutes per week</td>
</tr>
<tr>
<td>FTE capacity</td>
<td>1530 minutes per week</td>
</tr>
</tbody>
</table>

**Table J.3 Machine occupation data 80C & 80E fan mid shaft repair process**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Occupation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Painting</td>
<td>85%</td>
</tr>
<tr>
<td>Grinding</td>
<td>62%</td>
</tr>
<tr>
<td>Masking</td>
<td>80%</td>
</tr>
<tr>
<td>Shotpeening</td>
<td>65%</td>
</tr>
<tr>
<td>HVOF spraying</td>
<td>25%</td>
</tr>
<tr>
<td>Oven</td>
<td>52%</td>
</tr>
</tbody>
</table>
Data processing operations

- Operation duration of less than 5 minutes filtered.
- For machine occupation calculation duration outliers are replaced by duration provided by mechanics.
- For machine occupation calculation duplicate logged operations are removed. Removal carried out if finish date, duration, operation number, operation description and operator are the same.
- Removal of 80C & 80E abnormal service orders. Removed service orders and reason for removal outlined in Table J.4

Table J.4 Removed 80C & 80E service orders

<table>
<thead>
<tr>
<th>Service Order</th>
<th>Repair Operations</th>
<th>Reason for deviation and removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>42477002</td>
<td>169</td>
<td>GEnx shaft instead of 80E/80C</td>
</tr>
<tr>
<td>42485512</td>
<td>169</td>
<td>GEnx shaft instead of 80E/80C</td>
</tr>
<tr>
<td>42494173</td>
<td>144</td>
<td>GEnx shaft instead of 80E/80C</td>
</tr>
<tr>
<td>42502131</td>
<td>101</td>
<td>Extensive rework</td>
</tr>
<tr>
<td>42541788</td>
<td>110</td>
<td>Extensive rework</td>
</tr>
<tr>
<td>42551557</td>
<td>109</td>
<td>Extensive rework</td>
</tr>
<tr>
<td>42396612</td>
<td>1</td>
<td>No work scope after inspection</td>
</tr>
<tr>
<td>42501183</td>
<td>2</td>
<td>Only simple ring replacement</td>
</tr>
</tbody>
</table>