Guidelines for the implementation of Lean and MTM techniques in remanufacturing factory planning

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Preface

This thesis is the result of my work as scientific assistant (TUB) and instructor for the course Methods-Time-Measurement (MTM) at the Berlin Institute of Technology from 2012 to 2017. This work originated from the research project “Networking for small and medium-sized companies for competitive remanufacturing” from the Brazilian German Research Initiative in Manufacturing (BRAGECRIM) [BRA-15]. From 2015 onwards, my responsibilities include the development of the Global Production and Engineering (GPE) master study program of the Vietnamese-German University (VGU) in Ho-Chi-Minh city in Vietnam. Along these five years, I have been advising numerous project-oriented student teams, bachelor and master theses for selected cases in remanufacturing-oriented factory planning.

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Summary

Rising global consumption of limited non-renewable resources urgently calls for change in production paradigms [Dob-11, Leo-11, Sel-10]. One possible path to answer growing demand without a proportional use of resources is an appropriate management of used products after their respective usage phases [EMF-14, Sel-05]. Among known production strategies, remanufacturing gained momentum as the most promising for keeping value encapsulated in products after original production [Lun-10, Ste-98, Sut-08]. It is an industrial process consisting in the identification, disassembly, cleaning, testing, reconditioning and reassembly of used products, replacing only defective or worn components, to retrieve at least the same characteristics, requirements and warranty as new products [APR-16, Ayr-97, BSI-09, Ste-06, Sun-04]. Until recent times, lack of recognition and identification across industries limited remanufacturing growth to a comparatively limited number of products [U.S-12].

Despite its advantages, remanufacturing must handle specific uncertainty factors influencing operations management. Such problematics as the distribution and variance in forecasting the amount of end of life (EOL) products serving as raw material in the remanufacturing facility complicate production planning and scheduling [Öst-08b, Mat-16]. Shifting quantity, quality of EOL products and variability of products types leads to uncertainties in material matching and inventory management [Gui-03, Öst-08a]. Education is a powerful but untapped lever to release the potential for remanufacturing to mainstream [Fer-03, Ham-98]. Guidelines can help to structure learning and engineer solutions to handle remanufacturing complexity.

A guideline for exploiting Lean and Methods-Time Measurement (MTM) methods in remanufacturing production planning is proposed. Lean management is globally recognized and allows a portfolio of individual methods for continuous improvement in production systems. In complement, MTM offers a standard for work methods and workstation design and allows application before the Start of Production (SOP). The approach integrates elements from strategic, tactical and operational levels. First, the business model of the company determines the timing, quality and quantity of used product returns based on new product sales data, the network of companies involved and the location of markets. Quality requirements define process steps, for which MTM analyses per product variant are realized. Operations are grouped in workstations and the process economics checked to allow a common factory layout for different product types. Layout flexibility is organized to match forecasts of used product returns and of remanufactured products sales. Economic feasibility is computed for average, best and worst simulated system performance. Results are detailed scenarios demonstrating the effects of remanufacturing factory planning strategies on a given time period. Prototypical application is tested as a project-oriented course for Master students in Industrial Engineering based on virtual case studies describing potential remanufacturing development in Vietnam.

Zusammenfassung

Der zunehmende globale Verbrauch begrenzter, nicht erneuerbarer Ressourcen erfordert dringend den Wandel der Produktionsparadigmen [Dob-11, Leo-11, Sel-10]. Eine mögliche Vorgehensweise zur Bedienung der wachsenden Nachfrage ohne proportionale Zunahme des Ressourcenverbrauchs ist ein Management von Altprodukten entsprechend ihrer jeweiligen Nutzungsphase [EMF-14, Sel-05,]. Die Refabrikation/Remanufacturing ist eine Produktionsstrategie, um die akkumulierte Wertschöpfung der Erstproduktion im Wert der Produkte zu erhalten [Lun-10, Ste-98, Sut-08]. Es handelt sich um einen industriellen Prozess, der aus Identifizierung, Demontage, Reinigung, Prüfung, Wiederherstellung und Wiedermontage von gebrauchten Produkten besteht und defekte oder verschlissene Komponenten ersetzt. Am Ende der Refabrikation sollen mindestens die gleichen Eigenschaften, Anforderungen und Garantieleistungen wie bei neuen Produkten erreicht werden [APR-16, Ayr-97, BSI-09, Ste-06, Sun-04]. Bis heute fehlt es an Wertschätzung der Refabrikation über viele Branchen hinweg, was die Anwendung stark beschränkt [U.S-12].

Erfolgreiche Refabrikation muss spezifische Unsicherheitsfaktoren bewältigen, die die Betriebsführung beeinflussen. Die Verteilung und Abweichung bei der Prognose der Menge an Altprodukten, die als Rohstoff in der Refabrikationsanlage dienen, erschweren die Produktionsplanung und Steuerung [Öst-08b, Mat-16]. Die sich ändernde Anzahl an Altprodukten bei einer hohen Variantenvielfalt sowie deren unterschiedliche Qualität führen zu Unsicherheiten bei der Materialabstimmung und Bestandsführung [Gui-03, Öst-08a]. Eine entsprechend ausgerichtete Ingenieurausbildung wäre ein wesentlicher und bisher wenig erschlossener Hebel, um das Potenzial der Refabrikation als Standard zu realisieren [Ham-98, Fer-03]. Leitlinien können dazu beitragen, das Lernen zu strukturieren und Lösungen zu entwickeln, um die Komplexität der Refabrikation zu bewältigen.

Es wird ein Leitfaden für die Implementierung von Lean und Methods-Time Measurement (MTM) bei der Produktionsplanung der Refabrikation vorgeschlagen. Lean Management ist weltweit anerkannt und stellt ein Portfolio von individuellen Methoden zur kontinuierlichen Verbesserung von Produktionssystemen bereit. In Ergänzung bietet MTM einen Standard für Arbeitsmethoden und Workstation-Design und erlaubt die Anwendung vor dem Start der Produktion (SOP). Der Ansatz integriert Elemente aus strategischen, taktischen und operativen Ebenen. Zuerst bestimmt das Geschäftsmodell des Unternehmens das Timing, die Qualität und die Menge der verwendeten Produktrückläufe auf der Grundlage neuer Produktverkäufe, des Netzes der beteiligten Unternehmen und der Lage der Märkte. Qualitätsanforderungen definieren Prozessschritte, für die MTM-Analysen je Produktvariante durchgeführt werden. Den Operationen werden Arbeitsplätze zugewiesen und die Prozessökonomie überprüft, um ein gemeinsames Fabriklayout für unterschiedliche

Produkttypen bereitzustellen. Ein flexibles Fabriklayout erlaubt, die prognostizierten Altproduktrücksendungen und die Verkäufe von refabrikierten Produkte anzupassen. Die wirtschaftliche Machbarkeit wird für die durchschnittliche, beste und schlechteste simulierte Systemleistung beurteilt. Ergebnisse sind detallierte Szenarien, die die Auswirkungen der ausgewahlten Strategien in der Produktionsplanung der Refabrikation innerhalb einer bestimmten Zeitperiode darstellen. Die prototypische Anwendung wird als projektorientierter Kurs für Masterstudierende im Bereich Industrial Engineering auf der Grundlage von virtuellen Fallstudien zur potenziellen Entwicklung der Refabrikationsindustrie in Vietnam getestet.

Résumé

La hausse de la consommation mondiale de ressources non renouvelables limitées nécessite d'urgence un changement dans les paradigmes de production [Dob-11, Leo-11, Sel-10]. Une manière possible pour répondre à une demande croissante sans impliquer une utilisation proportionnelle de ressources est une gestion appropriée des produits usagés après leurs phases d'utilisation respectives [EMF-14, Sel-05]. Parmi les stratégies de production connues, la refabrication est reconnue comme la plus prometteuse pour maintenir la valeur contenue dans les produits après leur production originale [Lun-10, Ste-98, Sut-08]. Il s'agit d'un processus industriel consistant à identifier, démonter, nettoyer, tester, reconditionner et remonter les produits usagés, en remplaçant uniquement les composants défectueux ou usés, afin d'assurer au moins les mêmes caractéristiques, exigences et garantie que pour les nouveaux produits [APR-16, Ayr-97, BSI-09, Ste-06, Sun-04]. Jusqu'à ce jour, le manque de reconnaissance et d'identification interindustrielle propre à la refabrication a limité sa croissance à un nombre comparativement limité de produits [U.S-12].

Malgré ses avantages, la refabrication doit gérer des facteurs d'incertitude spécifiques influençant la gestion des opérations. Des problèmes comme la distribution et la variance dans la prévision des retours de produits usagés, qui servent de matière première dans l'installation de refabrication, compliquent la planification et l'ordonnancement de la production [Öst-08b, Mat-16]. Des fluctuations dans la quantité, la qualité de produits usagés et la variabilité des modèles entraînent des incertitudes dans la gestion des matériaux et des stocks [Gui-03, Öst-08a]. L'éducation est un levier puissant mais peu exploité pour libérer au maximum le potentiel de la refabrication [Fer-03, Ham-98]. Des lignes directrices peuvent aider à structurer les procédés d'apprentissage et à générer des solutions pour gérer la complexité de la refabrication.

Une ligne directrice pour exploiter les méthodes Lean et Methods-Time Measurement (MTM) dans la planification de la production de refabrication est proposée. La gestion Lean est globalement reconnue et propose un portefeuille de méthodes individuelles pour l'amélioration continue des systèmes de production. En complément, MTM offre une norme pour les méthodes de travail et la conception des postes de travail et permet une application avant le démarrage de la production (SOP). L'approche intègre des éléments stratégiques, tactiques et opérationnels. Tout d'abord, le modèle économique détermine la qualité et la quantité des produits utilisés en fonction des données sur les ventes de nouveaux produits sur une période donnée, du réseau d’entreprises concerné et de l'emplacement des marchés. Les exigences de qualité définissent les étapes du processus industriel, pour lesquelles les analyses MTM sont réalisées par modèle de produit. Les opérations sont regroupées par poste de travail et les résultats financiers du processus sont contrôlés pour permettre un schéma d’agencement

d'usine commun pour chaque type de produit. Ce schéma d'agencement flexible de l'usine est organisé pour faire correspondre les prévisions de retours de produits usagés et les ventes de produits refabriqués. La faisabilité économique est évaluée pour la simulation des meilleures moyennes, et pires performances du système. Les résultats sont de scénarios détaillés démontrant les conséquences de stratégies de gestion d'usine de refabrication sur une période de temps donnée. L'application prototypique est testée sous la forme d'un cours pratique pour les étudiants en Master en génie industriel basé sur des études de cas virtuelles décrivant le développement potentiel de la refabrication au Vietnam.

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ABC	ABC Analysis
ACS	Air Conditioning Systems
APRA	Automotive Parts Remanufacturers Association
ARO	Asset Recovery Operation
ATO	Assemble to Order
B2B	Business to Business
B2C	Business-to-Consumer
B2E	Business-to-Employee
B2G	Business-to-Government
BEP	Break-Even Point
BRAGECRIM	Brazilian German Research Initiative in Manufacturing
BSI	British Standards Institution
CAD	Computer-Assisted Drawing
CCH	Cylinder and Cylinder Head
CE100	Circular Economy 100
CEL	Current Event List
CLEPA	European Association of Automotive Suppliers
CLSC	Closed-Loop Supply Chains
ConWIP	Constant work in progress system
CPS	Cyber-Physical Systems
CR	Contracted remanufacturer
CRC	Collaborative Research Centre
CRR	Centre for Remanufacturing and Reuse
CSR	Corporate Social Responsibility
CT	Cycle Time
CUP	Clock Update Phase
DES	Discrete Event Simulation
DfE	Design for Environment
DfLCM	Design for Lifecycle Management
DfM	Design for Manufacturing
DfR	Design for Recycling

DfRem	Design for Remanufacturing
DfX	Design for X
DIN	German Institute for Standardization
DL	Delay List
DLBP	Disassembly Line Balancing Problem
DoE	Design of Experiments
DSL	Domain-specific simulation languages
ECMPRO	Environmentally Conscious Manufacturing and Product Recovery
ECU	European Customs Union
EEA	European Economic Area
ELV	End-Of Life Vehicles
EMF	Ellen MacArthur Foundation
EMP	Entity Movement Phase
EMS	Environmental Management System
EN	European Standard
EOL	End of Life
EPR	Extended Producer Responsibility
EU	European Union
FEL	Future Events List
FIFO	First-In, First-Out
FIRM	International Federation of Engine Remanufacturers and Rebuilders
FMCG	Fast Moving Consumer Goods
FMEA	Failure Mode and Effective Analysis
FPS	Ford Production System
FSC	Forest Stewardship Council
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GHA	Global Hectares
GNI	Gross National Income
GPE	Global Production Engineering
HDI	Human Development Index
HDOR	Heavy-Duty and Off-Road equipment
HoQ	House of Quality

IAS	International Accounting Standards
IFAA	Institut für angewandte Arbeitswissenschaft (Institute for applied work science)
IFRS	International Financial Reporting Standards
IMD	International MTM Directorate
IMVP	International Motor Vehicle Program
IR	Independent remanufacturer
ISO	International Organization for Standardization
IT	Information Technology
JIT	Just-in-Time
LCA	Lifecycle Assessment
LCC	Lifecycle Costing
LCIA	Lifecycle Impact Assessment
LCSA	Lifecycle Sustainability Assessment
M7	Seven Management and Planning Tools
MCA	Machine Capability Analysis
MDG	Millennium Development Goals
MDLR	Methodology for the Development of Lean Remanufacturing
MFA	Material Flow Analysis
MOST	Maynard Operation Sequence Technique
MTM	Methods-Time Measurement
MTO	Made-to-Order
MTS	Made-to-Stock
NVA	Non Value Added
OECD	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OER	Original Equipment Remanufacturer
OPF	One-Piece Flow
OSF	One-Set-Flow
PC	Personal Computer
PCA	Process Capability Analysis
PDCA	Plan-Do-Check-Act
PLT	Production Lead Time

PMTS	Predetermined Methods for Time Study
PPC	Production Planning and Control
PSS	Product-Service-System
PT	Process Time
Q7	Seven Quality Tools
QBTU	Quadrillion British Thermal Units
QFD	Quality Function Deployment
QM	Quality Management
R&D	Research and Development
ReOpT	Remanufacturing Opportunity Tool
RoHS	Restriction of the use of certain Hazardous Substances in electrical and electronic equipment
ROI	Return on Investment
RPN	Risk Priority Number
RSC	Reverse Supply Chains
RUI	Residual Useful Life
SAC	Chinese Standardization Authority
SAPEPR	Systematic Approach to the Planning and Execution of Product Remanufacture
SDG	Sustainable Development Goals
SLCA	Social Lifecycle Assessment
SMART	Specific Measurable Achievable Relevant and Timely
SME	Small and Medium Enterprise
SMED	Single Minute Exchange of Die
SOP	Start of Production
SPC	Statistical Process Control
SWOT	Strength Weaknesses Opportunities Threats
TDM	Time Data Management
TPS	Toyota Production System
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem Solving
TT	Takt Time
TUB	Technische Universität Berlin (Berlin Institute of Technology)

U.S.	United States of America
UML	User Managed Lists
UN	United Nations
UNDP	United Nations Development Program
USITC	United States International Trade Commission
VA	Value-Added
VDA	German Association of the Automotive Industry
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
VGU	Vietnamese-German University
VSM	Value Stream Mapping
WEEE	Waste Electrical and Electronic Equipment
WIP	Work in Progress
WP	Water Pump
5S	Sort, Set in Order, Shine, Standardize, Sustain
8D	Eight Disciplines problem solving method

1 Introduction

The evolution of global living standards with the market-driven consumption by society threatens mankind by damaging the natural environment through high levels of natural resource extraction. The need is urgent to shift to more responsible standards in the processes used to provide goods and services to people while reducing negative environmental and social impacts of human activities. This thesis focuses on the adaptation of production planning to the multiple usage phases characterizing remanufacturing for offering more functionality with less resources to ultimately achieve a higher usage productivity of resources. Based on sales figures from newly manufactured goods, guidelines are designed for engineering students to handle the complexity factors inherent to remanufacturing using strategic, tactical and operational solution elements and ensure their economic feasibility. An introduction of the current situation regarding the societal challenges in manufacturing and motivations to consider remanufacturing as an exemplary solution are presented in section 1.1. Section 1.2 details the objectives of this dissertation as a contribution to the development of remanufacturing and specifies the scope. The logical framework to accomplish the objectives is detailed in section 1.3.

1.1 Current situation and motivations

In the 20th century, the development of mass production resulted in an unprecedented increase in living standard of early industrialized countries as it provided wide access to technology. Engineers constantly improved machinery aimed at facilitating the development, production, and distribution of products to meet the needs of an increasing number of people in these countries. The mechanization of agriculture in Europe as of 1870 increased yields from crops while reducing the work required by humans and animals [Zan-91]. In the 1990s, the emergence of the Internet and of affordable and compact personal computers provided easy access to knowledge and allowed users to choose which information they would receive on demand. Technology drove the emergence of a globally connected, market-driven society, in which manufactured goods play a key role for providing products and services in adequate quality, in the right place, and at the right time. The organization of industrial activities is traditionally driven by privately owned companies holding a competitive position that enables their survival. Companies strive to innovate by choosing appropriate technologies to manufacture products able to satisfy customer needs, while generating enough profit to ensure future development and reward stakeholders for their investment in shares.

Natural resources are essential for the production of goods, as they are the raw material to be manufactured. A finite ecosystem disposes of non-renewable natural resources in finite quantities. Resource extraction is performed to the extent of the economic profitability of operations, and market adapts by adjusting resource price to balance between offer and demand. Middle-class development in emerging economies results in an increasing demand for manufactured goods, which in turn leads to an unprecedented high level in the consumption of natural resources, while the capacity of the planet to regenerate has been reached since the early 1970's [WWF-16]. The preservation of earth as a common living space becomes one of the toughest challenges for humanity in the 21st century.

The need for social improvement has been clearly expressed at the highest international level. The General Assembly of the United Nations (UN) saw resolution 55/2 accepted by all 189 members on September 8, 2000, which defined a roadmap for defining goals for social evolution worldwide, with the Millennium Development Goals (MDG). These goals target specific needs for human development by listing basic needs to be fulfilled, such as providing food, water, health, security, and education at twice the current amounts for the poorest citizens of the world by increasing their income [Uni-01]. The achievement of such goals requires an increased access to manufactured goods, which would signify a sharp increase in the natural resources needed as raw material. In 2012, in preparation for the Rio+20 summit, UN Secretary-General Ban Ki-Moon suggested a new set of long-term goals, called Sustainable Development Goals (SDG), as a flagship for leading actions for the next 15 years. The UN General Assembly voted in resolution 70/1 for the implementation of such goals for 2030, adding the goals of industrial innovation, ecosystem consideration, and responsible production and consumption to stress that environment and resource preservation is vital for human development [Uni-15a]. Therefore, the globalized manufacturing industry has the challenge to provide goods and services for improving the living standard for up to 9.7 billion of consumers by 2050 [Uni-15b], while reducing its consumption of resources and ensuring income growth. Sustainability is mainly expressed as the consideration of economic, environmental and social consequences of an human activity [Elk-97, Elk-94]. As a result, it is vital to research new paradigms that will drastically improve the resource effectiveness of manufacturing systems while reducing waste and using technology to achieve more sustainable production and consumption patterns.

A traditional paradigm for manufacturing companies is that selling of a maximum number of products in a given market is necessary for maintaining a competitive position. Before electric lighting was invented in the late nineteenth century, John D. Rockefeller made a fortune with the idea to lock in customers by distributing oil lamps for a highly reduced price, provided that the lamps would only function using Standard Oil kerosene [Yer-11]. The strategy to subsidize products to ensure recurring revenues is frequently employed and illustrates the concept of flooding a market with products for purely economic reasons. Once products are sold, they cease to be a focus of the manufacturer, which then can focus on strategies for increasing future sales. Marketing strategies are developed in a parallel fashion to ensure the medium- and long-term development of sales through multiple media. As a result, consumers are educated to focus attention solely on the consumption phase of a product and diverted from the conditions in which a product is developed, manufactured, distributed, and disposed of [Leo-11]. As natural resources are under-priced [Lov-99] and disposal of old products managed by public authorities, traditional manufacturing maximizes profits through a "take-make-dispose" linear process at an ever accelerating pace [EMF-14, Sel-10, Leo-11]. The University of United Nations established that in 2014, 41.8 million tons of electronic waste in the world represented US$52 billion of potentially reusable resources, but only 6.5 million tons were collected by official take-back systems, leaving the remaining 84,6% handled by unofficial or illegal systems. It is estimated that 5 to 10% of electronic waste are exported from European to African, Asian and South American countries without control from public authorities [Bal-15]. The resulting toxic pollution of uncontrolled waste management and material recovery processes damages the local communities' health and environment where exerted [Wil-08].

An alternative to the linear production and consumption process is suggested with the principle of circular economy by the consideration of discarded products as raw material for the manufacturing of new products [EMF-13]. The principle of circular economy encompasses several processes such as recycling, repairing, or remanufacturing products at the end of their useful life to facilitate multiple use phases and reduce environmental impacts. In early industrialized and many emerging countries, policy makers enacted laws to promote and provide financial incentives for the practice of circular processes in local industry [Kan-12]. The absolute efficiency of different circular processes contributes in varying extents to the aim of a more resource efficient production, when measuring factors such as energy intensity, value-added, or length of subsequent use phases [Lun-10].

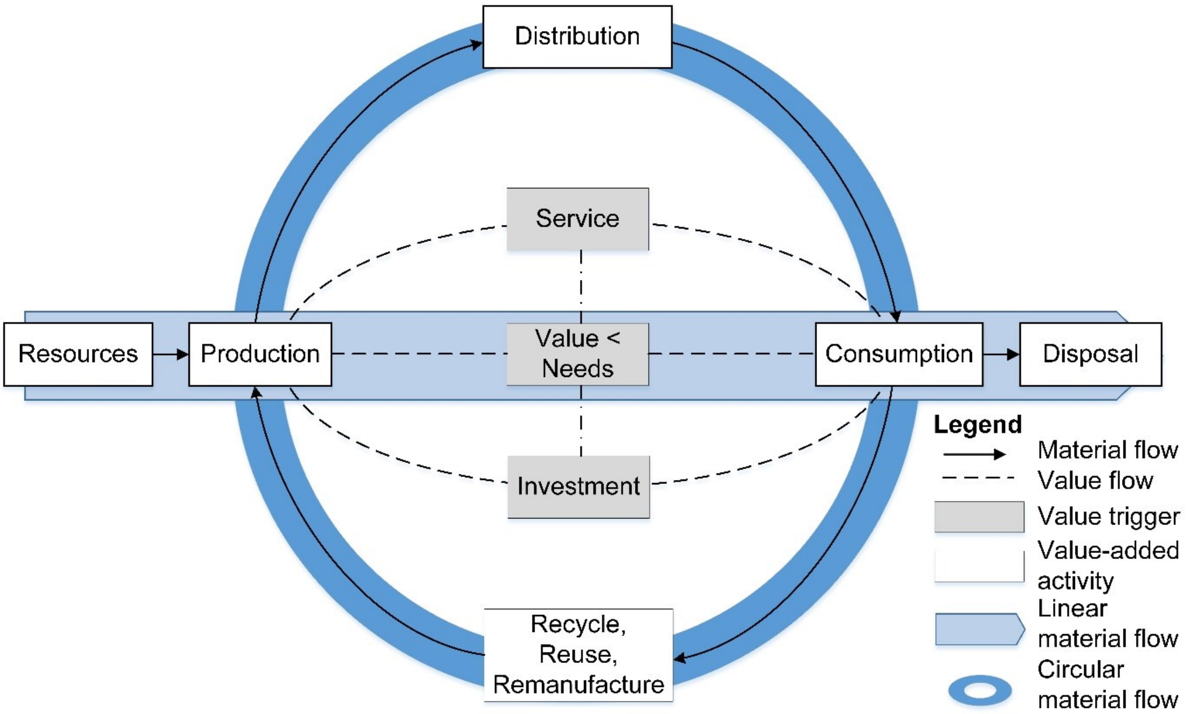


Figure 1-1: Sustainable Consumption and Production framework, adapted from [Ver-14]

Figure 1-1 shows a framework detailing advances towards a circular and sustainable production and consumption system. Recycling is a popular and widely used process for transforming used products in raw material, to substitute extraction from natural sources. However, the financial yield of recycling activities is rather low, as it requires efforts for the separation of materials, and the value of recycled materials is a fraction of the value of pure, new raw materials. As another kind of reuse strategy, repair sector is also active in many countries, as it is an efficient activity to ensure access to goods by consumers with a lower purchasing power and it generates local activity. The issue of repair processes is that the length of the additional use phase is significantly shorter and of lower quality than for a new product, including potential security issues for the user. Only a reduced warranty is offered, as repairing the product solves the failure that prevented operation of the product, without thoroughly checking other potential issues with the product. Remanufacturing offers an alternative for balancing the drawbacks from other circular processes as it targets the transformation of a discarded product in a fully functional artefact with at least the same quality and warranty as a new product [APR-12, BSI-09, Sel-07a]. At the cost of a standardized process, the old product is dismantled to enable all the potential failures of a product to be preventively tested and repaired to the specifications of a new product.

Although remanufacturing gained momentum in the last decade, with an impressive increase of 166% in dedicated scientific publications between 2009 and 2013 [Wid-14], the concept of remanufacturing was first examined in the U.S. during the financial crisis of the 1930s [Gra-07]. Remanufacturing brings a contribution to rising resource price volatility, to reduce the pressure on the environment and to offer cheaper, qualitative products to new consumer targets while supporting local qualified job creation and value creation [Pos-14]. LUND described the potential of remanufacturing as a “hidden giant” to characterize the untapped opportunity for development in the application of this process. Remanufacturing advantages for manufacturers lies in the reduction of material and energy costs, and consumers benefit from the access to quality goods and services at a lower price. But since its inception, remanufacturers remain difficult to identify, as belonging to an industrial group due to the lack of distinctive standards for their industrial processes and for lacking public representation [Lun-96]. In an effort for the international recognition of the remanufacturing process, the Chinese Standardization Authority (SAC) suggested the creation of standards for the remanufacturing of mechanical products to the International Organization for Standardization (ISO) [ISO-13], but the request was rejected by several countries for the protection of patents and intellectual property. Although a national standard emerged with the definition of remanufacturing by the British Standards Institution [BSI-09], the name of remanufacturing lacks recognition, as it competes with industry-specific terms such as refabrication, restoration, rebuilding, rethreading, recharging, overhauling, and rewinding [Gra-07]. As the interest in such a method is tied to the quality standards it ensures, its lacks of visibility for consumers hinders its expansion, and accepting the price premium for remanufacturing compared to repaired products may be difficult [Öst-08b]. A potential solution to customer acceptance of remanufactured products reside in product-service systems (PSS) in which the customer buys the product's use and the service provider retains the product ownership [Gui-14, Öst-09, Sun-08].

The consequences of business models on production planning and control (PPC) in remanufacturing operations are important as they determine requirements for the material flows to be handled. It is important to note that differences with the production of new goods are hindering an achievement of production objectives [Gui-00, Jun-12] using standard methods. Uncertainties in the frequency and quality of old product deliveries, a higher product variance and variety, and small batch sizes increase the challenges for PPC management teams to obtain better results with remanufacturing [Fer-06, Giu-03, Ham-98]. The success of Lean Production as a standard for the improvement of PPC is enacted by the extent of companies applying the principles of the “Toyota Way” in their organizations [Erl-13, Sch-13, Wom-03]. Lean Production offers a series of tools for the enhancement of both quality and productivity in production activities. The tools can be used in the context of remanufacturing in a slightly adapted form from the production planning stage, and the results can be improved with the support of a simulation tool [Dun-08]. In order to describe manual work methodologies, to ensure the highest efficiency from the start of production (SOP), and to estimate the operation time using an international standard, Methods-Time Measurement (MTM) offers an appropriate method [Bok-06, MTM-08]. MTM provides an additional level of detail in identifying waste in production processes and yields further productivity gains when used in combination with Lean Production principles [Kuh-08, MTM-08]. Both methods are regarded as a promising approach to plan, construct and improve remanufacturing process from the conceptual phase. To support the improvement of the economic process of remanufacturing operations from the planning phase and to support the evaluation of new products to be remanufactured, the following questions are addressed in this thesis:

- What step-by-step approach should be taken to create and continuously improve quality and productivity levels in remanufacturing processes using Lean and MTM?
- How should the economic feasibility of remanufacturing for new products be assessed from the production planning phase while considering strategical, tactical, and operational dimensions of production planning and control?
- How can specific remanufacturing challenges and opportunities be taught to engineering students to motivate and support future production managers to contribute to remanufacturing implementation in their future industries?

1.2 Objectives

This thesis has a two-fold objective: to contribute to the emergence of a larger remanufacturing industry by the systematization of process definition and to examine potential new product families on an ongoing basis for economic feasibility. For this purpose, a multi-product and multi-period remanufacturing activity is analysed at strategic, tactical and operational levels following pre-defined order. The first step is to define a corporate remanufacturing strategy by selecting descriptive elements of the Canvas Business Model, in order to determine the material flow and strategic influence factors. A series of tools determines which information to collect for the future process to systematically handle potential failures that can occur on a product. In the production planning phase, requirements are deduced from the material flow of the product portfolio to determine theoretical performance evaluation and economic results of a future state of a remanufacturing system by discrete-event simulation (DES). The development of the guideline is targeted to assist in the creation of a standard for collaboration in education by providing situated learning about remanufacturing systems. The need for further research in the systematic identification of products with potential to be remanufactured was identified and motivated the development of the present work. Expected results from the development of situated remanufacturing education are the intensification of remanufacturing venues as well as answering qualification needs of the current industry. Academic specialists and production managers agree about the need for a systematic approach of remanufacturing, illustrated by the works on process definition for remanufacturing from PARKINSON AND THOMPSON [Par-04]. As a result, investment for remanufacturing ventures is related to an array of average, best and worst values characterized by inherent uncertainty factors, in order to determine the potential range for return on investment.

1.3 Structure of the thesis

The elements of reflection presented in background, motivations, and objectives of this thesis are represented in the thesis structure. In chapter 2, contributions from academia, industry, and public authorities is presented to convey the state of the art on circular production and consumption systems. An overview of sustainability and its implications for manufacturing introduces the principle of multiple product usages phases, and measurement techniques are suggested. Challenges and opportunities of circular economies are presented; circular processes are listed and their contribution to resource efficiency presented. Matching the scope of the thesis, PPC and lean topics are presented and their contributions for the improvement of remanufacturing justified. Based on findings from the advances in the field, chapter 3 demonstrates the relevance of the development of a guideline for the implementation of Lean and MTM in remanufacturing by defining requirements to evaluate the integration of methods in the guideline. The methodology for the guideline development is presented in chapter 4. The methods presented in chapter 2 are first examined through an objective evaluation based on a structured set of requirements derived from chapter 3, for financial, strategic, tactical, and operational aspects. A guideline is developed to organize the remanufacturing process definition and transposed in the context of a project-based course for engineering students. Chapter 5 gives examples of application for water pumps, air conditioning systems, and motorbike cylinder and cylinder head in the economic context of Vietnam and suggests an evaluation for the guidelines. Key knowledge gains, limitations and development perspectives are summarized in Chapter 6. Figure 1-2 graphically summarizes the structure and results for each of the above-mentioned chapters.

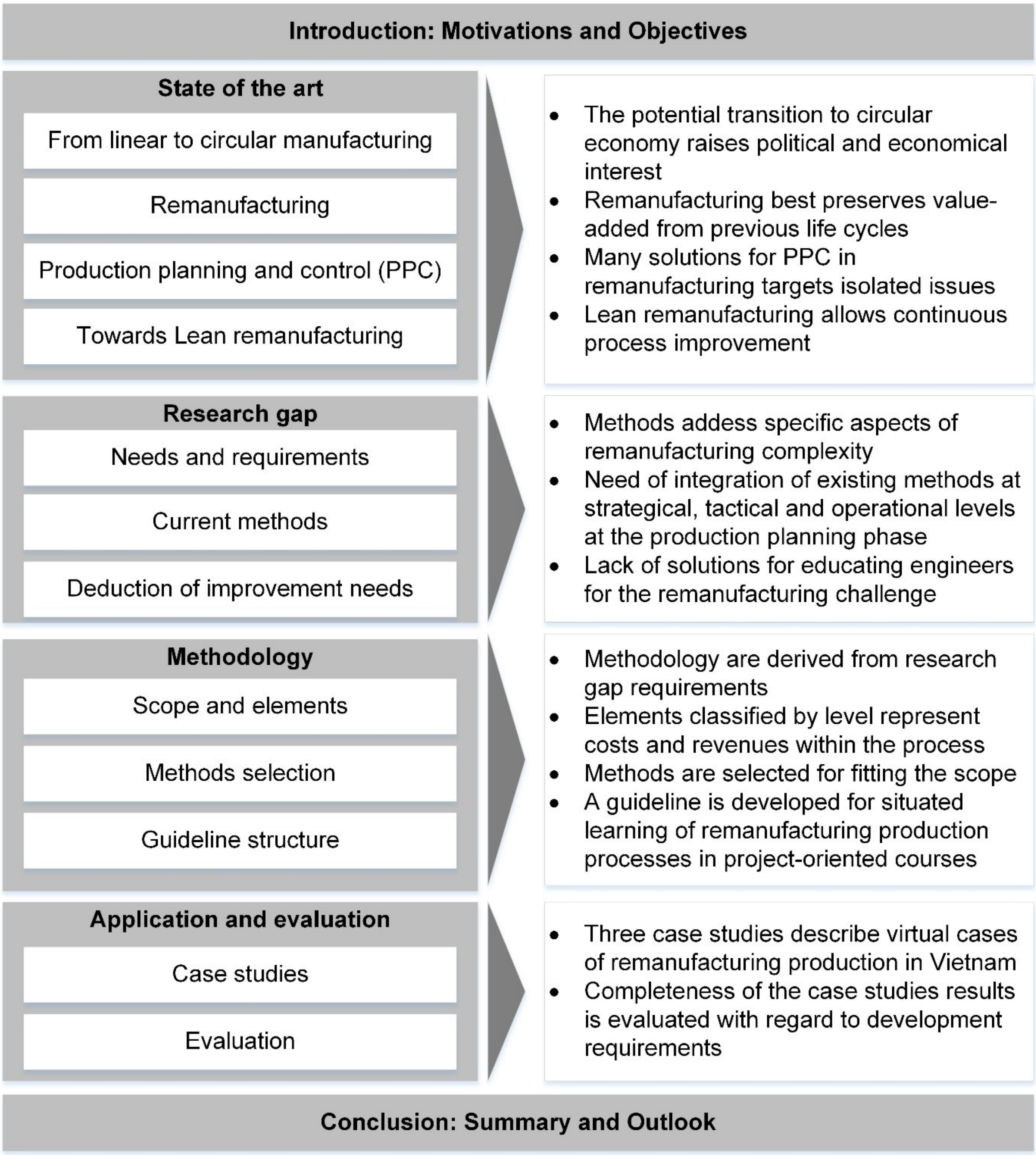


Figure 1-2: Thesis structure

2 State of the art

This chapter introduces state-of-the-art developments in remanufacturing technology by presenting the current works of authors from academic research and industry backgrounds. Section 2.1 introduces dimensions and motivations for the considerations of sustainability in the context of production activities. The concept of a circular economy is presented in a political, industrial, and academic context as an opportunity to reach the challenging sustainability objectives by designing circular loops in resources used for manufacturing activities. Further, section 2.2 defines the characteristics of remanufacturing, with a focus on end-of-life (EOL) strategy. Industrial success stories and international development are detailed, as well as the barriers and opportunities linked to its development. In section 2.3, PPC activities with a focus on time study and predetermined time systems are presented with the tools to manage remanufacturing activities. The renowned concept of Lean is then presented in section 2.4 to introduce quality and productivity management as two key success factors of remanufacturing ventures.

2.1 From linear to circular manufacturing

Manufacturing is a major contributor for wealth creation among developed countries. For instance, in 2010, amongst the 27 member states of the European Union (EU), the manufacturing sector has over 34 million employees and contributes to a total Gross Domestic Product (GDP) share of approximately 14,5% [Eur-10]. If manufacturing is undeniably a key factor in the national value creation network and is an important job provider, it is by definition a resource-intensive activity sector. Since the inception of industrial manufacturing in the 18th century, the manufacturing industry has been organized along a linear production process with strong emphasis on consumption, as illustrated in Figure 2-1.

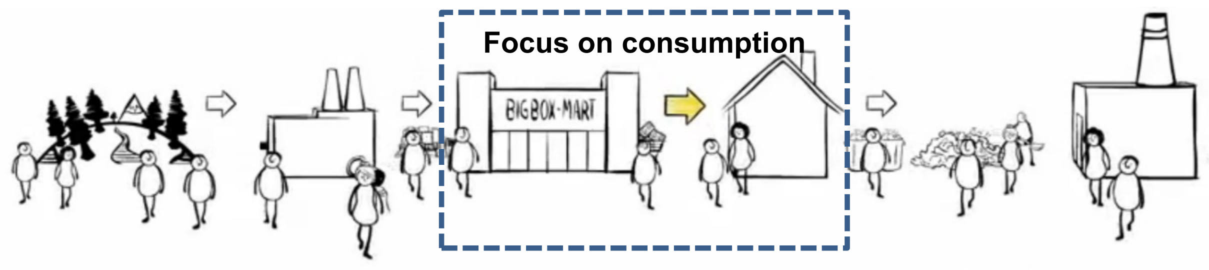


Figure 2-1: The linear material economy [Leo-11]

Natural resources are extracted to be transformed into industrial raw materials, then manufactured into products which are distributed, consumed, collected at their end of life, and finally disposed of [EMF-14]. With an expected 9 billion inhabitants by 2030, shorter product durability, and the domination of incremental innovation on new products, the stress on finite natural resources from a finite ecosystem becomes unbearable. Moreover, product design and production processes primarily focus on improving short-term profitability of operations, with little consideration of environmental or social consequences for the management of a product's EOL [Leo-11]. Therefore, new solutions are needed to maintain the positive contribution of manufacturing for society while reducing its negative impacts and thus to sustain manufacturing over the long term.

2.1.1 Sustainability in manufacturing

DOBBS ET AL. indicate that compared to the 1.85 billion in 2009, 4.88 billion middle-class consumers are expected to enter the market by 2030. Almost 90% of these consumers are expected to live in the Asia-Pacific region. With increased spending power of consumers, the need for manufactured goods is expected to rise at even faster paces than in the previous decades. If current manufacturing practices are projected, this would mean a 90% growth in primary energy over the next two decades [Dob-11]. SELIGER mentions that more than half of the value created is generated by nearly one-tenth of the global population, while the resource consumption already represents today more than 1,5 times the earth's regeneration capacity. Population growth, coupled with a demand for better living standards in emerging markets, increases resource consumption even further. Guidance toward a responsible development path is essential for preserving resources to meet the needs of future generations. Figure 2-2 shows the relation between resource living standard, resource consumption, and ecological limits for emerging and early industrialized countries

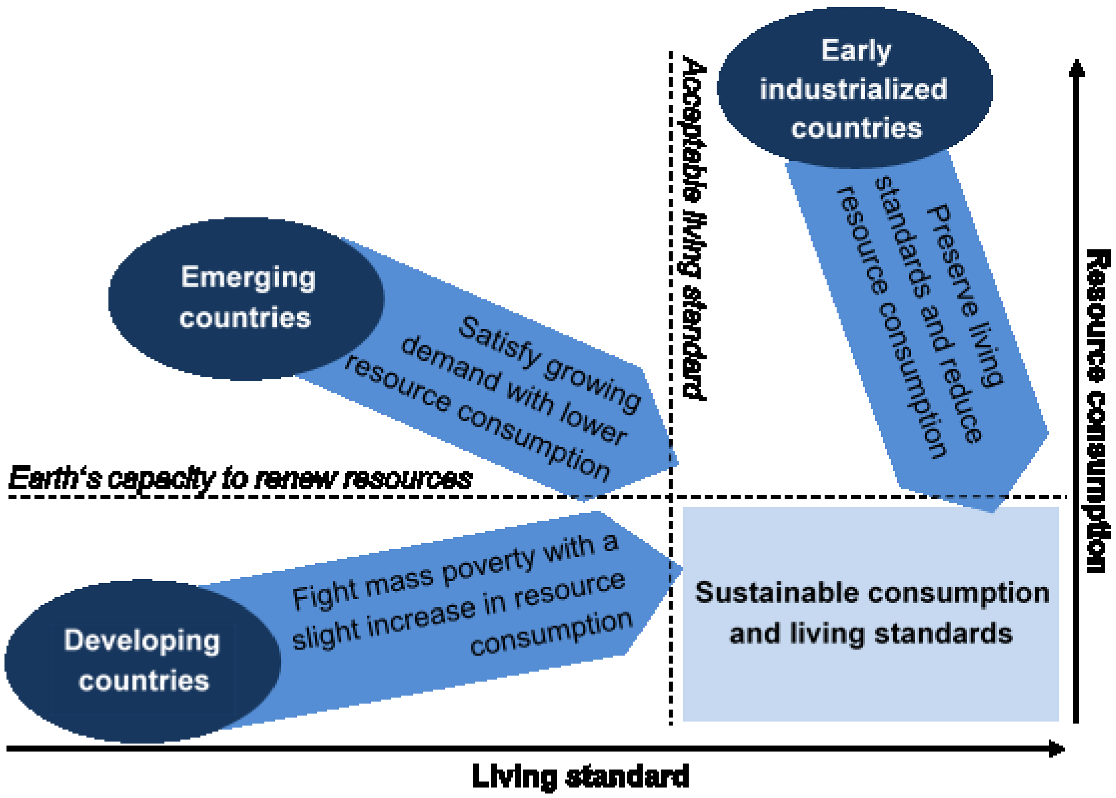


Figure 2-2: Increasing living standards by responsible use of resources [Sel-10].

Although the term sustainability is widely used, its high degree of complexity is often the source of incorrect use. Only a few systematic definitions are accepted in literature. CARLOWITZ is recognized as the inventor of sustainability, defining as soon as 1713 the importance of a continuous renewal of forestry resources to ensure their long-term availability [Car-13]. The most modern definition of sustainability was provided by Brundtland Commission in 1987 as being the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [Bru-87]. ELKINGTON contributed to a wider use of three pillars of environmental, social, and economic sustainability, which forms the accepted standard of the triple bottom line for the interpretation of sustainability, as illustrated in Figure 2-3. Traditional economic measures of profits, return on investment, and shareholder value are complemented by environmental and social measures in corporate sustainability reports. However, the debate on finding common metrics for the comparison of economic, environmental, and social triple bottom line remains open. As no measuring standard is yet universally accepted, organizations adapt metrics to their own needs [Sla-11].

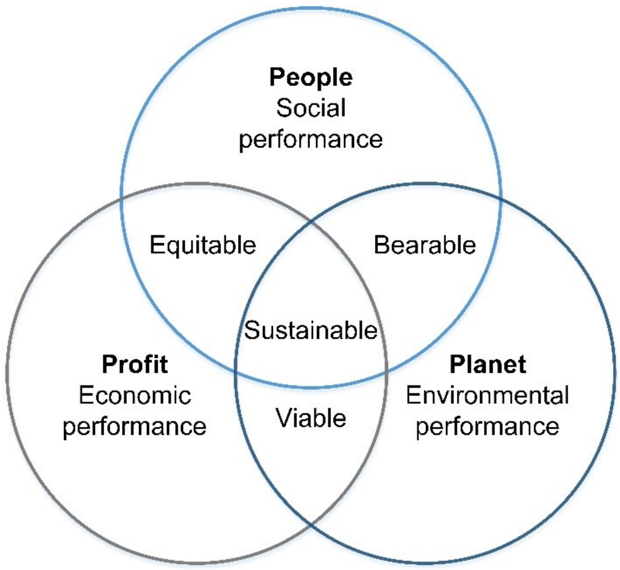


Figure 2-3: The triple bottom line for sustainability interpretation [Elk-94, Elk-97]

ELKINGTON contributed to sustainability by designing guidelines and best practices and identifying success stories for companies to find inspiration for organizing a revolution toward better practices. Companies shall adapt soft corporate values, stakeholder-inclusive governance, and openly transparent policies to differentiate in globalized markets with high competition. Their decisions should be flexible but oriented on a long-term vision, and partnerships should evolve from subversions to symbiosis to reach co-opetition success. Regarding product manufacturing, advice is given to go from selling product to selling functions, to incentivize in maximizing product use along the whole lifecycle of their products [Elk-97]. In summary, the shift to sustainability requires a systemic change to allow transition to a responsible capitalism model.

The economic dimension of sustainability motivated the widest range and amount of literature. In 1946, HICKS defined the term economic sustainability as a system that satisfies the current consumption needs without exceeding future needs; this meant that an entity would not impoverish itself at the end of a given period [Hic-46]. However, international harmonization of standards for accounting and financial reporting is yet to be reached as International Financial Reporting Standards (IFRS) and International Accounting Standards (IAS) compete for national adoptions. In addition, standards are not exclusive. According to IAS, interpretation of asset value is left to the fair judgement of company management when a standard does not specifically apply [IAS-10]. Such operations as inventory valuation are typical for the difference between subjective accounting value and real market value, should the company valuate it to raw material or to finished good value. Different interpretations paved the way for the development of abstract assets to consider, such as intellectual capital or organizational capital [Roo-97, Ste-01b]. DYLLICK AND HOCKETS recognize that accounting and financial systems only give an estimation of economic assets, categorized in financial capital such as debts and equity; tangible capital as machinery, factory, or inventory; and intangible capital for brand value, know-how, and reputation. The economic sustainability of a company stops long before the cancellation of its accounts, as it happens after the effective and final stop of activities. Therefore, an economically sustainable company guarantees at any time cash flow sufficient to ensure liquidity while producing a persistent above average return for its stakeholders [Dyl-02].

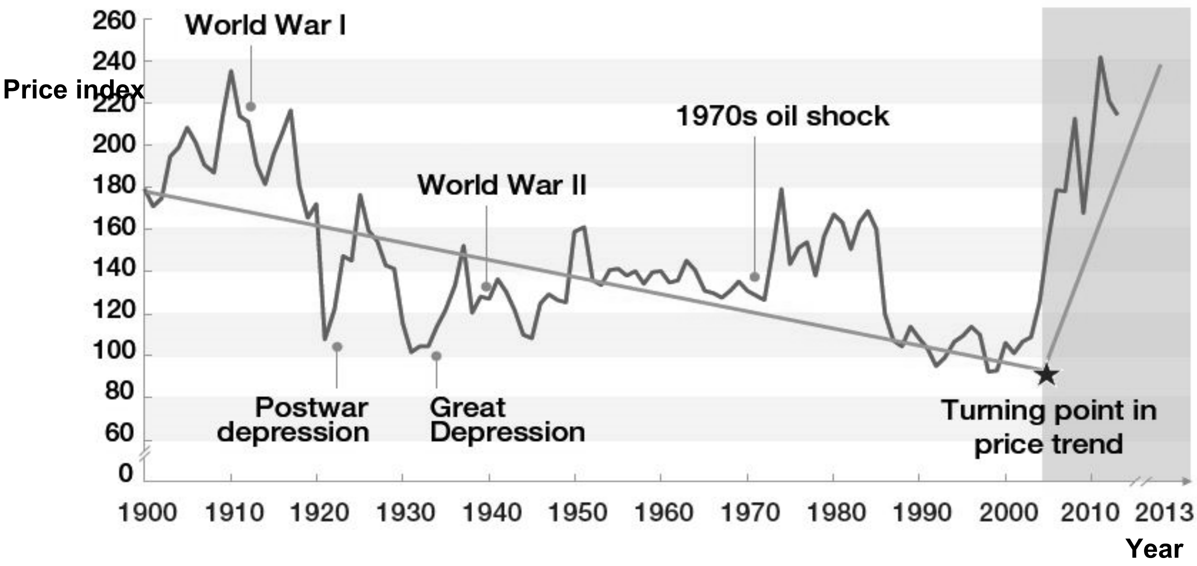


Figure 2-4: Price of commodities from 1930 to 2013 [EMF-14]

In the last decade, many companies have begun to notice that a linear production paradigm increases their exposure to risks – mostly in resource prices and supply disruptions. The real price of natural resources has increased significantly since 2000, essentially erasing a century's worth of real price declines, as illustrated in Figure 2-4. In an effort to maintain economic sustainability, manufacturing companies are looking for new strategies to reduce their exposure to these risks.

There is consensus that environmental sustainability concerns the relationship between the needs for resources from manufacturing companies and the finite natural resource capital depletion on Earth [Ayr-89, Leo-11, Lov-99, Sel-10]. Natural capital is composed of renewable resources, such as animals or plants, and non-renewable resources such as oil, minerals, or even biodiverse materials. Natural services such as water provision and purification or climate regulation support mankind in its activities. AYRES suggests use of the term industrial metabolism to represent the links between industry and eco-system. The industry is represented as a living organism fed by resources, and consuming energy for the production of desirable outputs of products or services and undesirable outputs of waste and polluting gas emissions. If too much is consumed or emitted, the organism is unsustainable [Ayr-89, Ayr-94]. The estimations of LOVINS for evaluating the natural services for at least the world gross domestic product [Lov-99] are disputed, as many natural services have no known alternative. DYLLICK AND HOCKETS suggest that ecologically sustainable companies use only resources and produce emissions that are consumed at a rate below the natural capacity for renovation or assimilation, and do not undertake the degradation of ecosystems [Dyl-02].

The illustration in the current industry trends relates to the rise in demand projections for energy, food, water, and materials as these new middle-class consumers emerge. The demand on primary energy is estimated to grow by 33%, or 162 Quadrillion British Thermal Units (QBTU), from 2010 to 2030. This additional demand for energy is equivalent to the combined annual current consumption of all Organization for Economic Co-operation and Development (OECD) members, accounting for the nearly 1,3 billion wealthiest citizens worldwide. The main drivers for resourced demand growth are the emerging counties, as their per capita energy consumption converges toward the levels of early industrialized economies due to a higher GDP annual increase. This phenomenon is exponential, as 162 QBTU growth in demand expected over the next two decades is significantly higher than the 100 QBTU growth in energy demand in the last 20 years. Given the importance of steel to the global manufacturing industry and its linkages with other resources, steel is assumed as an indicator for the rise of other types of materials. The demand for steel is forecasted to increase by about 80% from 1,270 million tons in 2010 to 2,290 million tons in 2030, primarily driven by increasing demand from China, India, and other emerging markets. Alone, the construction industry accounts for 50% of global steel demand growth, with demand driven by increasing urbanization in many emerging countries. Demand for water will increase by 41% from 4,500 billion cubic meters in 2010 to 6,350 billion cubic meters in 2030. Increased agricultural output is likely to account for 65% of incremental demand, growth in water-intensive industries an additional 25%, and municipal demand the remaining 10%. Resource demand projections are summarized in Figure 2-5.

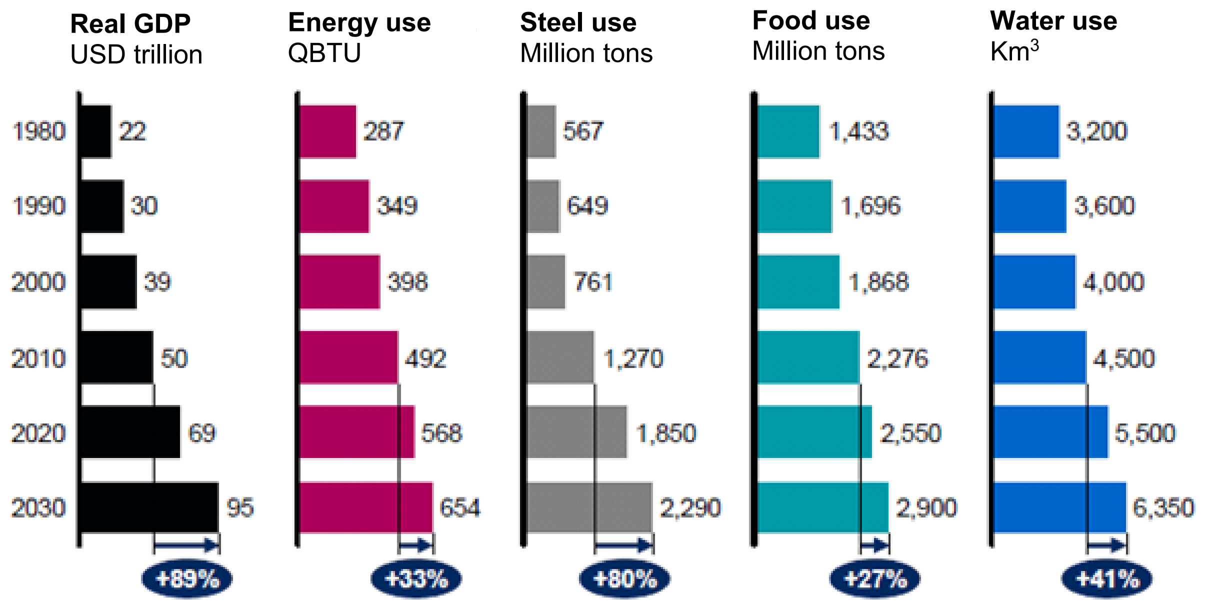


Figure 2-5: Projections for resource demand from 1980 to 2030 [Dob-11]

Considering that the current resource consumption already exceeds the global renovation capacity of ecosystems by 1,5 times, a rise of resources due primarily to an increase in living standards in emerging counties is particularity threatening. Between 1961 and 2010, the global human population increased from 3,1 to 7 billion, while the average resource consumption increased from 2,5 to 2,7 Global Hectares (GHA) per capita. GHA is a common unit to measure both bio capacity for natural resource supply and ecological footprint for human-related emissions output [McL-14]. The challenge for ecological sustainability is to reduce at least by 75% the amount of resources for the same desired production output.

Social capital is the least developed and measurable sustainability pillar because of the different interpretations concerning its scope and because of the difficulty in measuring social benefits. Social capital can be categorized in human capital, referring to skills, motivation, and loyalty for single internal or external company stakeholders and in social capital for the quality of local public services such as education systems, infrastructures, or cultural promotion [Dyl-02]. The concept of corporate social responsibility (CSR) originated in the UK and U.S. in the 1960s with the works of LIKERT AND GOYDER [Goy-61, Lik-67], but it didn't receive much attention until the 1990s. GLADWIN ET AL. suggest for a company to handle various activities for the development of its social capital, such as internalizing social costs, varying employee choices, or distributing resources and property rights fairly amongst stakeholders [Gla-95]. Beyond potential variance in interpretation and approximate measurement of effective and efficient actions, such broad criteria require different skills that are not linked to a company's activity sectors and therefore may be difficult to obtain. Trade-offs between different stakeholders, such as employees and client, could only be efficiently solved through a common communication to all stakeholders in the definition of social corporate standards [Kap-01, Zad-97] . Even in the case of decisions having a negative social impact, transparency concerning the causes can validate the decision to be essential for the company's social sustainability as a whole. A socially sustainable company is therefore adding value by increasing human capital and supporting the social capital of the stakeholder community they are operating their activities within, while ensuring that its motivations are well communicated and agreed upon [Dyl-02]. In a global economy, however, the notion of stakeholder community can be misleading. To keep a good image while reducing costs, many companies are tempted to externalize negative social impacts far from the consumption markets, especially in countries with low labour costs and permissive social legislation [Leo-11].

SELIGER ET AL. suggest that every citizen in the world should have a minimum of resources, ability, and qualifications for taking initiative in a value-added activity, and name an indicator for measuring social sustainability using the Lorenz curve. Equity factors, or GINI indexes, are determined statistically by the accumulated income distributed from the poorest to the richest decile of the population. A higher level of equity, determined by empirical data, is needed for reaching sustainability within the present globalization process [Sel-06]. A country with perfect equality in wealth distribution would have a GINI index of 0, whereas a country with the richest person owning the whole nation's wealth would have a GINI index of 100. OXFAM determined that if the 1% richest citizens accumulate 48% of the global wealth, the world's 80% poorest individuals share only 6% of the latter [OXF-15]. Figure 2-6 shows the world map of GINI index per country according to the 2014 World Bank estimates [Wor-14].

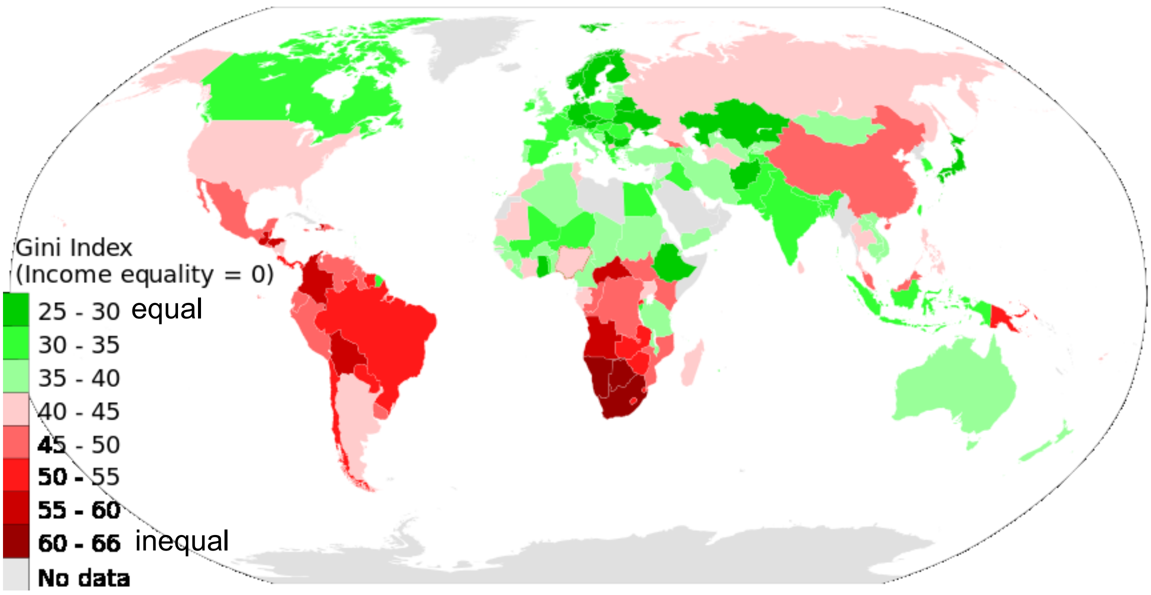


Figure 2-6: Gini Index World Map, income inequality distribution by country [Wor-14]

The United Nations Development Program (UNDP) has monitored for more than 20 years the key dimensions of human development using three dimensions: a long and healthy life, knowledge transmission, and standard of living. The health index is the average life expectancy in years; the education index is a combination of expected and mean years of schooling; and the standard of living is the Gross National Income (GNI) in purchasing power parity (PPP). The overall Human Development Index (HDI) ranges from a minimum of 0 to a maximum of 1 and reflects the human development on a country scale. Figure 2-7 shows that if the HDI trend is globally positive, huge disparities remain between early industrialized countries and developing countries. The 34 members from the Organization for Economic Co-operation and Development (OECD), grouping the most developed countries and some emerging countries, has an index almost twice as high as in the Sub-Saharan Africa region.

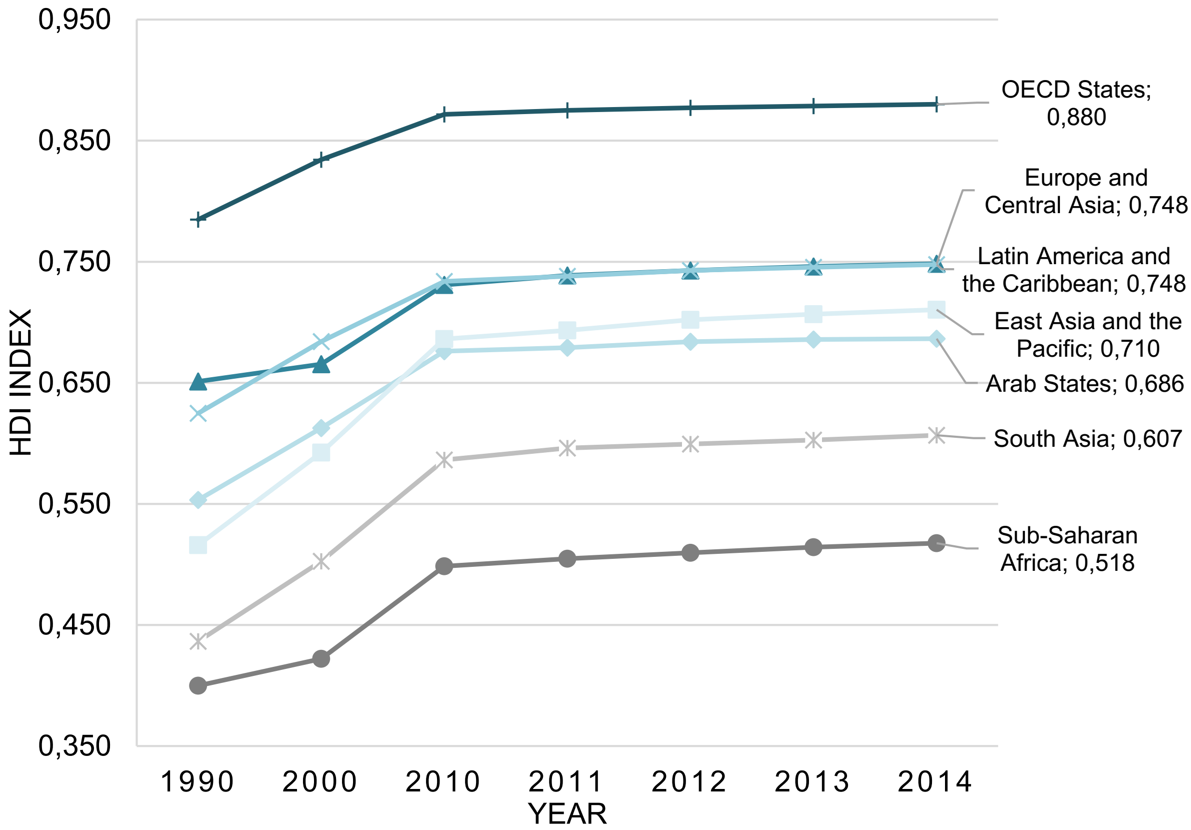


Figure 2-7: Regional comparison of HDI index evolution 1990-2014, data from [UND-15]

2.1.2 Product lifecycles and material flows

The shift from traditional linear production systems to circular production and consumption systems requires a transverse collaboration of private and public actors both at a regional and global scale. Ensuring an efficient and effective international support to permit the coordination of industrial ecosystems for product reuse while at the same time forecasting implementation effects at local level translates into a very high degree of complexity for policy making.

The notion to create circular supply chains is not a new concept. According to LEGRAIN, the first definitions of such a concept were published in the early 1970s. The issue is that the concept lacks a concrete guideline for a profitable extension of the value chain. Therefore, researchers intend to trigger new activities framed by innovative business models, while reaching sustainable product differentiation to face major instantiation barriers [Leg-14]. One of the most promising approaches for reaching sustainability in a manufacturing environment while simultaneously increasing the standards of living on a global scale was formulated by the Ellen MacArthur Foundation (EMF) under the notion of a circular economy [EMF-13]. This concept was developed in contrast to the traditional linear economy relying on abundant resources and disposing of all or most of the products reaching their end of life stage. Although most industry sectors still rely heavily on a linear model for ensuring the continuity of their activities, decision makers increasingly are recognizing the importance of a systemic change to a circular economy. To allow actors to create the conditions for the massive emergence of industrial models based on the circular economy principles, the EMF has recruited thought leaders able to recruit industries, academia, and governmental agencies to develop together concrete actions for a profound transformation of current practices. The Circular Economy 100 (CE100) is designed as “a pre-competitive innovation program established to enable organizations to develop new opportunities and realize their circular economy ambitions faster”. Composed of workshops, collaborative projects, and an annual summit, it supports the concrete design of privately funded research initiatives and pilot projects [EMF-13].

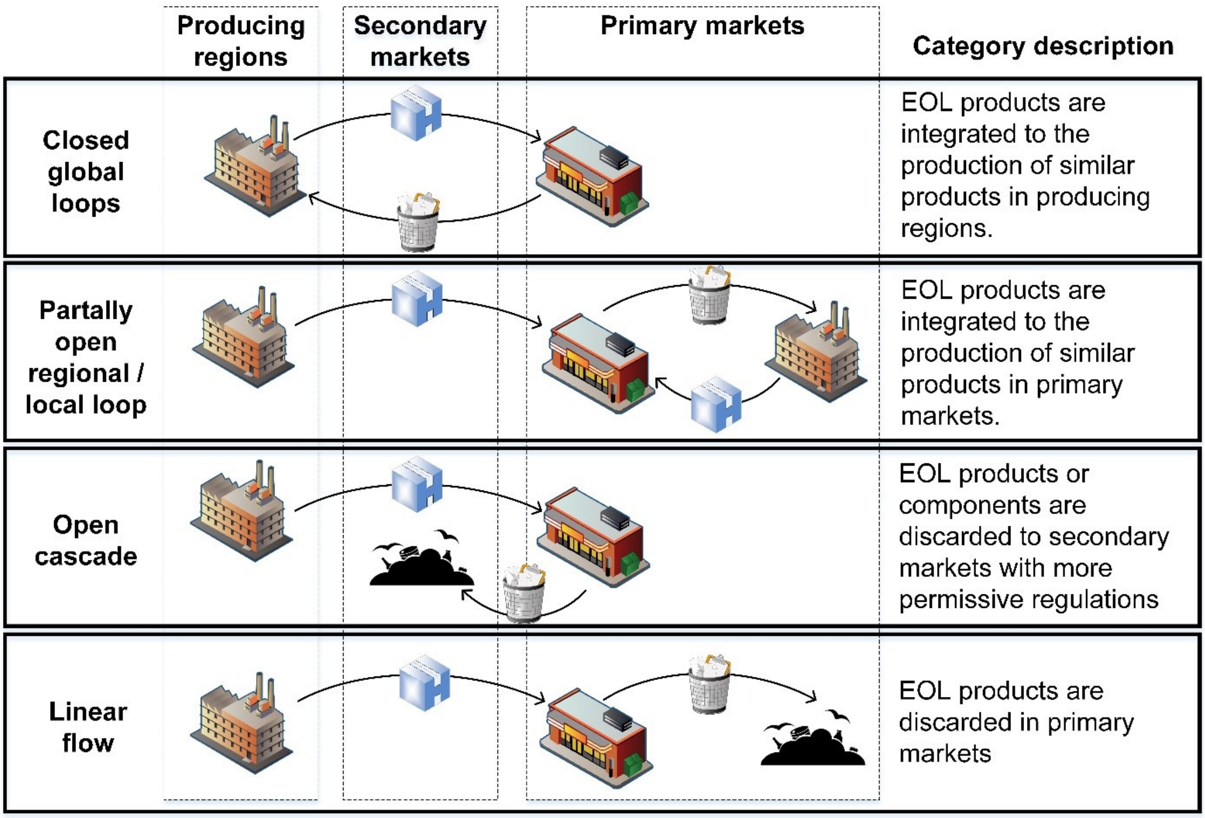


Figure 2-8: Types of material loops and flows, adapted from [EMF-14]

The concept of a circular economy is gaining momentum towards global industry leaders. It is presented as an alternative to the current linear “take-make-dispose” economy to enable production of agents in a manner that decouples growth from resource use. By 2030, three billion new middle-class consumers are expected to induce an unprecedented growth in demand for goods and services. This opportunity can only be tapped if the share of key resources per use phase is reduced, thus avoiding a surge in commodity price volatility. Beyond material savings estimated at over a trillion U.S. dollars a year, the circular economy is a tangible case for local job creation [EMF-14]. In the context of globalized manufacturing networks where production sites exist in a few locations, the shift to a circular economy can result in several types of material loops with different implications for regions, as illustrated in Figure 2-8. However, the shift to a circular economy cannot be accomplished by a single actor, even of critical size. A collaborative action is a prerequisite for change. Therefore, the Ellen MacArthur and McKinsey foundations joined forces in an initiative for large-scale collaboration among international governments, academia, investors, and civil society actors to allow large, steady, and pure signature material flows to be granted multiple lifecycles. The initiative suggests developing a proof of concept for unifying the design specification for four to five specific signature material flows around four building blocks – product design, new business models, global reverse networks, and enabling conditions over 24 months. Materials categories all prove high potential but are selected for their different maturity levels. A customized proof of concept is presented for one exemplary signature material flow per category. Once validated, the proofs of concept is expected to help in designing systematics for scaling a global circular economy transformation [EMF-14].

KIM AND MAUBORGNE illustrate an interesting paradigm in the definition of corporate strategy for industrial activity expansion through the war-tainted vocabulary of industrial organization and competition by describing markets as red or blue oceans. Red oceans are named after the colour of blood, left in fiercely competitive strategical wars between industries, which typically occur in consumer markets in developed economies where the rules of the game are defined and outperformance of the rival is the only survival chance. Blue oceans, in contrast, are named after the wild and untapped nature of markets in which rules are left to be set, competition is absent, demand must be created, and profit opportunities are high. If red oceans are to remain important to maintain a sustainable activity, blue oceans have a high significance in planning future activity growth [Kim-05]. However, many industries maintain focused on red oceans and prefer to find ways to renew sales in already saturated markets by the artificial reduction of a product lifecycle through obsolescence management. Several scopes can help such strategies to succeed. Technical obsolescence concerns the inclusion of voluntary weak points in the product construction combined with a prohibitive pricing of spare parts. Fashion obsolescence is applied by launching new models at a very fast pace with the objective to reduce the value of fully functional products. Economical obsolescence aims at motivating the replacement of a product by arguing that the running cost of a new product justifies a renewed investment. Policy makers can enforce regulatory obsolescence through the necessary disposal of goods which do not comply to new norms [EMF-13]. The direct consequence of such profit-driven strategies is a significant increase in raw material needs to satisfy the needs of a consumer. At the same time, billions of consumers worldwide do not get their needs filled as they are estimated not to have the necessary purchasing power for accessing these goods. Seliger refers to this situation by describing early industrialized countries as saturated markets and emerging and developing countries as hungry markets. An exceptional opportunity for a sustainable future of global industry is to bridge the gap between hungry and emerging countries, while simultaneously creating new strategies for decoupling growth from resource use [Sel-07a]. The strategical implications of blue and red oceans are summarized in Table 2-1 [Kim-15].

Table 2-1: Comparison of red and blue ocean strategies, adapted from [Kim-15]

Characteristics	**Red oceans**	**Blue oceans**
Market space	Exist in defined market space.	Create uncontested market space.
Competition	Objective is to beat the competitors.	Objective is to make the competition irrelevant.
Demand	Exploit the existing demand to the maximum extent.	Create and capture new demand with an innovative offer.
Trade-off	Reach the value-cost trade-off.	Break the value-cost trade-off.
Strategy	Base strategy on differentiation or low cost.	Combine strategy on differentiation and low cost.
Perspective	Defend current position at all costs.	Radical innovation for new opportunities.

The concept of circular economy led to a major change in how managers are assessing the impact of their activities based on a circular rather than a traditional linear conception. The concept of lifecycle thinking aims at identifying, accounting, and reducing the economic, environmental, and social impacts of a product throughout every activity it generates. It offers an integrated approach in efficiently targeting issues in the product value chain, without risking the transfer of negative impacts from one phase to another. To support managers in the application of this concept, a list of methods is documented. Lifecycle management allows lifecycle thinking to be integrated into operational tasks of company management [Ben-09]. It is directed to provide practical decision-making support for managers to help them consider and address all sustainability dimensions.

Lifecycle assessment (LCA) is a tool directed at understanding the environmental impacts of every activity along the value chain of a product or a service [Ben-09]. First, a Lifecycle Inventory (LCI) is performed, where the flows between a product or service and nature are represented using a technical input and output system. The second phase of a LCA is the Lifecycle Impact Assessment (LCIA). LCIA comprises the selection of impacts, indicators, and characterization models, assigning inventory parameters in categories, and measuring the impacts to finally characterize impacts [ISO-06a]. Both LCI and LCIA issues are identified, and their completeness and consistency are matched to make an informed decision from qualitative comparison of alternatives [ISO-06b].

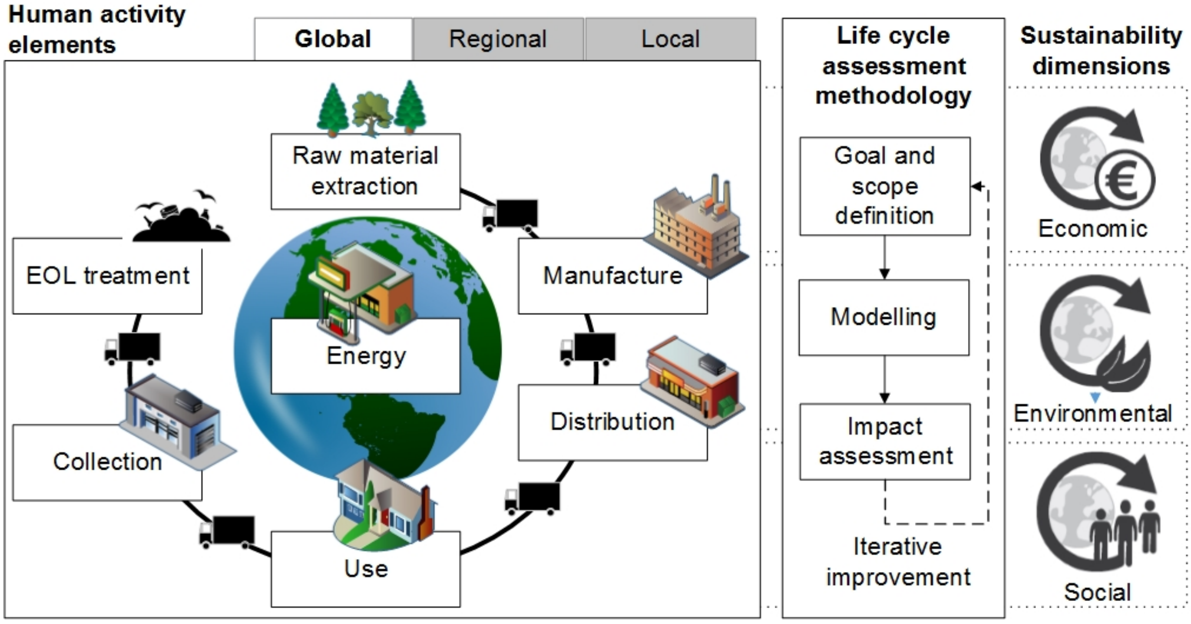


Figure 2-9: System elements in Lifecycle Assessment, adapted from [ISO-06a]

Lifecycle Costing (LCC) is a set of economic criteria of accounting for all costs related to the full product lifecycle. Because the accounting system and norms were defined before the emergence of a lifecycle thinking, an exhaustive consideration of such costs as end of life value in the case of multiple lifecycles is not possible. Although LCC predates LCA in its conception [Swa-11], the only dedicated international standard is limited to the buildings and construction assets industry [ISO-08].

Social Lifecycle Assessment (SLCA) targets the social impacts of activities along a product or service lifecycle. Social factors are difficult to measure for the versatile definitions of "social impacts". SCLA attempts to bridge this gap by interpreting quantitative LCA measures and suggesting further methodologies to effectively link impacts to society [Ben-09]. However, this method has not yet been standardized.

Lifecycle Sustainability Assessment (LCSA) attempts to combine LCA, LCC, and SLCA for giving a code of practice and a conceptual framework to establish the boundaries of a product sustainability assessment. Preliminary actions for reaching this objective are the definitions of international standards for LCC and for SLCA [Swa-11,Val-11]. Eco-labelling uses communication for informing consumers to make a more informed decision when purchasing a product. The different types of lifecycle approaches and methods are illustrated in Figure 2-9.

Ecolabels are classified under three types, subdivided in four categories. “Type I” identifies a comprehensive environmental impact and is certified by an international third party, such as Blue Angel in Germany, NF Environnement in France, or Ecomark in India. “Type I-like” certifies only one specific type of impacts and is given by agencies such as Rainforest Alliance or Forest Stewardship Council (FSC), which ensure that trees are replanted after cutting [ISO-99b]. “Type II” concerns self-declared certifications issued by the manufacturer itself [ISO-99a]. “Type III” is considered when detailed environmental impact data is directly displayed on the product packaging; it is often issued from a LCA [ISO-07].

2.1.3 End-of-life strategies

The European Union defined a hierarchy of waste by the directive 2008/98/EG which defined a standard guide for waste management processes. The legislator intends to promote the design and production of goods under the viewpoint of the whole lifecycle impacts [Eur-08].

Table 2-2: Waste hierarchy in the EU Waste Framework Directive [Eur-08]

Stages	Description
Prevention	Using less material in design and manufacture, keeping products for longer, re-using, and using less hazardous materials.
Preparing for re-use	Checking, cleaning, repairing, refurbishing, whole items or spare parts.
Recycling	Turning waste into a new substance or product; includes composting if it meets quality protocols.
Energy recovery	Includes anaerobic digestion, incineration with energy recovery, gasification, and pyrolysis which produce energy (fuels, heat, and power) and materials from waste, some backfilling.
Disposal	Landfill and incineration without energy recovery.

To goal for the directive was to motivate manufacturers to care about adequate options for the end of life of their products, without impairing or compromising the free circulation of goods throughout the European Economic Area (EEA) and the European Customs Union (ECU). Article 4 of the directive was designed as a guideline for companies to efficiently and effectively avoid waste generation and use waste as a resource by ranking the EOL options according to their outcomes for the environment, as illustrated in Table 2-2. Following the classification of the European Union, the EOL strategies are further described as follows:

The most efficient EOL strategy consists of avoiding waste generation by reducing the amount of materials used in manufacturing a product through improving the design of a product lifecycle. Manufacturers are encouraged to follow this strategy before considering any further option.

The necessity of improving product design to target lower material consumption has long been in practice. Eco Design suggests to integrate three types of design objectives in the product design process. The first objective focuses on reducing the impact of manufacturing processes. The two following objectives concern design for environmental packaging and for disposal and reuse, respectively. As a reduction in the material used implies a direct manufacturing cost reduction, this practice is naturally adopted as an element of the competitiveness strategy for numerous manufacturers. Further, lighter and smaller products, with optimized packaging through light-weighting, result in reduced logistics costs for transporting products from the manufacturing site to their intended distribution and consumption place [Mar-07]. More strategies for reduction can involve the democratization of reusable packaging associated with the research of durable and light materials [Mar-07, Hop-09]. Furthermore, the reduction of raw material consumption during the manufacturing process is an essential research topic for mechanical engineers. Innovation in machine tools, for instance, largely focuses on researching new processes for a more resource-efficient manufacturing. Industrial engineers work together with product design teams to improve processes and optimize the amount of raw material consumption in manufacturing a product [Kun-06, Smi-12]. Eco Design provides a guideline for integration in Environmental Management Systems (EMS) and Quality Management Systems (EMS) policies [ISO-11]. Design for Environment (DfE) is a regulation to design safer products by encouraging producers to design products according to the social and environmental impact of the chemicals used in the product design formulation. Combined with the results of the LCA, DfE provides optimized results [EPA-15].

According to SELIGER ET AL., another approach for waste reduction consists of adapting how the products are used by end consumers under the motto “selling use instead of selling products”. Represented as business opportunities, several strategies have emerged in recent years to increase the utilization rate of products. The utilization rate is defined by the time proportion a product is in use in comparison with the maximal potential use time. Such elements as an improved information, facility, service engineering, or logistics management help organizations to maximize both the availability of products and their utilization rate [Sel-05]. Many companies have also emerged in recent years with product pooling management strategies, to suggest a shared used of goods such as cars. In 2013, more than 2,3 million customers were using the services of a car-sharing company, and this number is expected to grow to more than 12 million by 2020 with the help of specialized consulting agencies [Nav-13].

The reuse strategy refers to the use of good components of a retired product for the same or another purpose but for the same use functionality [Ame-95], without modifications other than a thorough external cleaning. The aim of reuse is not to extend the lifecycle of a product, but rather to use a fully functional product by another user, once this product has been discarded by the previous user. As no action other than a visual function check is performed, the product carries no or a short warranty when distributed, and is usually sold at a fraction of the original price. Examples of reused products are typically electronic goods, such as mobile phones or personal computers, or equipment goods, such as large electro-domestic appliances or vehicles, which are used by another consumer group after the original user stops using the product while it is still functional. The EU Waste directive includes many different terms in the category of preparing for re-use. Such strategies as checking, cleaning, repairing, and refurbishing of whole items or of spare parts have the common aim to allow a discarded product to serve for a second life time. IJOMAH ET AL. uses the warranty as a quality indicator to differentiate between EOL strategies [Ijo-07b].

Reconditioning turns a product into a satisfactory or almost as-new condition with a lower warranty compared to a newly manufactured product. A reduced warranty period generally covers all parts of the product [Gra-07, Ijo-07b]. DUFLOU and GRAY ET AL. consider that reconditioning represents a similar process as refurbishment [Duf-08, Gra-07]. The products are only partially disassembled and the major issues tested. Popular reconditioned products are computers and photocopiers [Wal-10].

Repair usually means that a specific failure in a product is corrected. The product is then returned to the customer with a shorter warranty that only covers the repaired parts. The work content for repairing is therefore lower compared to remanufacturing, where the whole product has to be disassembled [Ijo-07b]. Repairing is often only used for fixing minor defects by replacing or restoring single components, while the rest of the product is not verified. In summary, repairing is limited to a relatively short expansion of the product lifetime.

Another possible use of a product at the end of its lifecycle is to use targeted components to integrate them in other products. Such cases are referred to as spare part cannibalization, and are mostly used for repairing products having an identified technical issue. Cannibalization is typically used when repairing electronic products that are still under warranty [Öst-08a].

Recycling ends the lifecycle of a product by destroying its original physical shape and extracting its raw materials. After an optional pre-sorting using destructive or non-destructive disassembly, components are shredded, separated according to the type of raw material, and then smelted, resulting in new raw material, generally of lower quality than original, which can then be used either for manufacturing new goods or as an energy source. Distinction is made between closed-loop recycling, considering the use of recycled materials for the same products, and open-loop recycling, when other products are concerned [Opa-10]. As the recycling process often is effected by specialized companies [Gui-13b], open-loop recycling is the most frequent option. Attention is brought to increasing efficiency of recycling operations.

For example, HEYER ET AL. suggests the development of bottom-up recycling networks to allow independent recycling companies to ease goal setting for corporate sustainability [Hey-12]. Another interesting example of recycling can be illustrated by the concept of Terra Preta. This ancient technique, which was used by indigenous Amazonian people for centuries and consists of recycling human excrement in crop fertilizers, is gaining momentum in developed countries as a sustainable waste management strategy [Aln-13].

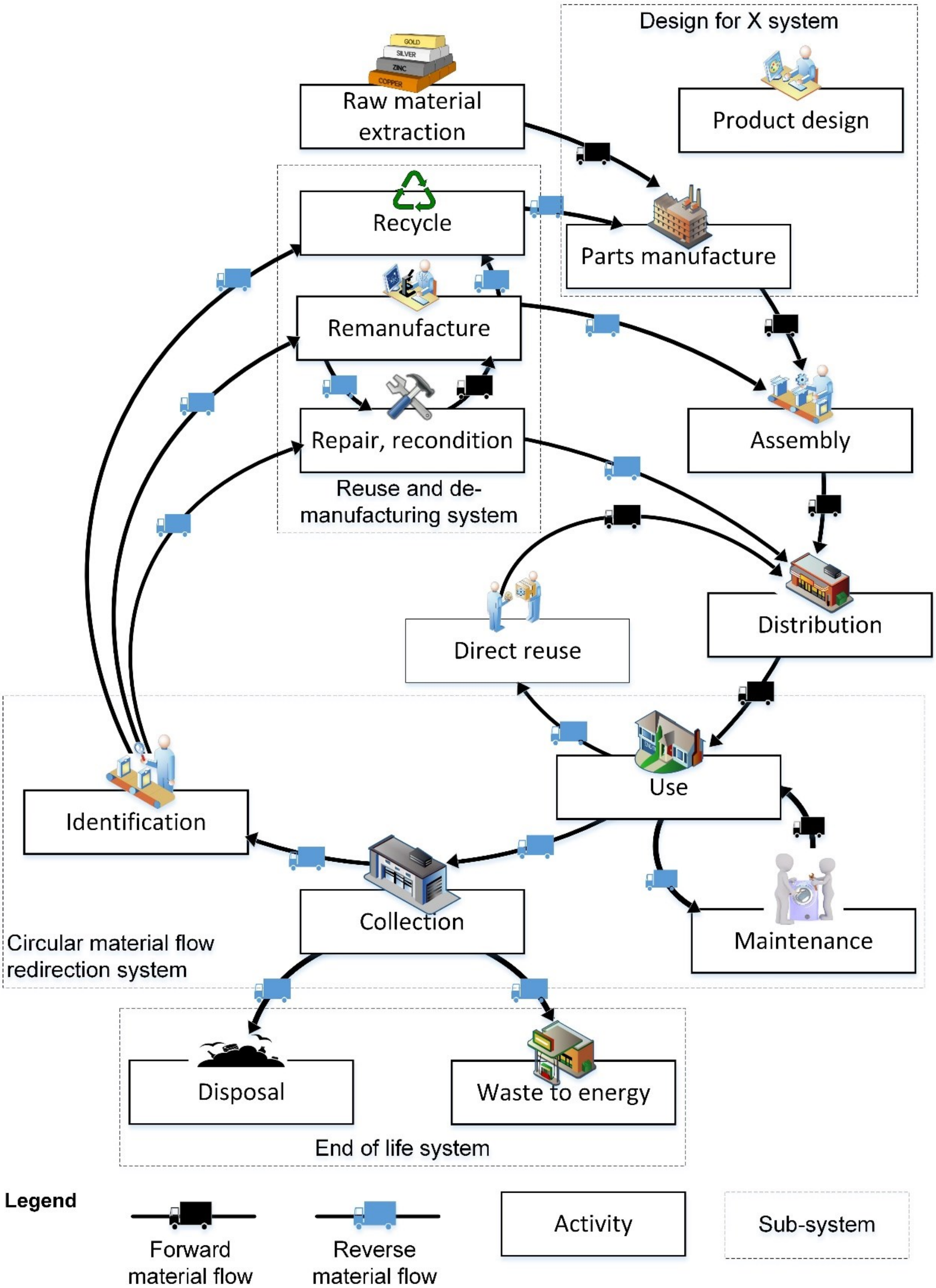


Figure 2-10: Linear and circular economy options along the material flow

Should a product fail to meet the conditions for any of the mentioned EOL strategies, a possible alternative is the destruction of the product for energy recovery purposes. It can represent a good alternative for organic waste. For example, transforming food waste and human faeces in energy through anaerobic digestion can support decentralized value creation [Tav-12]. However, energy recovery also can damage the environment, especially when urban waste is burned without a previous separation of materials. The incineration of plastics is particularly an issue, as it releases toxic particles into the air, causing public health issues [Leo-11].

By far the most damaging EOL strategy for the environment, the landfill is the predominant practice for many urban communities. Particularly in developing countries, technologies and infrastructures for municipal waste treatment are rare. As a result, waste dumping, as the disposal of waste in an uncontrolled, uncovered site of minimal or no structural design is the most common waste management strategy in many African and Asian countries. Effects of dumping are greenhouse gas emissions, surface and underground water pollution, and a high risk of disease transmission to local population [EAW-08]. Although developed countries enjoy better landfill engineering conditions than developing countries, the rise of common plastic use in manufacturing causes a global challenge. As plastics are constructed to be flexible and durable, they cannot biodegrade and are forming huge garbage patches known as Eastern and Western Rubbish patches, but they are also present in every sea of the world. The debris are estimated to represent over 250,000 tons from 5 trillion plastic pieces [Eri-14]. They present an immediate health issue for marine wildlife and through fish consumption also for human populations worldwide [UNE-09b]. GALL AND THOMPSON estimate that at least 690 marine species are consuming marine debris and that approximately 92% of debris are actually plastics [Gal-15]. Figure 2-10 summarizes the options presented for lifecycle management alongside with material flow redirection implications.

2.2 Remanufacturing

Closed-loop product lifecycles and industrial symbiosis allows the efficient coordination of product, material, energy, and water flows throughout the product lifecycles as well as between different factories. Reuse and refurbishing of products and components allow local activity development aimed at making an old product, or core, functional again and reselling the product at a fast pace. Remanufacturing distinguishes itself by the systematic process and quality measures that enable the product to be commercialized with at least similar warranty conditions to those of a new product by ensuring a match with the technical specifications defined by the original manufacturer [Nas-06]. The value capture today in the EU alone is estimated to be 10 to 12 billion USD per year [EMF-14]. In the U.S., the remanufacturing industry is estimated to provide at least 175,000 direct jobs. However, even in the most developed market and for the most representative product families, the proportion of remanufactured products does not exceed 5% of the amount of new products [U.S-12]. A glossary of specific terms employed within remanufacturing industry is provided in Annex A-1.

2.2.1 Current industrial practice

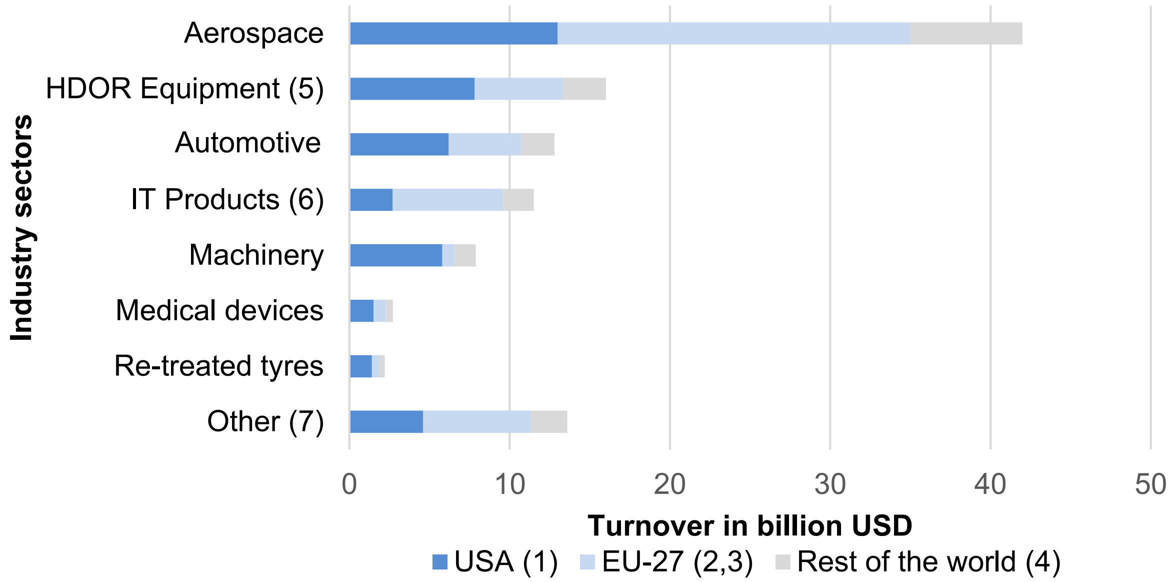
The developing remanufacturing industry is attracting increased attention worldwide for illustrating how economic growth can be coupled with higher environmental consciousness. The dominant remanufacturing industry sectors are aerospace, heavy duty off-road (HDOR) equipment, automotive components, information technology (IT) products, machinery, and medical devices [Zer-15, ERN-15, U.S-12]. Despite its long history full of success stories, the remanufacturing industry lacks visibility, representation, and inclusion of activities in a legal framework. However, the average volume of remanufacturing products is only estimated to reach 2% when compared to new product manufacturing [U.S-12]. Remanufacturers can be categorized by their relationship to the Original Equipment Manufacturer (OEM) [Sun-04], as the remanufacturer is the company responsible for the manufacturing of a new product. Three types of remanufacturers are commonly defined in the literature: the OEM, the contracted remanufacturer (CR), and the independent remanufacturer (IR) [Gui-13b, Jac-00, Sun-04]. To provide a brief background of current activities, a short description of industry sectors is presented before focusing on industry and legal development in the Americas, Europe, and Asia.

The aerospace sector is by far the largest activity sector for the remanufacturing industry, although the identification of eligible activities is complicated by the variety of terms used for the purpose of transforming a worn part into a functional part [CRR-10]. In this sector, a network of maintenance stations is following regulated specific procedures aimed at restoring specifications describing their “air worthiness”, as described in the Component Maintenance Manual established by European or American aviation authorities [ERN-15]. Aircraft engine and airframe remanufacturing is largely performed by the engine OEMs themselves, such as Rolls Royce or SNECMA, but they increasingly compete with maintenance subsidiaries of large airline groups such as Lufthansa and Air France-KLM [ERN-15, U.S-12]. System components of flight control electronics or landing gear represent a wide range of components which are more evenly distributed between OEM, CR, and IR [U.S-12].

The HDOR sector is estimated to be the second largest sector for remanufacturing in sales volume. It is composed of three sub-sectors comprising lifting and handling equipment, off-road machinery, and tire rethreading [ERN-15]. Remanufacturing is significantly more developed in the heavy duty and tire rethreading sub-sectors, but those areas function with different stakeholders. Heavy duty represents equipment for forestry, mining, and agricultural mechanical systems, and are primarily sold under leasing contracts to end customers. OEMs such as Caterpillar and JCB integrated remanufacturing as a base for their global manufacturing strategy [CRR-10, ERN-15, Zer-15]. The HDOR tire rethreading industry constitutes a large network of independent remanufacturers subject matter experts representing 18.000 employees, federated by the BIPAVER association in 10 EU member states, and capitalizing on high market penetration of 50% for commercial vehicle tires [BIP-16, Eur-16].

The third sector for remanufacturing comprises the companies operating remanufacturing of over 50 automotive component product families and represented by various trade associations such as Automotive Parts Remanufacturers Association (APRA) or European Association of Automotive Suppliers (CLEPA). The remanufacturing market, estimated to generate 5,7 billion USD per year, is evenly split between the original equipment and aftermarket distribution channels [CRR-10, Wei-14]. Original equipment is developed, manufactured, and supplied typically by multinational OEMs, such as Bosch or Valeo, to be assembled in new cars or replaced during the warranty period. The aftermarket, which is where new part production competes with remanufacturing, can be operated by the OEMs themselves or by smaller contracted remanufacturer (CR) or independent remanufacturer (IR) [CRR-10, ERN-15, Wei-14]. This sector is well established and employs approximately 32.000 persons in the EU [CLE-14]. Its growth is supported by the organization of major trade fairs, such as Rematec in Amsterdam [Rem-16a] and BigR / Rematec USA in Las Vegas [Rem-15].

In the IT sector, remanufacturing is observed for printing equipment and consumables, while consumer electronics such as computers or mobile phones are mostly reused, refurbished, or cannibalized and do not represent remanufacturing processes [ERN-15]. Office printers and copy machines are frequently used under a leasing contract that includes the supply of consumable and planned maintenance against a price per printed page [Mat-11]. The availability of detailed information on the product use and the programmed collection of worn products justifies a mature practice of remanufacturing by the major OEMs. The Japanese company Ricoh started remanufacturing black and white copiers in 1997 and colour copiers in 2009. The company applies product Design for Remanufacturing (DfR) [ERN-16] and leads research on cleaning processes [Ric-16]. Ink-jet and laser toner cartridges are widely remanufactured around the world as a consequence of the business model of entry-range printers that reports profits on the sales of consumables instead of on sales of the printer itself. The high value of consumables encouraged competitors to supply customers with a cheaper yet qualitative alternative using remanufacturing. OEMs reacted by introducing design measures such as smart chips or gluing components, which hindered non-OEM remanufacture; conditioned product warranty on OEM consumables; and set closed-loop collection schemes for cores [ERN-15, Mat-11].



(1) Modified data set from [U.S-12]
(2) Scaled using GDP ratios between the UK and EU27
(3) Calculated as 20 % of the sum of EU and US remanufacturing activity
(4) Modified data set from [Zer-15]
(5) Including construction, lifting and earth moving equipment
(6) Including printer cartridges
(7) Including catering, office equipment, pumps and compressors, rail, textiles and white goods.

Figure 2-11: Worldwide remanufacturing activity projections [U.S-12, Zer-15]

In the machinery sector, reconditioning or reuse are widely performed in the industrial machine tool, industrial food processing, and compressor sectors, although some operators may also perform remanufacturing [CRR-09a, CRR-09b, CRR-10, ERN-15]. The pump remanufacturing sector is well established and controlled by OEMs, as the products are durable and the reuse market is dominant. In addition, there has been a recent shift toward leasing for the distribution channels [ERN-15].

For medical devices, refurbishment replaces the term remanufacturing, and major OEMs such as GE, Phillips, Siemens, and Toshiba developed qualitative processes to handle worn equipment of high-value devices [GE -16, Phi-16, Sie-16b, Tos-16]. Specialized independent SME companies are also active in refurbishing less complex equipment, and their processes are less qualitative [CRR-08b, U.S-12].

The other industry sectors present a versatile industry landscape where remanufacturing actions are difficult to classify, particularly for cases in which the activity volumes are especially low. The white goods sector, with such widely spread products as dishwashers, washing machines, and refrigerators, is still marginal for remanufacturing, as cores are mostly collected by SME for low quality repair processes [ERN-15]. However, some OEMs expressed interest in integrating remanufacturing in their strategy for the future [Wid-14]. Janssen identified opportunities for remanufacturing in the shipbuilding sector [Jan-13], although at present the practice in this industry is limited to isolated interventions from HDOR companies [ERN-15]. The rail industry for rolling stock and engine parts counts a handful of companies operating remanufacturing processes with acceptable profit [ERN-15, U.S-12]. A last industrial example is the office furniture remanufacturing market, where several companies developed processes for taking back and remanufacturing cores while adapting them to new market trends [ERN-15, Lun-10, Sah-10, Ste-01a]. A comparison of the main activity sectors by estimated turnover is given in Figure 2-11.

The analysis of remanufacturing industries in several countries allows the identification and classification of stakeholders in the definition of support initiatives to EOL management from public and private organizations. Regional or national public regulation bodies define the legislative framework for EOL, the extent of producers' responsibilities, and customs regulation for used products. International, regional, and national technical standards organizations can play an important role in defining remanufacturing in terms of general characteristics or specific, product-oriented processes. In turn, their definitions can be referenced by regulatory bodies in legal provisions. They are public when linked to nations or regions and inter-governmental or non-governmental associations when international. Regional and national public research agencies and universities are offering support to the industry through the development and funding of specific technological and economic research projects to contribute to the development of the remanufacturing industry.

Table 2-3: Comparison of public and private support for remanufacturing [Gui-17]

Region	Country	Market intensity	Legal definition of reman.	Public-private partnerships	EOL Regulation level
Americas	U.S.	Highest	Key words	Yes	Moderate
	Brazil	Nascent	Key words	No	Nascent
Asia	South Korea	Developed	Key words Processes	Yes	Developed
	Japan	Developed	No	No	Earliest, developed
	China	Nascent	Key words Processes	Yes	Developed
	India	Nascent	No	No	Moderate
	Malaysia	Nascent	No	No	Absent
	Vietnam	Absent	No	No	Nascent
Europe	EU	Widest portfolio	Key words Processes (UK)	No	Most developed
	Russia	Absent	No	No	Nascent

Private industry associations play an important role in many sectors with support by representing a distinct remanufacturing sector toward regulation bodies, scientific communities, and society to a wider extent. An international comparison of relative remanufacturing market intensity with support initiatives is done using a qualitative description of the support measures. The stakeholder analysis enables identification of three categories of support measures from private and public actors.

The legal definition of remanufacturing indicates if and to what extent remanufacturing appears in the national regulation, as this is essential for recognition of the remanufacturing quality level. Public-private partnerships indicate whether concrete partnerships between public and private actors are undertaken for supporting the development of the remanufacturing industry. EOL regulation level acts as an indicator of the relative state of development of legislative material regarding the EOL of the industrial apparatus in a country. The comparison of support measures by country of origin is summarized in Table 2-3.

A best practice for the inclusion of quantitative objectives is the German legislation for electric and electronic equipment (ElektroG) which has been designed for enforcing both WEEE and RoHS European legislations [Eur-03, Eur-11, Eur-12a, Eur-15] in the national domain [Ker-09a]. It concretely transposes the waste hierarchy in quantitative objectives per EOL strategy and for ten concrete product categories to reduce the amount of waste disposed in landfills, as illustrated in Figure 2-12. By defining mandatory guidelines for disassembly and re-use preparation of products from the product design phase, it directs manufacturers to apply recommended EOL strategies by the waste hierarchy. Authorities reserve the right to control waste management companies to ensure that process options for re-use or re-use preparation of waste are economically and technically checked before a landfill option is considered.

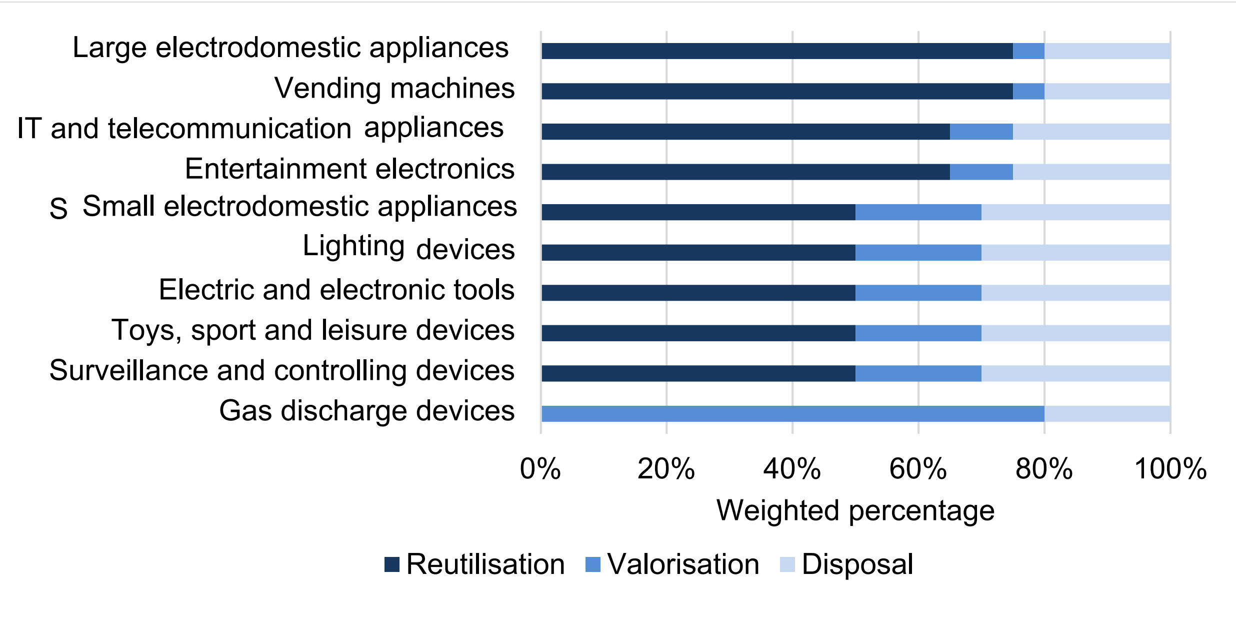


Figure 2-12: Targeted Recycling Percentages in the EU WEEE Directive

A tragic side effect of enforcing legislations with mandatory character, implicating costs increase for market actors, is the rise of illegal exportation of waste to developing countries to avoid the waste management costs implied by responsible and professional processes. A typical illustration of such activities is the exportation of second-hand obsolete computers, which are in most cases impossible to reuse, to Africa. Ghana has one of the largest landfills for such electronic waste arriving from the Americas and Europe; in the landfills, materials are burned for material recovery by unfortunate local communities, resulting on severe environmental and social disasters [3SA-11]. In China, open-air e-waste burning activities are organized in specialized locations with similar consequences [AFP-14].

As trade and industry are increasingly integrating global networks, international remanufacturing activities require export and import of cores from one country to another to become more cost efficient [Saa-13]. The EU shows the only cross-national application of consistent and constraining environmental laws, even if directives from the European Union have to be transposed in the national law by the member states and the implementation process can be slowed down. Other regions are considering the benefits of remanufacturing for developing their local industry. As an example, the Indonesian prime minister Saleh Husin authorized the import of second-hand capital goods for remanufacturing purposes if they meet specific requirements in the Regulation Number 14 of 2016 [Rem-16b]. A positive move toward the recognition of remanufacturing as a key strategy to achieve sustainable manufacturing practices was given in a declaration by the G7 leaders at the 2015 summit in Germany. The G7 Alliance on Resource Efficiency intends to collaborate with industry to foster best practices and innovation and named remanufacturing as a specific focus area [G7 -15]. Further, the Toyama Material Cycle Framework drafted a series of measures from public authorities to lead, promote, and follow-up initiatives for the promotion of a resource-knowledgeable society [Jap-16].

The above analyses summarize the strengths and weaknesses of the application of EOL strategies to reach a more circular economy. Progress has been made in the definition and identification of alternatives for manufacturers and a first step from non-binding recommendations to mandatory and controlled injunctions has taken place. This shows that the public authorities increasingly embrace their responsibility in defining a framework for sustainable manufacturing practices. However, such advances are considered as a constraint because they represent an additional cost for private companies. As legislation is not comprehensively enforced in developed countries such as Europe and developing countries have yet to introduce a legal framework for waste management, results stay theoretical. In the following chapter, a focus on remanufacturing as a promising solution to ally income generation and waste management is presented.

2.2.2 Processes and enabling technologies

Given the variety of terms and expressions used in reverse manufacturing activities and the low level of general customer awareness, it is essential for the remanufacturing industry to establish transparent definitions to justify the investment in qualitative processes and differentiate remanufacturing products.

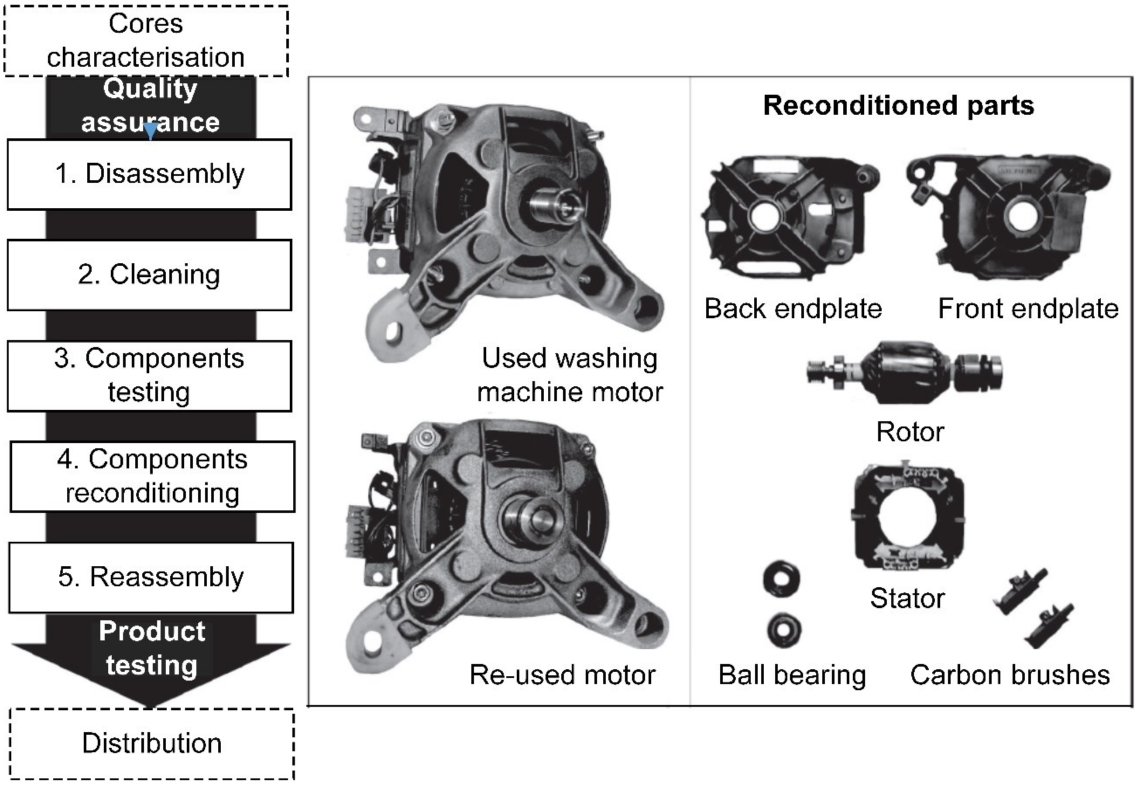


Figure 2-13: Process steps in remanufacturing, adapted from [Her-08]

This chapter gives an overview of definitions used for terms specific to the remanufacturing industry, that are specifically used in the later parts of the thesis. Figure 2-13 details general remanufacturing process steps with disassembly, cleaning, testing, reconditioning and reassembly, described in detail in this chapter.

In the literature, many definitions for remanufacturing are suggested. It is defined as an industrial process, whereby used or old products, referred as cores, are restored to useful life or to “good as new” products. Accordingly, remanufactured products reach the same warranty, reliability, safety, effectiveness, lifetime, and quality as new products [Ste-06]. In terms of quality, new specifications may be added to a product to meet additional customer requirements [Sun-04]. Remanufacturing enables products or parts to enter additional lifecycles in order to conserve resources, such as materials or energy [Ste-98]. It is therefore an EOL strategy that can decrease costs for manufacturing companies by reducing costs for purchased materials as well as costs for waste disposal. Used components can be used as spare parts for “good as new” products or for maintenance [Ayr-97].

There are very few legal definitions of what a remanufacturer is legally bound to for labelling a product as remanufactured. Despite several initiatives, the only standard available for the definition of a remanufacturing process is the BSI Standard BS 8887-2:2009. According to this document, “remanufacturing processes return a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product” [BSI-09]. Yet, a comprehensive definition for remanufacturing to date is specific to the automotive aftermarket and issued by the Automotive Parts Remanufacturers’ Association (APRA). It further defines remanufacturing in the following terms: “An industrial process, which is fully documented and capable to fulfil the requirements to reach specific products specifications developed in an engineering process by the remanufacturer or proven as state-of-the-art in the aftermarket, as defined in the norm ISO TS 16949” [APR-14].

To fully document the effort to reach the claimed remanufactured product characteristics, it is important to detail the process steps carefully. BS 8887-2:2009 standard mentions dismantling, restoration, and replacement as well as testing to original design specifications [BSI-09]. APRA suggests more detail in the minimum remanufacturing process steps: core management, core sorting, core disassembly, cleaning of all internal and external components, replacing of all missing parts, remanufacturing of all impaired or substantially worn parts to a sound condition or their replacement if no remanufacturing is possible, component assembly, and final testing of each part [APR-14].

Design is widely seen as a major lever for increasing the efficiency of remanufactured products, as it is a cross-cutting topic between business model, customer relationship technologies, and efficiency and economic feasibility of remanufacturing processes [Bar-07, Bar-15, Kin-06]. Customized design methodologies are referred to as Design for X (DfX) and inspire many fields of research, among which the most known are Design for Manufacturing (DfM) and Design for Assembly (DfA) [Gra-07]. Researchers active in EOL management have developed customized tools and techniques for design implementation such as Design for Recycling (DfR) [Ued-05b], Design for Lifecycle Management (DfLCM) [Ued-05a], and specifically Design for Remanufacturing (DfRem) [Gra-07, Hat-11, Lut-14]. The general approach of DfRem methodologies is to identify the issues linked with the implementation of new criteria for product design and to suggest appropriate solutions which would allow the development of relevant processes [Hat-13]. In an effort to reduce the transition period for the remanufacturing process, an integrated approach of DfRem, which considers product, process, and circular strategy development, is incorporated in most recent research efforts [Ume-15]. Ijomah developed comprehensive DfRem guidelines for product design teams [Ijo-07a, Ijo-07b]. The lack of appropriate business models and the organizational resistance in the implementation of DfRem remain the least researched barriers [Pre-17, Wid-15], while the payback for such methods depends on the typical low intensity and volume of remanufactured products in comparison with newly manufactured goods, offsetting their intended payoff.

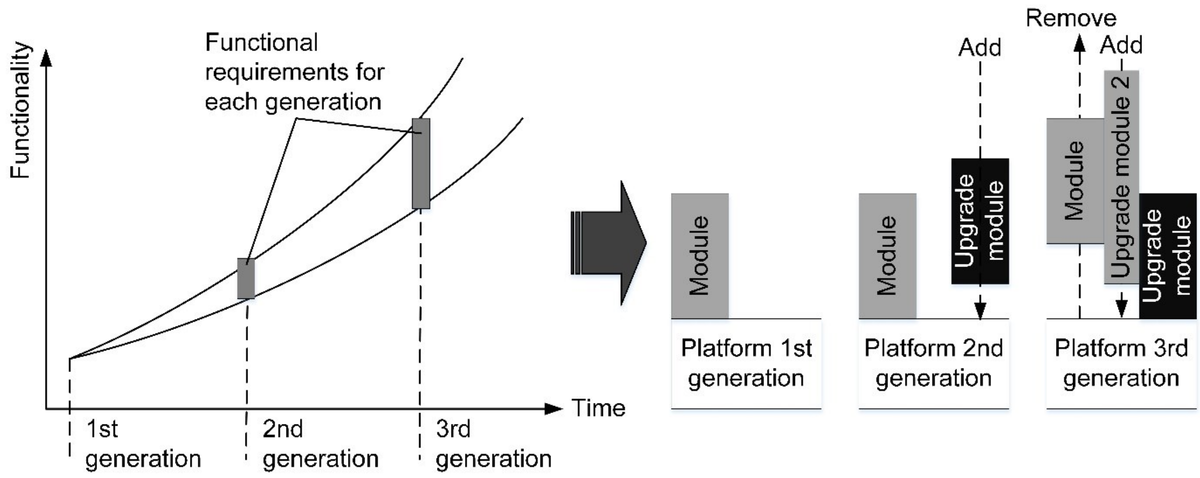


Figure 2-14: Modular product design over generations, adapted from [Ume-05]

Modular product design is of utmost interest for supporting re-use and remanufacturing, as it targets upgradability of products beyond restoration of original specifications through product modules reconfiguration, as shown in Figure 2-14 [Ibb-07, Kim-01, Sel-08, Ume-09]. Modular and upgradable product design brings major advantages to remanufacturing processes by increasing the technological lifetime of products, enhancing their market value from the second life phase onward while allowing shorter time-to-market innovation [Chi-16]. Optimization models for modular product upgradability are designed to demonstrate their contribution to circular strategies [Azi-16, Kri-15, Pia-12, Shi-99, Smi-10], particularly in product-service systems (PSS) focusing on selling use rather than selling products [Pia-17].

To ensure that the remanufacturing process achieves at least the same quality as for new products, the availability of the product specifications is essential to define which quality targets have to be achieved. In general, product specifications are confidential to the OEM and can only be obtained by independent remanufacturers by the means of reverse engineering of a new product purchased in the market [Sun-05]. Specifications are important for the preparation of the sorting and testing processes to determine easily if the product parts should be reused or rather should be discarded [Bei-93]. Such data as material composition, load limits, acceptable tolerances, and adjustments help to ensure that the remanufactured product can be considered of equal quality as a newly produced one [Hun-94].

As core availability is vital for the execution of the remanufacturing process, core collection is not only effectuated by remanufacturers themselves but also by specialized independent companies. While analysing the stakeholders in remanufacturing networks, GUIDAT ET AL. found that the core collection at least is partially outsourced by the company in charge of remanufacturing in most stakeholders' networks [Gui-13b]. As a result of the fierce competition in core collection and the potential for high profits, major OEMs involved in remanufacturing are integrating the core collection in their activities' portfolio [APR-13]. One of the major issues in managing cores arriving in the remanufacturing facility is core quality. This versatility in the products to be managed can have critical consequences on the next steps of the process. Therefore, SUNDIN suggests the inclusion of visual and functional tests during the core management phase to identify and set aside cores with obvious issues and try to value them for the recycling worth of their materials [Sun-04].

GUIDE ET AL. describe two systems for collecting cores for remanufacturing, with different influences on remanufacturing processes. With the first method, called the waste stream system, manufacturers are legally responsible for the collection of discarded products and must accomplish their collection. In this case, the main focus is to minimize costs and disregard the quality of incoming cores. Variances in quality, quantity, and timing are greater, and further space for sorting and testing of returned products is necessary. The system is further characterized by a high inventory and more work in progress (WIP). The second method is called the market-driven system. With this method, end-users have financial incentive to return cores by themselves. In a market-driven system, the products are sorted and graded by a seller before they enter the remanufacturer's process. Therefore, the quality of incoming cores is higher compared to a waste stream system, which means that the number of disposals can be reduced due to the reduced inventory needed for remanufacture to meet a certain demand. In addition, processing times become more stable, and lead times can be predicted more easily. These improved routing conditions allow flow shop remanufacturing to be organized [Gui-01].

There are three market-driven approaches to be observed in the core collection industry. In the first approach, a swap system, remanufactured products are provided in exchange for a core. According to the product distribution channel, a swap can be done with the end consumer, the distributor or workshop, or with the wholesaler. Swap is used typically in printer cartridge remanufacturing and in certain areas of the automotive parts industry. As an effort to increase part quality, specific guidelines are designed to identify the characteristics of core worth being purchased. In the case of auto parts, several companies established a clear process for managing the exchange process [Cor-16, Val-08, Wab-14]. The second approach is the integrated collection occurs when the OEM or distributor keeps the ownership of the product commercialized during use phase, such as in PSS-based business models [Sel-04]. Core collection is facilitated because the supplier is informed about the product status by the consumer, who can organize the exchange of a core by a new or remanufactured product independently [Gui-13a]. This model is used in several remanufacturing industries where PSS systems are the norm for product distribution. AYRES ET AL. describe a core collection approach used in a PSS context. To identify the total quality level of incoming cores, Xerox, a copy machine manufacturer, enforced the Asset Recovery Operation (ARO).

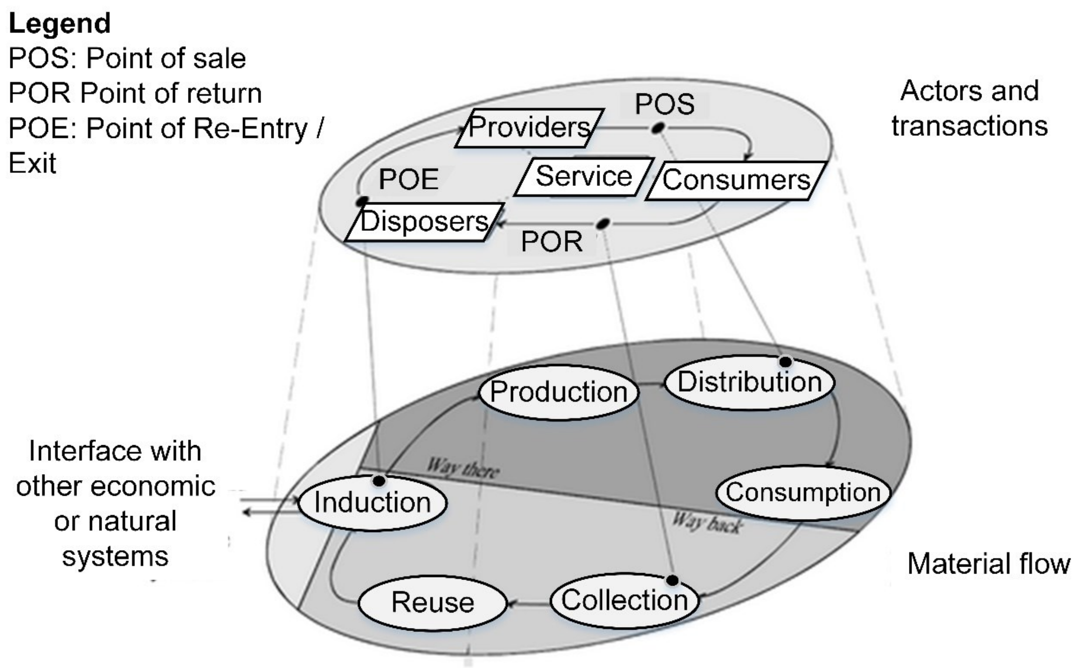


Figure 2-15: Actors and material flow in closed-loop supply chains, adapted from [Dyc-04]

Returned products are classified by four categories determine the most appropriate path for remanufacturing or valorisation, considering information such as their total use time and technological obsolescence [Ayr-97]. Other examples include HDOR equipment, high-end copy machines, hot beverage distribution machines, and food processing equipment [Gui-13a]. The third approach is core wholesale, Independent core collection companies can also work directly with remanufacturers and sell cores in bulk. This is typically the case with automotive parts, when core collectors are better able to collect from workshops or junkyards than the remanufacturers themselves. Figure 2-15 illustrates interactions between stakeholders, process design, material flows and highlights interfaces with other systems.

Once the products have been collected and transported to the remanufacturing facility, if no entrance assessment or inspection is performed [Gui-00], the first objective is to organize the liberation of the material to restore original functions of the product. The objectives of this step are to separate product components into (i) high-value reusable parts of the dedicated restoring process-chain and (ii) parts that need to be systematically replaced to ensure functionality of the remanufactured product. Restoring the value encapsulated in worn products is therefore highly dependent on this workforce-intensive process step. Disassembly processes with respect to the required component state are of three categories. Reuse processes require non-destructive disassembly to restore the integral shape of the component; semi-destructive methods allow the destruction of joints; and destructive disassembly allows a partial or full component shape destruction for recycling purposes [Von-15]. In remanufacturing, the product is disassembled to the single part level or at least to a level where no parts have to be damaged and parts cannot be loosened non-destructively [Ste-06]. Single parts or components not reaching a minimum level of quality are sorted out and may be used for spares or sold for recycling value. The quantity of parts that cannot be reconditioned is communicated to the purchasing department to guarantee a sufficient supply of parts for reassembly processes [Gui-00]. A number of factors must be considered to define the disassembly methodology, including the type of joints, material of the product, required performance, and automation degree of the product [San-02], as illustrated in Figure 2-16. If products are not completely designed to be disassembled, the disassembly operations are much more complex than just reverse assembly operations [Jun-12]. For instance, there are no simple operations for disassembly when joints were previously glued, riveted, pressed, or welded [Ste-98]. Research in developing product design for disassembly focuses on active disassembly, where detachable fasteners based on temperature, pressure, or impulse triggers could reduce disassembly time by 70% to 90% with comparable product robustness [Pee-17].

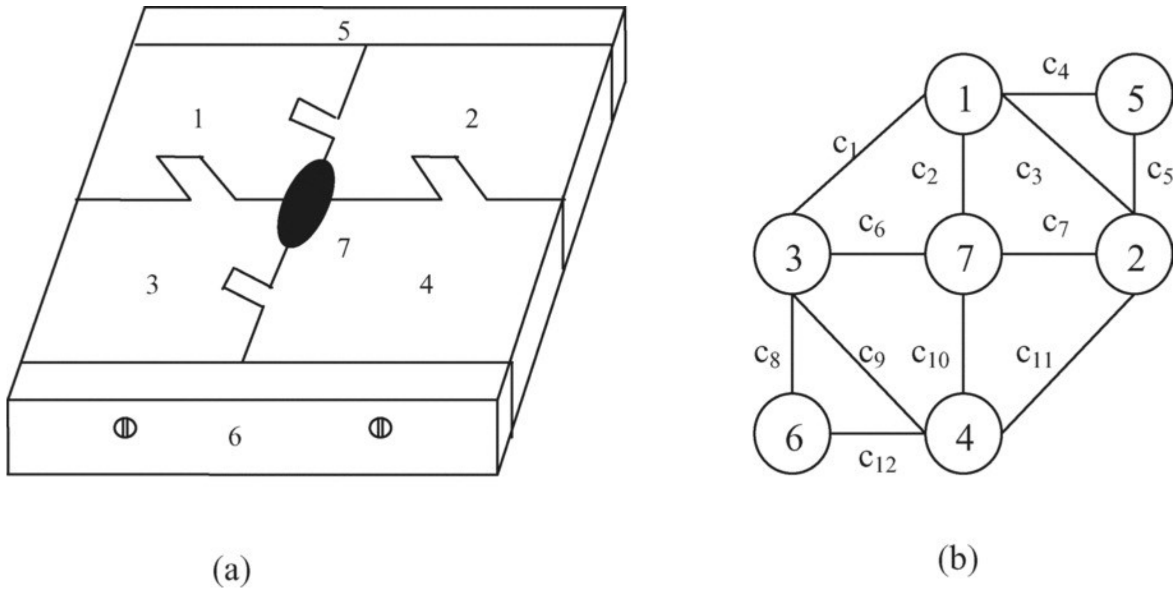


Figure 2-16: Sample product design and graph of disassembly connections [Koc-09]

For many products, disassembly processes are not economically feasible in high-wage countries, which results in application of EOL strategies such as recycling, incineration, or landfill instead of remanufacturing. As a result, the opportunity to save energy, production resources, and new materials by closing the loop on material flow is lost [Duf-08]. One approach to solve this issue is reflected in the efforts to develop tools for the integration of assembly and disassembly process planning in flexible or hybrid systems [Wes-99]. Process standardization through automatized disassembly has been tested for mobile phones [Kop-06], personal computers [Tor-04], lithium-ion batteries [Her-14], and washing machines [Duf-08], but it demonstrated limited product flexibility. A cognitive approach to enable robots to disassemble new product models without supplying preliminary information was developed by emulating human operator behaviour [Von-13a, Von-13b]. Applications from other research fields such as human-machine cooperation (HMC) have been applied to the disassembly field to automate low value-added tasks and dedicate manual operations to high-value tasks in the mechatronics product field [Col-14]. Barriers to the industrial development of such methods include the lack of currently enforced safety norms [ISO-15a] as well as missing methodologies to predict human reactions in collaborating with robots [Ara-10], although ongoing research shows potential in these areas [Mic-15].

According to the official definition from the German Institute for Standardization (DIN), cleaning is defined as the removal of unwanted substances from the surface of work pieces up to a required, agreed, or possible degree and includes processes of mechanical, chemical, and thermal cleaning [DIN-03]. In a remanufacturing process, cleaning is generally performed after components are disassembled in preparation for the inspection and sorting phase. This phase is critical for achieving the quality objectives in remanufacturing processes because the surface cleanliness is a pre-requisite for proper inspection, reconditioning, finishing, and reassembly. The goal in this phase is to facilitate testing and identification of damaged parts and specific failures to finally bring components back to like-new condition. Cleaning operations can be manual or automatic, depending on the selected machinery and cleaning technology. Factors for cleaning technology selection come from four different elements: cleaning object, contamination source, cleaning mechanism, and cleaning medium [Gam-13]. Cleaning technologies generally can be categorized in five groups: organic solvents, jet, thermal, ultrasonic, and electrolytic cleaning, but specific cleaning processes can be engineered for specific product characteristics [Nee-13]. In some cases, the process of cleaning is simultaneously used for enhancing the performance of a component, as for example in glass bead blasting cleaning technology, where surface treatment and hardening result in a cleaner and barer surface [Ste-98].

According to SUNDIN AND BRAS, cleaning is not only technically critical, but also a significant cost driver in remanufacturing operations. The process is described as possibly labour intensive and time consuming, but also cost intensive due to consumable supplies such as abrasive materials, chemicals, or solvents [Sun-05]. Reasons for increased cost and complexity in cleaning can be component complexity, excessive debris, material type, corrosion, environmental regulations, and expected output [Gam-13]. Cost reduction in the cleaning process may be approached with a comprehensive pre-inspection of parts before beginning the cleaning process to avoid the expense of cleaning defective components. Since the cleaning process follows the disassembly process, both processes have to be dimensioned jointly to avoid overload or idle times. Another important factor to achieve flexible cleaning processes is to manage activity variance in the remanufacturing process. Seliger et al. mention a lack of flexibility of cleaning processes because of potential material contamination. Many challenges remain to reach the objective of environmentally friendly, economical, fast, flexible, and reliable cleaning processes [Sel-07b].

Type		Interaction
Medium	Solvency and dispersion force	Contaminants dissolve in water or organic solvent and steadily dispersed into the cleaning medium.
	Surface active force	Comprehensive effects of wetting, permeating, emulsifying, scattering and solubilizing contaminants by lowering interfacial tension between surfactants and contaminants.
	Enzyme force	Organic contaminants are resolved by hydrolysis reaction accelerated by the enzyme before dispersing in the cleaning medium.
	Chemical reaction force	Contaminants are dispersed by chemical reaction with chemical agent.
Physical force	Thermal effect	Change of contaminants physical properties by thermal effect
	Pressure	Force is generated by high, medium or negative pressure or vacuum
	Friction	Contaminants on the surface are removed by rapidly scrapping
	Abrasive force	Contaminants on the surface are removed by mechanical force
	Ultrasound effect	Contaminants on the surface are removed by the function of cavitation of ultrasonic waves in cleaning medium
	Electrolytic force	Contaminants on the surface are removed by electrolytic action
	Ultraviolet ray	Atoms of organic contaminant molecules absorb certain wave length of ultraviolet light and the priming effect causes their decomposition

Table 2-4: Different types of cleaning forces [Nee-13]

Inspection is common at three stages of the remanufacturing process: post-use product acceptance, part inspection, and final product testing. Each stage has its respective objectives [Err-13]. First, in the market-driven collection phase, cores are inspected and classified according to their quality, with the aim to recognize failures which impede a possible or economically feasible remanufacturing process [Gui-01, Sun-04]. This task is generally framed by criteria decided by the core collecting organization and may be performed before reaching the collection centre. The second inspection phase decides which individual process a part follows for ensuring its functional quality and the compliance to specifications; it is typically conducted immediately after the disassembly or the cleaning process [Jac-00]. The product properties should allow the identification of the product status; the verification should be done according to an adequate documentation of the specifications, and access to the testing points should be granted [Sun-05]. More information on the status of the product can be determined, and the components are sorted according to their condition. Visual, dimensional, and further non-destructive tests are used to detect defects or failures of these parts. After the inspection, components are sorted into three different classes of components: parts which are reused without further remanufacturing, parts which are remanufactured to regain their performance, and parts which are not suitable for the remanufactured process and therefore not reusable [Ste-98]. Similar tests are performed after the reconditioning process to validate that the product meets the quality expected for remanufactured products. In contrast with new product manufacturing where inspection is based on sampling methods, inspection in remanufacturing is very often performed at the core level and systematically at the component level and at the final assembly stage [Err-13].

Those components that are identified as suitable after disassembly, cleaning, and inspection are reconditioned to regain the specifications expected for new products, as detailed in the specifications from the product's OEM. The technologies used at this stage depend on the components' features and on the specific related failures, but a common pattern of reconditioning process can be distinguished [Kin-14]. The first step consists of removing all defects such as cracks, burns, corrosion, and incursions in surface and shape through subtractive manufacturing processes such as drilling, grinding, milling, and turning, with the elimination of all stress raisers as a major objective. Second, material addition and deposition fills cavities and brings areas where material is lacking to the original shape after pre-heating through additive processes like welding, powder deposition, and laser cladding. In the third step, material property restoration occurs through heat treatments which can prevent unwanted residue and reinforce its operating condition. The last step concerns surface finishing which, depending on the expected quality and product properties, may include grinding, hard turning, honing or reaming, spray coating, painting, and polishing. Additive manufacturing represents an interesting field of research for the next generation of component reconditioning processes because of its ability to customize operations for a wide variety of forms, which characterize worn parts with random defects. The possibility to control precisely the material composition of added layers supports regeneration strategies able to improve a product's characteristics beyond its original specifications through the inclusion of materials with a better wear resistance [Mat-16, Tho-16]. Computing shape requirements from a digital model, dies and moulds are typically reconditioned using direct energy deposition and power bed fusion [Che-14, Mat-16], while selective laser melting is used for treatment of the blades and burners in gas turbines [Nav-14]. To improve inferior surface roughness to meet remanufacturing standards, fused filament fabrication and computer numerical control (CNC) milling has been combined with inspection on a single platform, for better control over the additive-subtractive machining processes [New-15]. The aforementioned production techniques or parts replacement ensure that the functionality of the component is restored and can hold full warranty conditions. Replacement components are generally sourced from a specialized supplier, but they can be integrated in the remanufacturer's facility. The entire process is characterized by a high quality control to ensure that the specifications tolerances are respected [Ste-98].

During the process step of reassembling, all remanufacturing parts as well as replenished parts and auxiliary materials are reassembled. Fundamental for reaching the same quality as newly manufactured goods and for working economically is the use of the same power tools and assembly equipment as in the new product production line. This guarantees a standardized way of working, thus aiding in future production planning [Ste-98]. In the reassembly phase, some parts that cannot be remanufactured technically or economically are added as new parts; principally, these are wear parts such as joints or bearings. For components targeted to be remanufactured but with low success rate, due to a core batch of low quality or inexperienced operators, for example, new components will be used in the assembly phase [Ste-99]. After passing the final testing, the finished product will be packaged, distributed, or stored for further Usage, thus beginning its next lifecycle [Ste-98]. Information about the remanufacturer is clearly mentioned aside from the OEM product reference, to guarantee the traceability for the end user [APR-14].

In a similar fashion to traditional manufacturing plants, internal strategies are applied for transporting the work in process between workstations in remanufacturing processes. Discrete part flows and batch processes co-habit in the form of conveyor belts and racks, depending on the level of process automation, but have the general characteristic to be rigid and leave little space for reconfiguration. Some examples of hybrid pneumatic-mechanical transportation systems can be observed with the application of cyber-physical systems where pallets are guided according to the locally available resources in electronics remanufacturing plants according to the IEC61499 standard [Cop-12]. In conclusion, these process steps ensure that remanufactured goods run through a standardized process that produces fully functional products, having a full warranty. Within each step, quality assurance should identify and solve failures occurring during the remanufacturing process. Especially during the remanufacturing process, high-quality manufacturing is fundamental because the product has already been used and has already fulfilled its lifecycle.

2.2.3 Business models

An important number of articles about remanufacturing highlight that the main motivation for remanufacturing is the potential for cost savings as compared to traditional manufacturing of new products. HAUSER AND LUND further illustrate this consideration by classifying the value embedded in a product in four categories: material, labour, energy, and plant or equipment. From this perspective, they estimate that remanufacturing keeps 85% of the total value of the product, while recycling merely retrieves 8%, as illustrated in Figure 2-17 [Lun-10]. As remanufacturing companies have access to cheaper raw materials, they are more competitive than other companies on the market and are able to address new market segments with less competition [CRR-07, Lun-10].

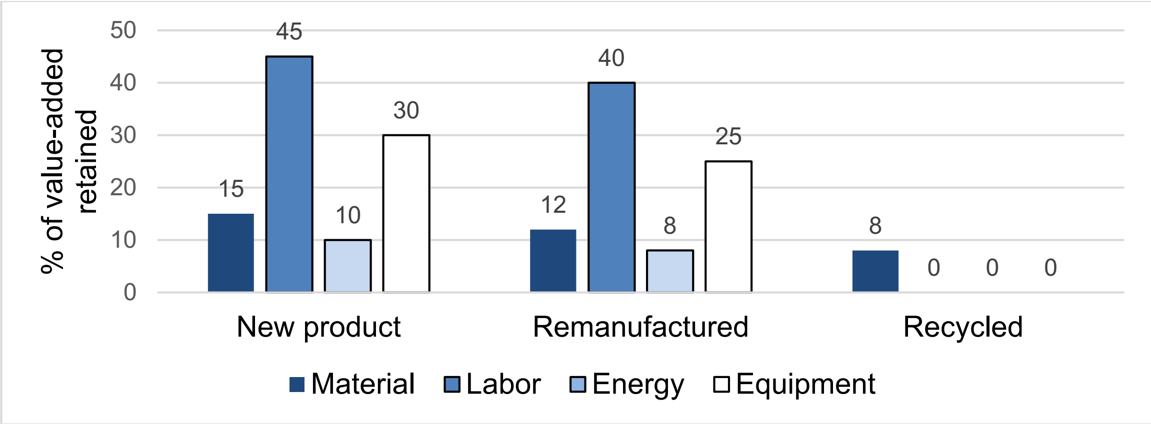


Figure 2-17: Value-added retained in remanufacturing and recycling [Lun-10]

A further economic advantage for remanufacturing companies is the additional control of potentially volatile material costs, and ability to secure access to materials with reduced availability, as in the case of rare earths [CRR-08a, Eur-12b]. Sutherland et al. demonstrate important savings in remanufacturing by considering costs in materials and energy, but additionally in transportation and disposal costs, as compared to new production [Sut-08]. The advantages of implementing a remanufacturing strategy depends on the nature of the company in charge of the operations, whether they are OEM for new products, or operating remanufacturing as an activity detached from the creation of new products, as in the case of CR or IR, as described in section 2.2.1 [Ker-09a, Sun-04, Wid-14]. HAUMANN mentions that as the OEM handles products developed internally, a privileged access to documentation, manufacturing processes, and cost figures make the OEM systematically more efficient then third-party remanufacturers [Hau-11]. Besides the advantages directly related to cost or cost control, OEM companies have several strategic advantages in performing remanufacturing. Organizing remanufacturing operations for their own products allows OEMs to better understand the issues occurring during the utilization of their products by the final consumer by a direct communication of failures identified during the remanufacturing process to the product design team. Keeping in contact with the customer and informing them that their feedback is considered also improves customer relations [CRR-08a, Ste-98]. Further, remanufacturing allows access to spare parts in the case of contracts with a long lifetime and long warranty periods [Gal-12], as with the supply of military machinery. Several authors highlight that remanufacturing can support OEMs to diversify their product portfolio by creating a new brand for remanufactured products and allowing them to become active in several price segments of a market [Ata-08, Ata-10, Vor-06]. Potential for a better market reach can be tapped by using remanufacturing to build an OEM company image as a sustainable manufacturer, and providing access to customer groups valuating this approach [Bar- c, CRR-08a, Mic-15]. As they are under increasing pressure to reduce the environmental impacts of their activities, OEMs can see with remanufacturing a possibility as a preparation to comply with more stringent legislations [Bar-13, Gui-13b, Saa-13, Ste-98].

GAMAGE ET AL. performed a review of case studies where the advantages of remanufacturing in terms of environmental impacts are defined for specific products. Compared to manufacturing, potential savings of 50% to 80% in energy consumption, 20% to 80% in costs, and 90% for greenhouse gas emissions are attributed to remanufacturing [Bis-11, Gam-13, Giu-03, Sun-09]. Nasr defines the superiority of remanufacturing by its ability to keep the embedded energy which was previously needed to manufacture a finished product from raw materials. A recycling alternative will, in comparison, only save a percentage of the original material value of the new product. Remanufacturing is also distinguished with the case of reuse, as the product certainly will have lost some of its reliability or efficiency, and its shorter life time and reduced functionality cannot be considered as a complete second life time [Nas-06].

The advantages of remanufacturing allow for companies to tap new markets requiring lower sales prices with steady product quality, which could not be exploited with new production, and therefore this will open possibilities for new business models [Wat-08]. Customer behaviour strongly influences the quality of post-use products, which in turn increase the degree of complexity in the planning and execution of de- and remanufacturing processes, provided that internal barriers are identified and overcome [Wid-15]. Keeping product ownership has the potential to overcome challenges linked to customers by selling products as “a service in their lifecycle” [Öst-08]. PSS-based business models have the potential for overcoming customers’ negative opinions of remanufactured goods [Gui-13a] and are especially promising when associated with modular product design for upgrade [Azi-16, Chi-16, Pia-17, Shi-99]. The value proposition consists of designing products for prolonged use cycles and motivates service providers to collect and value post-use products as a direct strategy to increase economic benefits. As customers are solely interested in reliable product functionalities for an agreed price, they do not perceive used products as problematic as long as the use availability is ensured [Gui-10]. Canvas Business Model allows the description of a series of business models under a common framework

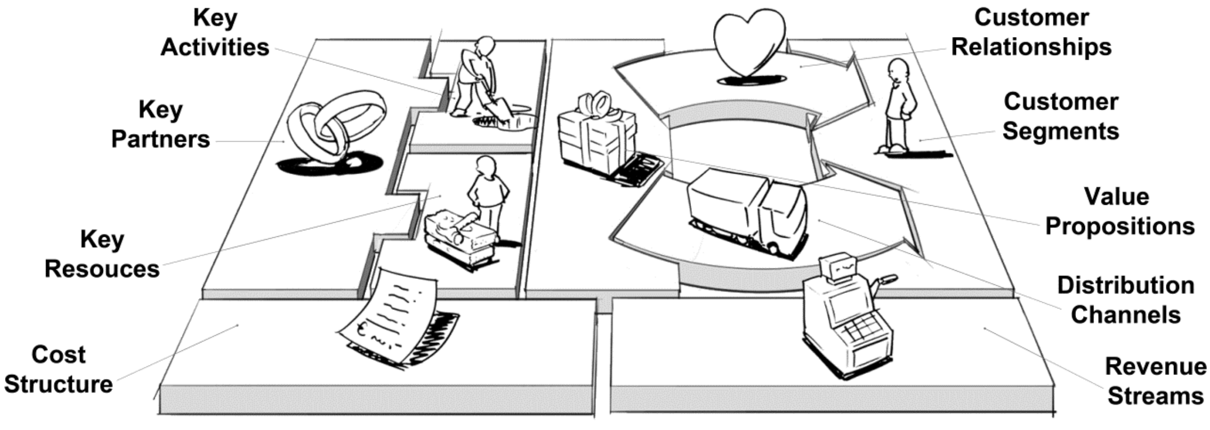


Figure 2-18: Canvas Business Model dimensions [Ost-10]

This tool allows a simple but comprehensive description of the relationship between the objectives of a company and the assets it should possess and gained recognition among industry and academia [Ost-10]. A graphical representation of the dimensions considered in this framework summarizes its working principle in Figure 2-18.

Increasing competition at a global scale requires company to focus on core competencies and lead to organisation in value creation networks. The management challenge arises how to keep the balance between breadth of knowledge about an increasing manifold of potentials in different technological disciplines without frittering away and the economically required concentration on core competencies and without losing innovation chances by lack of understanding. Dynamic observation frames for potentials of competition and collaboration through the integration of remanufacturing activities within value creation networks, must be exploited to deal with this challenge. The idea of cooperation is to combine forces of several actors to solve tasks, while responsibility is shared. For a good cooperation a good communication and coordination is essential [Luc-99]. The goals of a company are to minimize risk, increase flexibility, increase know-how, speed up the product development and order processing, secure company growth, increase market share, sustain their position in terms of competition, enter new markets and improve the company´s image [Zhe-02]. In production networks communication can be on the vertical, but also on the horizontal level. In addition to the intensive sharing of information between suppliers and producers, suppliers themselves may develop synergies. This encourages sharing information with other companies and can maximize value adding due to a better understanding of the other actors of the network. This mixed form of cooperation and competition is named coopetition [Zhe-02]. The coopetition in between all participants of the network allows quick changes in the collaboration and increases the flexibility.

The strategic planning and configuration of networks represents a starting point for production planning [Klö-00]. The general approach to production planning is to separate value creation tasks and subsequently assign them to individual manufacturing sites within a network and to reduce complexity of multi criteria planning tasks [VDI-11]. Configuration and management of logistics networks are the key aspects of logistics and Supply Chain Management (SCM). Current research projects are focused on process-oriented logistics planning. The management of logistics networks has been investigated within the German Collaborative Research Centre (CRC) 559 by modelling large logistic networks [Kuh-07] The project investigated, defined and tested methods and tools for transportation planning for different products. To support the planning process, an internet based integrated process chain paradigm has been created with various methods for planning of logistics networks [Kes-07]
International remanufacturing networks also are of high interest to the industrial sector as they can benefit from lower workforce costs in developing countries, while simultaneously avoiding

cannibalization with new products in the country where the cores are collected [Gui-09]. Delocalizing remanufacturing activities also can assist in the creation of local, high value-added activities and facilitates access to affordable products to new customer segments [Nno-10]. The development of the remanufacturing industry and research in emerging countries such as Malaysia prove that OEMs have already integrated this strategy in the international deployment of engineering competencies [Ahm-14, APE-15]. These opportunities still fail to encounter consensus in legislation to allow the free movement of cores, principally because the still-lacking remanufacturing industry definition prevents distinguishing of cores from e-waste [Kho-12, Nno-08, Yos-10]. Further benefits can be generated in a network, such as employee qualification, technology and organization development. Through common objectives, a productive distribution of tasks, a joint execution of certain business functions and a limited economic independence of the partners can yield high economies of scope while reducing investment risks [Zhe-02].

Besides the logistic efficiency of a network, the make-or-buy decision, in evaluating outsourcing or insourcing possibilities can be explained with the transaction cost approach [Sch-07]. The transaction process is the transmission of a product or a service from one contract partner to the other. The transaction costs of a product are the fees, which are caused by the organization and completion of the transaction. They include all the costs of the transaction process which are not already included in market price of a product. Examples of transaction costs are the search of information about possible cooperation partners, the costs and fees of the negotiation with partners and the costs of coordination and controlling resulting from the agreed activities and parameters. The amount of independent network partners is negatively correlated to the amount of transaction costs. As a promoter of networks, Porter describes the success of local clusters in American cities, in which transaction costs are reduced by good condition for cooperation, allowing to increase the number of associated companies [Por-09].

Value chain integration is another strategic opportunity to boost circular economy businesses. It entails collaboration between businesses at the level of planning and information sharing among different stakeholders in the value chain. By creating stable partnerships among stakeholders a better alignment and higher efficiency of de-and remanufacturing operations can be achieved [Wid-15]. Including the product lifecycle perspective in the identification of stakeholders is essential to create multilateral information systems as tool to ensure systemic efficiency of a remanufacturing strategy [Duf-06], maximizing added-value and use efficiency [Wes-03]. The concept of networking of Small and Medium Enterprises (SME) for competitive remanufacturing is focusing on the identification alternative business models in key areas of application, in order to create guidelines for the implementation of value chain network in remanufacturing. A reference model for the analysis of the stakeholders within the remanufacturing value chain was created, as illustrated in Figure 2-19. Surveys were carried in Europe as well as in Brazil in order to identify in which activities potential external stakeholders were involved. Generally, logistic and collection activities are outsourced to specialists, when the whole remanufacturing process is managed by only one company [Gui-13a, Gui-13b, Gui-14].

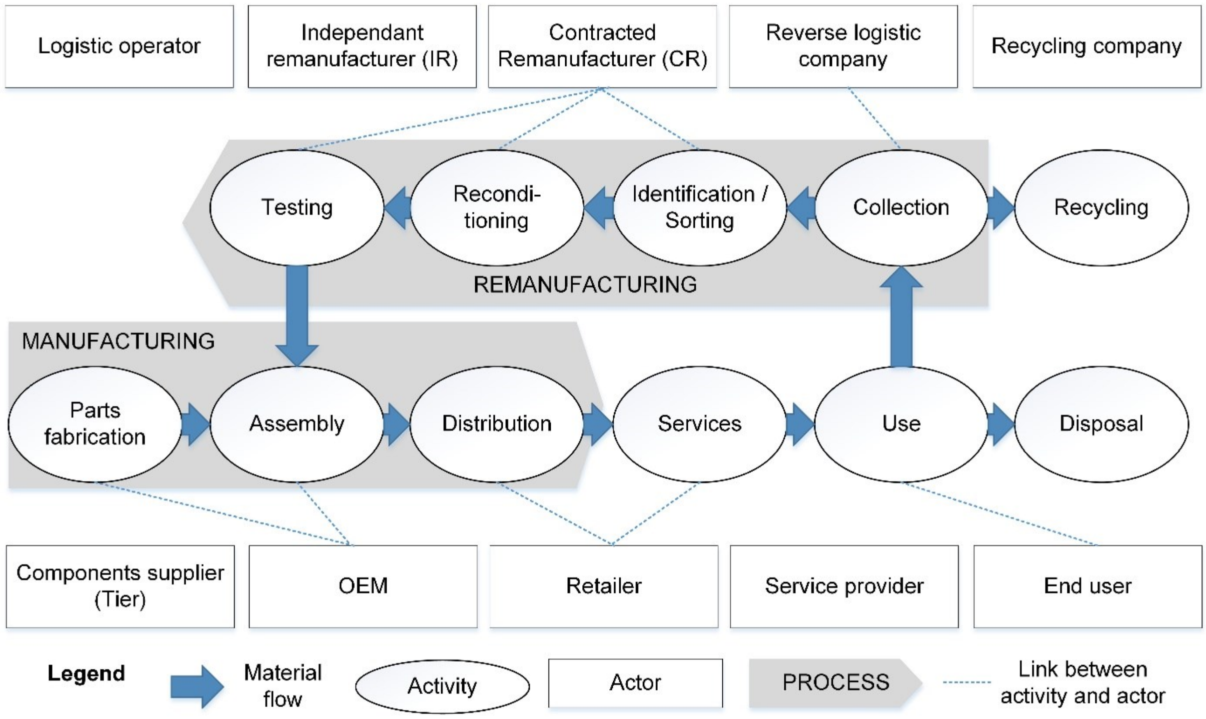


Figure 2-19: Reference model for the identification of remanufacturing networks

A detailed classification of the types of networks has been established based on which company controls remanufacturing and which activity is outsourced, and indicated that more the 82% of the networks are controlled by OEM or CR. When comparing the type of network control to the challenges for remanufacturing, it is interesting to note that IRs are much less affected by core collection challenges than OEM and especially CR, whereas the issue of independent networks are a low demand for their products and the complexity of the remanufacturing process [Gui-13b]. A guideline for support of business model creation for remanufacturing is provided online [REM-14].

The objectives of reverse supply chains (RSC) are to determine what facilities are necessary for used components to be physically transported from the end user to the remanufacturing facility while ensuring the maximum network efficiency. Under the consideration of Extended Producer Responsibility (EPR) principle, strategies aim at determining the organization and capacity of the necessary logistics network under economic and legislative factors taking into account different forms of incentives between stakeholders [Gov-17, Ara-08, Gov-15]. The models generated to optimize these networks must therefore handle complexity due to networks structure, core sources and market opportunities beside the uncertainty of product returns quantity and quality [Han-08]. Studies about these issues consider modelling tools based on stochastic programming [Jei-16, Sol-14], fuzzy programming [Sub-15, Jin-16] and discrete event simulation (DES) [Kar-07]. Factors as product location and type, population density, transportation effort confirm that the collaboration in network design is critical to increase collection efficiency [Han-08]. Hybrid integration of forward and reverse supply chains are considered under OEM management, where efficiency gains are allowed by the integration of various end of life strategies under a single logistic system [Fac-14]. Product-specific case studies based on hybrid Closed Loop Supply Chains (CLSC) models are developed for heavy-duty machinery [Yi-16], electronic equipment [Ami-17], and batteries [Sub-15].

Service implementation also is a possible strategy to increase the value proposition of business models associated with remanufacturing. Embedded sensors for monitoring the product use phase can support manufacturers in deciding the time when a product upgrade should be offered to the customer, and for the planning of remanufacturing processes [Ilg-11]. Such information also can be collected at the collection phase through the implementation of reporting processes between the core collector and the remanufacturing facility [Shu-14, Clo-10, Toy-10, Öst-09]. Cloud-based systems permit an efficient communication between end-users, collectors, and remanufacturers and centralize valuable information [Cor-16, Val-08] to reduce planning uncertainty [Ben-14b, Ben-15b, Eic-14].

2.2.4 Application challenges

If remanufacturing gains increasing attention in both industrial and academic sectors, many barriers and challenges hinder its emergence as an industrial revolution. These challenges can be classified according to their origin. LUND AND SKEELS suggest six criteria to assist remanufacturing planning from the OEM point of view. Product selection describes the selection of products within the product portfolio. A marketing strategy must be conceived to increase remanufacturing product sales in identified markets classified by customer groups and solve conflicts with new product sales. The optimum remanufacturing technology must be investigated for appropriate investment planning. Financial planning must ensure a positive balance sheet and must define the return on investment (ROI) of the remanufacturing investments. Organizational factors such as company culture must be addressed. Finally, legal considerations, if any, must be complied with. MATSUMOTO identified three major requirements influencing the implementation of remanufacturing inside an organization: collection of used products for a stable core supply to bring high productivity and low downtimes, an efficient and stable remanufacturing process induced by the holistic planning of every process step to ensure a stable remanufacturing process, and a demand for remanufacturing products to ensure success of distribution and sales [Mat-11, Mat-15a]. WIDERA suggests four categories of barriers for remanufacturing: core acquisition, remanufacturing activities within the factory, product selling, and supplementary barriers, as illustrated in Figure 2-20.

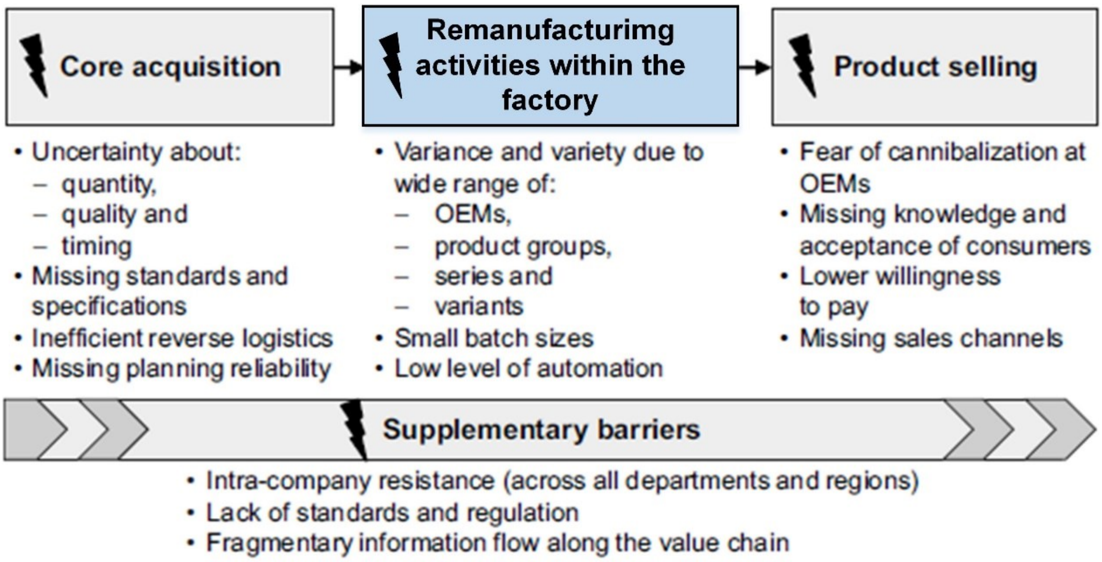


Figure 2-20: Summary of barriers in remanufacturing [Wid-15]

Challenges linked to core collection include a lack of control regarding quantity, quality, and timing for cores arriving to a remanufacturing facility. These issues are caused by uncertain product life, unknown product-lifecycle stage of a defect product, different rate of technological change, and stochastic return pattern in the reverse logistic chain [Gui-00, Lun-09, Öst-09]. According to a survey conducted by GUIDE ET AL., 28 out of 48 remanufacturers have no control over timing or quantity of returns [Gui-00]. As cores are the raw material for executing a remanufacturing process [Ste-98], influences of core supply on the planning of remanufacturing operations have been thoroughly documented. Among the most cited influences, uncertainties about core quality [Fer-06, Gui-03, Jac-00, Öst-08a, Öst-08b, Mit-08, Toe-04], core return quantity [Gui-03, Öst-08a, Sun-04, Tok-00], and timing [Jac-00, Öst-08a] focus on the state of the cores returned. Second, uncertainties in the planning of core acquisition comprise issues due to a variable core price or core failure rates, the effect of individual product usage, and seasonal fluctuation [Gui-03, Öst-08a]. Due to market uncertainties as well as social and technological factors [Han-08, Kar-07, Sab-15], the imbalance between core supply and demand for remanufactured products over time leads to a high error level in core return forecasting, as illustrated in Figure 2-21 [Mat-16]. Third, inefficiencies in the reverse supply chain can be due to an unstructured supplier network [Jac-00, Öst-08a], an increased need for inventory space for cores waiting to be remanufactured [Bar-07, Kin-05], a potentially diverse location of the cores after use [Bar-07, Jac-00], and the costs of transporting cores that do not meet the standards for remanufacturing [Bar-07, Jac-00, Sun-04]. WIDERA adds a fourth category, missing standards and specifications, although it is more likely to happen in external remanufacturers than in OEM companies, aside from the case of bad internal organization [Wid-15].

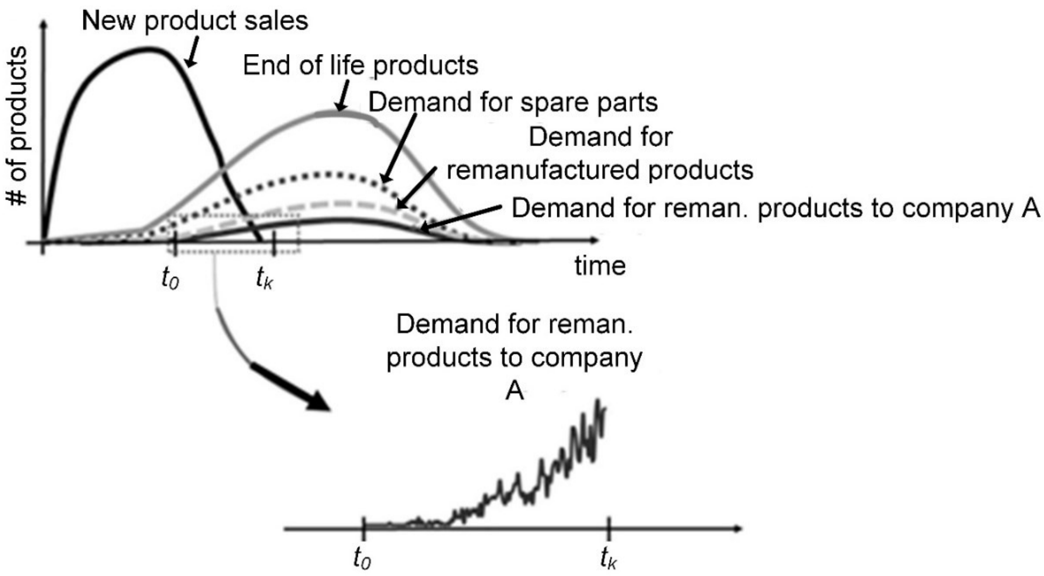


Figure 2-21: Issues in forecasting returned products [Mat-16]

The main issue for the organization of activities within the factory is due to the typical high product variance and variety, characterized by the different product OEMs, series, and variants to be remanufactured. Therefore, production planning is a particular challenge for the overall efficiency of remanufacturing operations [Fer-03, Giu-03, Ham-98]. The uncertainty in planning implies a lower control on effective costs generated by the remanufacturing process, which renders profitability questionable for products with low added-value in the remanufacturing process [Nas-06].

AYRED ET AL. mentions the level of skill necessary in disassembly, which varies with the tasks performed. It is stated that a combination of both skilled and unskilled labour is needed for disassembly processes, but mainly skilled workers are qualified to identify different product types and recover the most valuable parts [Ayr-97]. As the quality of incoming products - with various physical or functional parts defects - is characterized by a high degree of uncertainty, disassembly processes are operations with high variance even for identical products with respect to the time required [Gui-00]. STEINHILPER ET AL. states that the existence of dirt, rust, and oil can increase the time required to perform disassembly processes [Ste-06]. HAUMANN describes the product quality or core quality as a driver of variants. Every single quality variance leads to a different product variant, which results in different operation times [Hau-11]. GUPTA AND GUNGOR studied disassembly line options for product recovery strategies, including remanufacturing [Gup-01]. A disassembly line provides the highest productivity rate compared to single work stations or cells, although the flexibility is lower. In line with this, a gap in the literature has been identified on the topic of the disassembly line balancing problem (DLBP). DLBP is defined as the problem to assign disassembly tasks with specific processing times and prioritize relationships to an ordered sequence of workstations to optimize the performance of the disassembly line. Since its identification, DLBP led to abundant discussions in literature [Avi-14, Ben-14a, Ben-14b, Ben-15a, Fis-05, Gha-15, Kal-15a, Kar-06, Zül-08].

According to SUNDIN AND BRAS, most products are not designed to be disassembled. Products are primarily optimized for manufacturing processes without thinking about disassembly [Sun-05]. This is also a reason why disassembly activities are labour intensive. Increased automation would lead to a lower flexibility and the necessity of full capacity usage due to high capital investments. Mass production or large batch sizes to cover these expenses are not common in remanufacturing. Additionally, the differences in core quality require an increased flexibility, which is not yet given when using automation solutions. Accordingly, flexible mechanized disassembly operations are more common in practice [Ste-98]. However, new approaches for process technologies, tools, and automation were developed which can improve disassembly processes [Bas-03, Sel-07a]. The disassembly process is labour intensive also because of the excess of fixation points in the products to be remanufactured, which were not designed to be disassembled [Ame-95, Bar-07, Gey-04, Ijo-07b, Jac-00, Öst-08b].

According to BARKER AND KING, during the inspection process, the quality of the core must be analysed. With high variance and variety of products, a full observation of the core, combined with the Usage of several optical and mechanical measuring devices, becomes costly [Bar-07]. Therefore, the management of testing activities can have high potential for improvement, as confirmed by earlier research [Ham-98, Sun-04]. Moreover, the management of the cleaning stage can be complicated for specific products. In this case again, effects of product variety on operational efficiency are specifically mentioned [Ame-95, Ste-03].

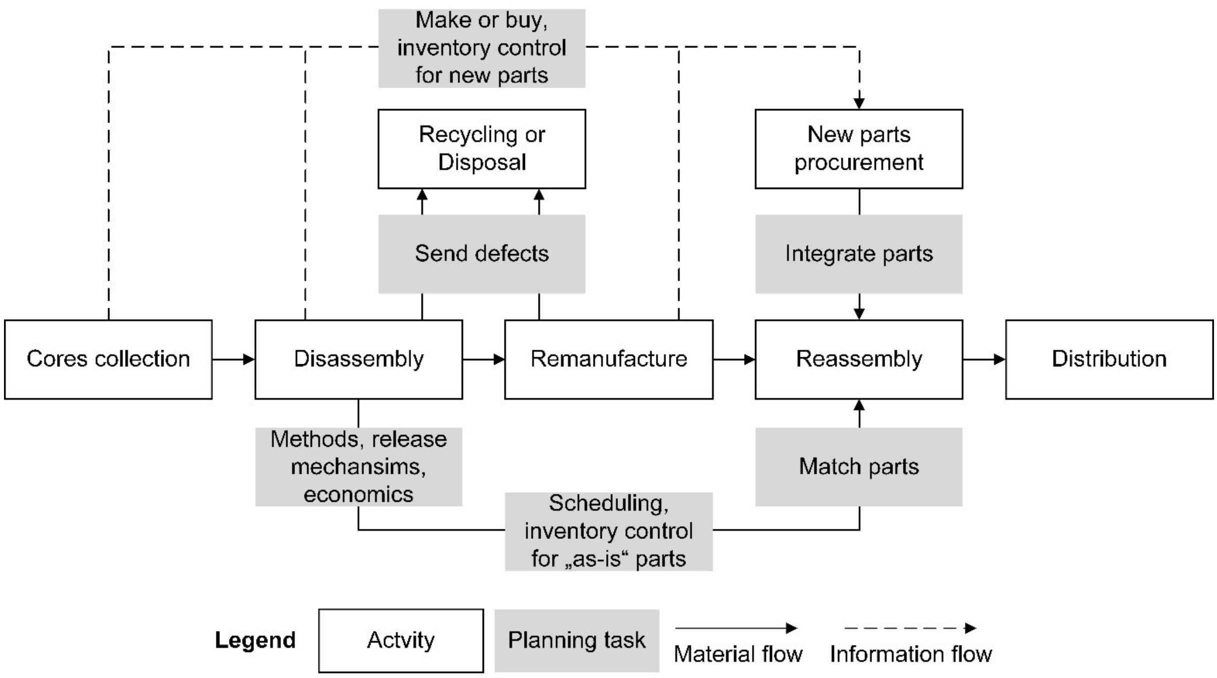


Figure 2-22: Challenges in remanufacturing production planning, adapted from [Gui-03]

In comparison with new production, remanufacturing is hindered by generally low lot sizes, which imply a larger amount of manual work [Gal-06, Sei-04]. This makes the process more labour-intensive, and the variance and variety of products hinders the creation of automated processes [Fer-00]. GUIDE coined the issues of remanufacturing planning in Figure 2-22. Another important factor hindering remanufacturing is the management of knowledge and abilities of the employees inside the facility. The operational management of the variety of components, product references, and processes potentially occurring in a remanufacturing line is handled by experienced employees using standardized work processes [Jac-00]. Surprisingly, both operators and management employees were not aware of the true meaning and implications of remanufacturing as an EOL strategy as shown by GRAY AND CHARTER or IJOMAH [Gra-07, Ijo-04]. Skill management is therefore vital for an efficient remanufacturing process. However, with an underdeveloped education often present in such industries, recruitment of skilled employees can be problematic [Fer-03, Ham-98, Sei-04].

Supplementary issues are raised by decision makers in OEM companies, as they are considering negatively the development of remanufacturing activities because of the assumed danger of cannibalism of their new products' range [Ata-08, Ter-12, Vre-13, Vor-06,]. Through cannibalization, producers are afraid that customers will not buy new products if they know that a cheaper alternative of equal quality can be acquired. Therefore, promotion of remanufactured products is not automatic by OEMs. In some cases, OEMs are constrained from adopting a remanufacturing strategy because of IR becoming too visible on their markets, as in the case of printer cartridges [Mat-11].

When a company adopts remanufacturing, the demand for remanufactured product can be the source of major issues, either because it is too low [Bar-07, Gey-04, Giu-08, Jac-00] or because it is too unstable [Bar-07, Kin-05]. As previously mentioned, remanufacturing processes are less flexible than new production processes, and it is more complicated to adapt product supply and demand when depending on cores as raw material. Moreover, as the differentiation between remanufacturing and other EOL strategies is not widely known, customers are uncertain about the quality of remanufactured products [Ame-95, Bar-07, Giu-08, Ijo-04 Ijo-07b, Ijo-07b, Jac-00, Öst-08b]. As a result, the willingness to pay for a product that cannot be considered as new is as low as 10% for institutional customers and 15% for private customers [Ata-10]. Further, issues such as inefficient supply chains inducing long lead and waiting times, the loss or limitation of warranties during the transfer of ownership, as well as uncertainty about the part´s reliability after the remanufacturing process can build up mistrust between suppliers and customers [Giu-08]. Managing the necessary information regarding cores, suppliers, customer satisfaction, and market development is a major task for remanufacturers [Fer-03].

In addition to challenges linked to core acquisition, manufacturing activities, and product selling, remanufacturers face several issues in setting up their activities. A first challenge is identified in the management of the support functions necessary for all industrial activities, such as human resources, finance, marketing, logistics, and sales. In the case of an OEM, a separation generally exists between new production and remanufacturing, either because of the fundamental and strategic differences between both activities, or because of the profit centres of an organization. As a result of a parallel organization of support functions, inefficiencies and redundancies can be a source of sensitive conflict to be managed [EMF-13, Vre-13, Vor-06]. According to WIDERA, the separation of activities is justified by the paradigm that a maximization of profits is only possible by focusing on new product production [Wid-14], although this statement has been contradicted by advances in research [Ata-10, Gal-12, Vor-06]. Aggravated by the lack of standards, regulations, and identification of remanufactured products, the market entry of CR and IR with lower quality standards can damage the brand image of an OEM [CRR-08a], especially when the remanufacturer’s name is not duly mentioned. A loss of control over the effective producer of remanufactured goods as well as distribution of confidential information can lead to a loss of intellectual capital to third party remanufacturers and enable them to become direct competitors [Ata-10, CRR-08a].

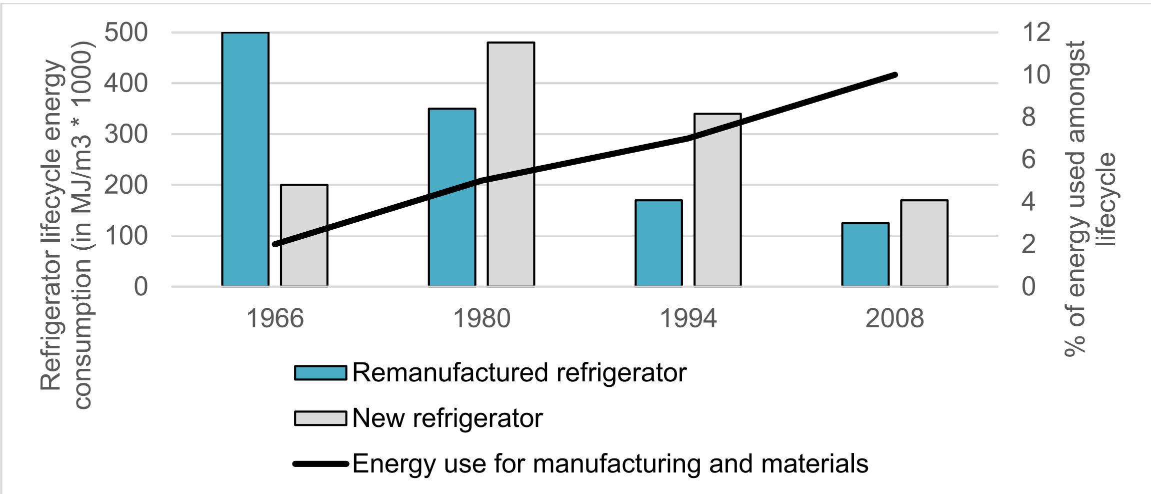


Figure 2-23: Lifecycle energy consumption for new and old refrigerators [Gut-11]

A further important barrier to remanufacturing relies on the environmental impact of the product to be remanufactured. The amount of energy which is needed to manufacture a new product is much greater than the energy needed for remanufacturing. However, it is essential to compare energy consumption in the use phase to the energy needed for production. Research conducted by GUTOWSKI shows that remanufacturing does not result in energy savings when the energy use phase predominates over the production phase and that newer products have lower energy consumptions, as in the case of refrigerators, as illustrated in Figure 2-23. WIDERA developed a tool for a clear identification of the barriers and challenges within OEMs of specific industry sectors. An extensive literature research on the best practices and on practice-oriented information enabled identification of 130 business model characteristics. The business model characteristics, reported on the 4 categories, and the 14 identified barriers, in turn, identified 279 positive, negative, or neutral influences, in an effort to characterize in a systematic and transparent way which business model elements are the most likely to resolve specific barriers [Wid-14].

2.2.5 Growth potential

The Ellen MacArthur Foundation developed an approach to identify the products with high potential for the ability to enter the circular economy. The products are assessed by suitability in terms of product design, reverse logistics, and likelihood of developing circular activities; and by ease of implementing these, which is driven by customer acceptance of circular practices and products, and convenience/incentive to return goods. The qualitative assessment is then validated by experts during interviews. Their results, including fast-moving consumer goods (FMCG), office furniture, white goods, medical precision and optical equipment, office machinery and computers, or even constructed buildings, are insightful although already represented in several documented case studies. Moreover, every EOL strategy is considered jointly in the assessment, making the results difficult to apply for remanufacturing [EMF-13].

To unveil the hidden potential of remanufacturing, the complex issue of defining a methodology to systematically identify the potential of a product to be remanufactured was examined. Critical product factors for remanufacturing include a stable product process and technology over time, longer lifetime from critical components than the product, functional rather than dissipation failure, and high proportion of recoverable value-added [Mat-16]. Further suggestions include a preliminary market existence for remanufactured products and a combined economic and environmental benefit [Tch-12]. To obtain product-related criteria for remanufacturing potential, GUTOWSKI analysed conventional products, such as consumer goods, with respect to their potential for energy savings through remanufacturing. His results state that remanufacturing potential rises with product standardization, higher transport costs, or slower development cycles [Gut-11]. AMEZQUITA ET AL. suggest guidelines for DfR based on general criteria [Ame-95].

ZWOLINSKI AND BRISSAUD transferred into measurable criteria by suggesting remanufacturable product profiles of principal components, clustering products using external and internal criteria. External factors refers to the context of the remanufacturing process, and internal criteria refers to the technical characteristics of the product [Zwo-06, Zwo-08]. The external criteria category is divided into four areas according to the motivation. External economic aspects of new production and the remanufacturing process are compared by examining the profitability of each process to decide if remanufacturing is applicable. External technological aspects aim to identify which technological issues affect the product remanufacturing potential. To assess the integration of a new technology, impact on a product remanufacturing potential is examined. External market aspects interrelate the customers' needs of the specific market sector to assess if remanufactured products have the necessary characteristics to answer to targeted needs. External environmental aspects aim at quantifying resources and waste materials produced during the lifecycle of the product to identify the environmental gain induced by the product remanufacturing [Zwo-08]. To analyse internal criteria for assuming the remanufacturing potential of a product, several authors attempted to identify categories into four factors. First, the product structure is a determinant that will affect the disassembly and collection of the product. Second, the ease to implement quality tests determines the complexity of the product to be evaluated and inspected. Third, the refurbishment ability of the parts for cleaning, repairing, and restoring operations is mentioned. Finally, the valorisation ability of components at their end of- life indicates the intrinsic value of a used product [Ame-95, Sun-10, Bra-96].

STEINHILPER gives a holistic insight of technical, environmental, and economic factors which must be analysed and planned when implementing remanufacturing. Technical criteria refer to the product characteristics and suitability of performing the operational remanufacturing process. Quantitative criteria relate quantity, time, and regional availability of core supply. Value criteria reflect the value added by the OEM in a new product and compares it to the value that can be regained from the core when performing the remanufacturing process. Time criteria compare the maximum product lifetime to the single-use cycle time. Knowledge about the use-phase of the product supports future planning significantly. Innovation criteria characterize the innovation trend in an OEM product range to judge the obsolescence factor of remanufactured goods that cannot be upgraded. Disposal criteria address the challenges and costs to dispose of hazardous, contaminated, defective, or unused components of a core. Interference with new manufacturing criteria judges the extent in which a remanufactured product affects newly manufactured goods in an OEM by inducing in-house competition. Other criteria include market behaviour, liabilities, patents, and intellectual property [Ste-01a]

FANG ET AL. highlight major improvements to the assessment of internal potential for remanufacturing by improving the development of an integrated assessment approach using product design information included in computer-aided design (CAD) data. Constructing on previous works for their development of design metrics for remanufacturing and the identification of sacrificial parts [Bra-96, Des-03, Kro-99], they developed four numerical metrics to measure remanufacturing potential disassembly complexity, fastener accessibility, disassemblability, and recoverability [Fan-14, Soh-14]. The metrics allow comparison of potential processes for disassembly of each component, and actions for their remanufacturing is determined by the failure modes [Lam-01, She-00] and the capacity of the remanufacturer.

In turn, quantitative feedback for the product design team is facilitated by the common use of CAD-based information [Fan-15]

The approaches for identifying technical design elements to determine the potential for remanufacturing a product suffer from a gap between theory and practice, as few academic recommendations to are validated in industrial application. Moreover, several factors are limiting the concept of DfRem. First, when planning design of new products, OEMs are setting a clear focus in designing products for new manufacturing instead of for remanufacturing. The reasons are pure economies of scope: new products are mass produced, whereas remanufacturing only concerns less than 5% of the new products assembled, even for the most successful products [U.S-12]. In specific products with high return rates, such as alternators, OEMs apply design rules to improve DfR, and competitiveness constraints are considered. As with many OEMs, CR and IR are competing for the same cores, regardless of the product brand [Cor-16, Val-08, Wab-14]; design options are made when a competitive gain can be obtained solely in remanufacturing products from an OEM’s own brand.

2.3 Production planning and control

The purpose of production is to meet and satisfy customers’ needs by offering products with specific characteristics and functionalities. Products are to be produced with respect to a specific quality, in a given time, and below a given price. The production process needs to consider these goals to meet customer requirements. This chapter details a general overview of production goals, production planning, production control with quality management, production scheduling with time data management, and discrete-event simulation of production systems as major tools for production planning and control. Finally, these concepts are used to highlight specificities in the remanufacturing industry and opportunities for improvement.

2.3.1 Definition and goal setting

Manufacturing can be defined as the application of physical and chemical processes to modify material properties and includes design and management of production facilities with their respective equipment listed as machines, tools, fixtures, energy and manpower [Lap-14]. A factory can be defined as a place of adding value by production with the help of production factors. Factory planning see a factory as a complex socio-technical system consisting of objects. A clear classification of changeable factory objects is suggested with means, organization, and space to allocate them to the structured levels of the factory. Other classifications are possible for aspects such as resources, processes, and organization. SELIGER suggests an object-oriented framework for the classification of factory objects into five categories: equipment, process, product, and organization, and all framed by the human dimension, as illustrated in Figure 2-24. This innovative graphical approach enables a dynamic classification of value-added modules at different levels of the production system [Sel-07a].

The evolution of factory planning is geared toward a gain of flexibility in the organization. The modern factory is changeable and modular and sets agility targets to improve its responsiveness to innovation targets [Wie-07].

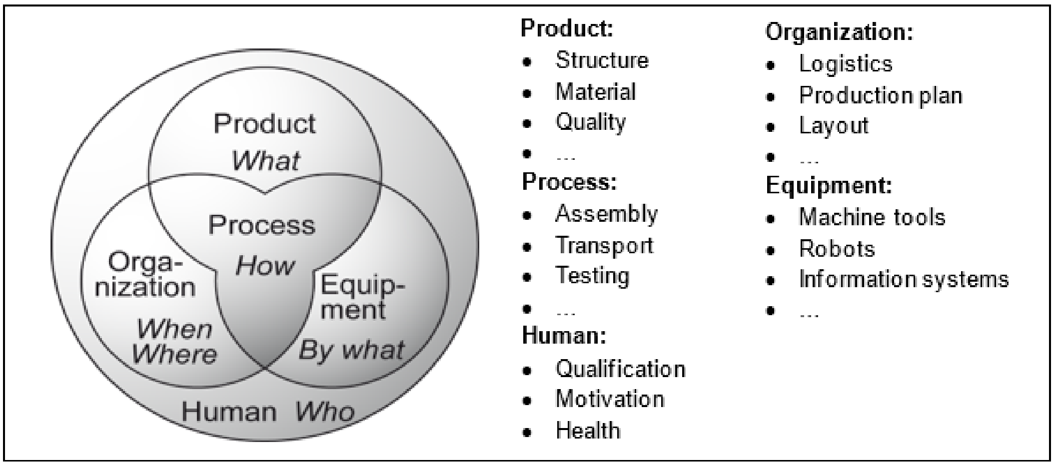


Figure 2-24: Object-oriented factory planning in value stream modules [Sel-07a]

SPUR represents the interaction in production systems according to a simple model of inputs and outputs representing the transformation of material in main, side and residual products by operating production using energy and influencing the environment in Figure 2-25. Manufacturing companies must follow a manifold of demands under a broad array of disciplines and skills and technological specialisations. Products must be manufactured according to design requirements, specifications and standards by the most economical and environmentally-friendly methods.

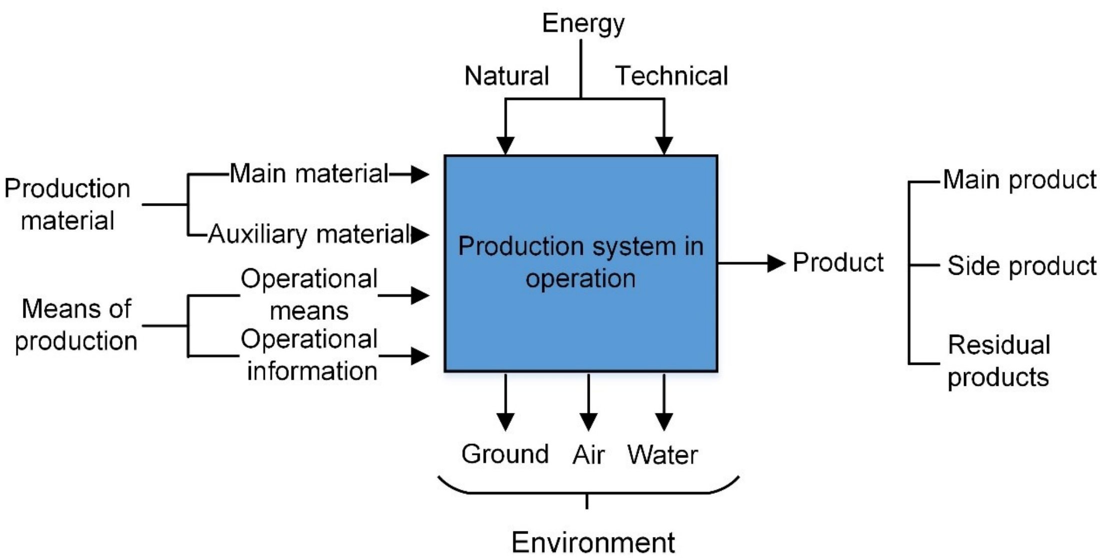


Figure 2-25: Production system model [Spu-12]

The processes should build quality in products from design to assembly while gaining flexibility to respond to shifting customer requirements in highly competitive global market demand, by offering the right product quantity, variety and time. Production networks are large systems whose components are interrelated, so that the timely implementation and management of new materials, methods and information systems technologies require continuous product and process improvement. A constant strive for productivity improvement is characterized by the optimal use of limited resources.

ERLACH mentions that on a general level, the efficiency of production is determined by four different goal dimensions: variability, quality, speed, and economy. Variability determines the level of customization using product variants and the flexibility of production and describes the production adaptation to market fluctuations. Quality indicates the ability to meet product tolerances and the reliability of production processes, as well as determines work ergonomics and work safety. Speed indicates the production lead time, uptimes, and breakdown times, including auxiliary processes as changeovers. Economy measures the productivity in relation to all production factors: material and capacity utilization, energy and space efficiency, and employee productivity. The relative importance of each of the four production goals depends on specific customer requirements. However, the four goals are shown in a logical sequence: a range of products or variants is defined, the quality for products and processes is determined, process times are calculated, and economy must be adjusted with all other dimensions to meet cost requirements [Erl-13].

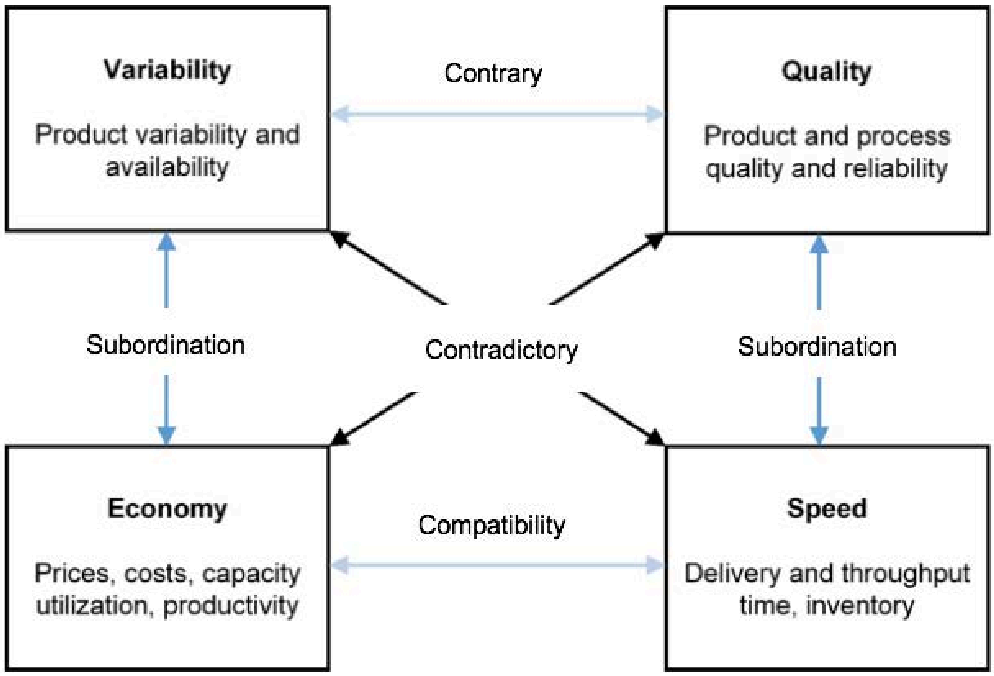


Figure 2-26: Logical square of production goals with six relation lines, adapted from [Erl-13]

The Logical Square of Goals describes the relationships between the four goal dimensions and indicates positive or negative influences between goals. The arising conflicts are categorized by the effects of the impacts achieving one goal has on another one. A contradiction happens when an improvement of one goal will lead to the deterioration of another one. Contrary goals describe when only one of two goals can be improved at one time.

The subordination of goals means that one goal may logically be easier to approach than another one. The compatibility of goals describes two goals that can be improved simultaneously and independently. Six conflicts are endemic between the four goals and are shown in Figure 2-26. Quality and economy are contradictory: an improvement of quality will automatically lead to an increase in skills or technologies for quality assurance processes. Better economic conditions induce higher lot sizes, leading to increased inventory and waiting times and reduced quality in delivery reliability. Second, variability and speed are also contradictory: if a higher number of variants is produced, the process mechanically slows down, which results in a deterioration of speed. Variability and quality are contrary: an increased range of products increases the complexity toward reaching quality goals, while an improved quality dimension restricts flexibility and the amount of variants. However, adaptation is possible. Variability and economy are subordinated, as it is easier to achieve a better productivity than it is to increase the number of product variants, but both goals can be improved to a certain level. The same relation prevails in quality and speed because it is more difficult to increase quality than it is to reduce speed. Economy and speed illustrate compatible goals, as both dimensions do positively correlate to a certain level and can therefore be improved simultaneously [Erl-13].

2.3.2 Production planning

Production planning depends on scope definition. It differentiates the resource view, which concerns technical and human resources needed to maintain the process, from the space view, where appropriate space is allocated for the resources. The processes are performed by resources in space and therefore link both views. At the structuring level, production networks represent the resource as production units along the supply chain, joined by material and information flows, including one or more geographic sites linked by transportation means. At the end of the chain, single workstations have their value-adding operations such as work piece and tool handling, which is organized in individual workplaces where ergonomics and safety guidelines for the employees are defined. Workplaces can be arranged into cells to perform most of the necessary operations to assemble a work piece, including quality assurance. Cells and systems can be merged in the space view into a working area, which describes a zone with similar working conditions in terms of floor load, height, climate, and light energy provision. If the processes are interlinked, the system is known as a manufacturing system or an assembly system. Several systems are considered as segments and contain tasks such as manufacturing, assembly, and packaging. Segments are commonly structured into manufacturing, assembly, buffers, and quality measurement resources. They typically need one or more buildings that also contain technical and staff rooms. A site concerns a production unit containing several product segments.

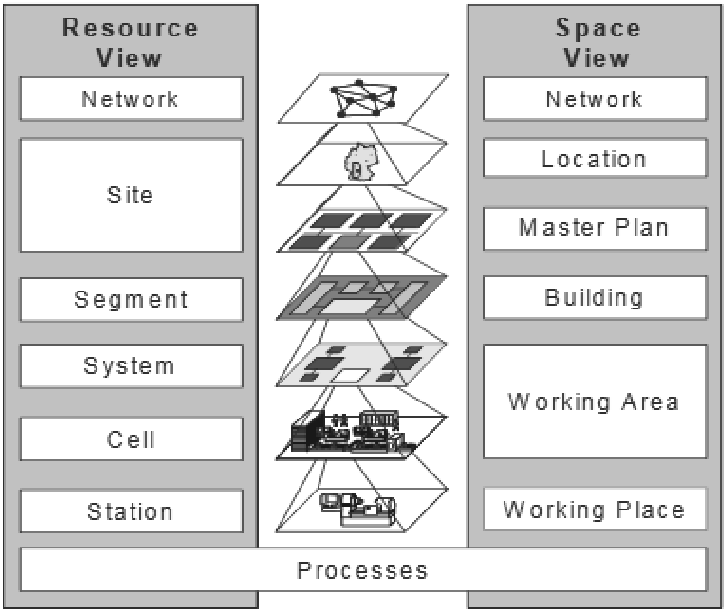


Figure 2-27: Levels of production under resource or space view [Wie-07]

From the space view, a master plan is defined that describes a factory location layout including factory, offices, and infrastructure equipment and is illustrated in Figure 2-27. The location describes the space where a site is geographically embedded as well as the local infrastructure [Wie-07]. Factories are industrial organizations conceived for profit-making and setting cooperative goals. The organization of production includes the factory, information flow, and production process [Erl-13]. They are organized in distinctive areas in which various processes and facilities are interrelated. Factory elements are operating facilities, divided into manufacturing equipment, auxiliary equipment assisting manufacturing equipment, and technical building services providing good working conditions, as well as manual workstations [Sch-14, Thi-11]. Activities inside factories are organized in projects, relating a series of activities to a tangible output. Project management activities are needed to plan, direct, and control resources to comply with time, cost, and resource availability constraints [Wys-07]. Projects in factories are led by a project management team, which is, in turn, positively or negatively influenced by stakeholders internal or external to the factory, according to their own interest. Manufacturing companies are subject to continuous changes, as they need to adapt to a living framework of influences, many which are beyond the control of the production management [Sch-14]. A flexible factory planning is needed for internal and external reasons. Internally to a company, corporate strategies can change rapidly: new products must be developed, process must be continuously improved, and machinery must be adapted to the evolution of production technology. The external environment is also in constant evolution: innovation, legal framework, global economy and the natural environment are factors to be considered [VDI-11].

The VDI 5200 norm for factory planning suggests a linear representation of the steps for factory planning, as illustrated in Figure 2-28. In goal definition, the objectives of the company and the factory are evaluated by the establishment of assessment criteria and work packages for the creation of the factory plan. Data about the product, production, and real estate are then acquired and analysed to verify the achievability of the goals. In concept planning, an ideal state of the factory is determined by dimensioning a first structural plan of business and production chain processes, before a realization plan is defined and assessed for implementation variants. The fine planning phase concerns the preparation of functional requirements after cost and layout details have been checked and legal compliance ensured. In this phase, the production process is already defined up to the design of the workstations. In preparation for realization, tenders are placed to ensure the resource availability; human resources are planned, and ramp up of production is determined. The monitoring of realization involves a coordinated agreement of all relevant project documentation and assessment to determine if cost estimations are realistic. Run-up support is the phase where the SOP is prepared and run, and the effectiveness of the production performance is evaluated. Finally, in the project termination phase, the project goals are reviewed for variances, and the sustainability of the knowledge gained for the continuous improvement of the factory operation is assessed [VDI-11].

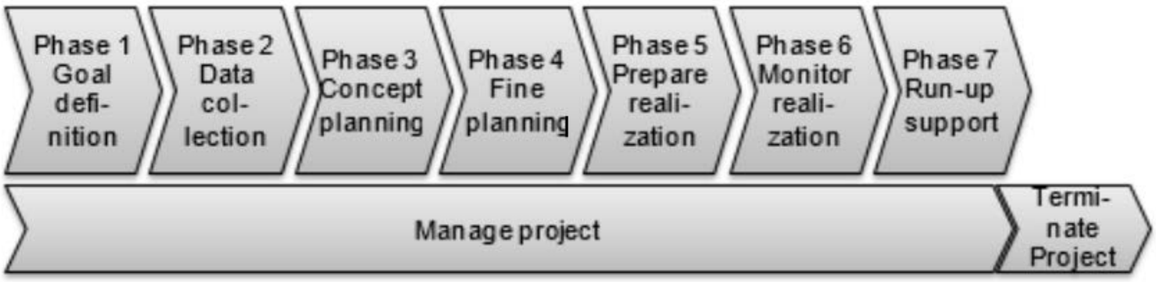


Figure 2-28: Factory planning phase model [VDI-11]

Planning of production processes may need to include different process steps for manufacture of product variants, requiring different production technologies, in turn. Therefore, the factory is divided according to horizontal or vertical segments. Horizontal segmentation is equipment- or qualification-oriented to material characteristics, which result in a job-shop production arranged by machine technologies or by workers' skills. These job-shops create long distances between areas needed for the same products, and may result in long transportation times. In contrast, vertical segmentation classifies production areas by product families. A product family consists of several products with similar characteristics in production processes, raw material, or parts. Vertical segmentation leads to a flow-oriented parts production process.

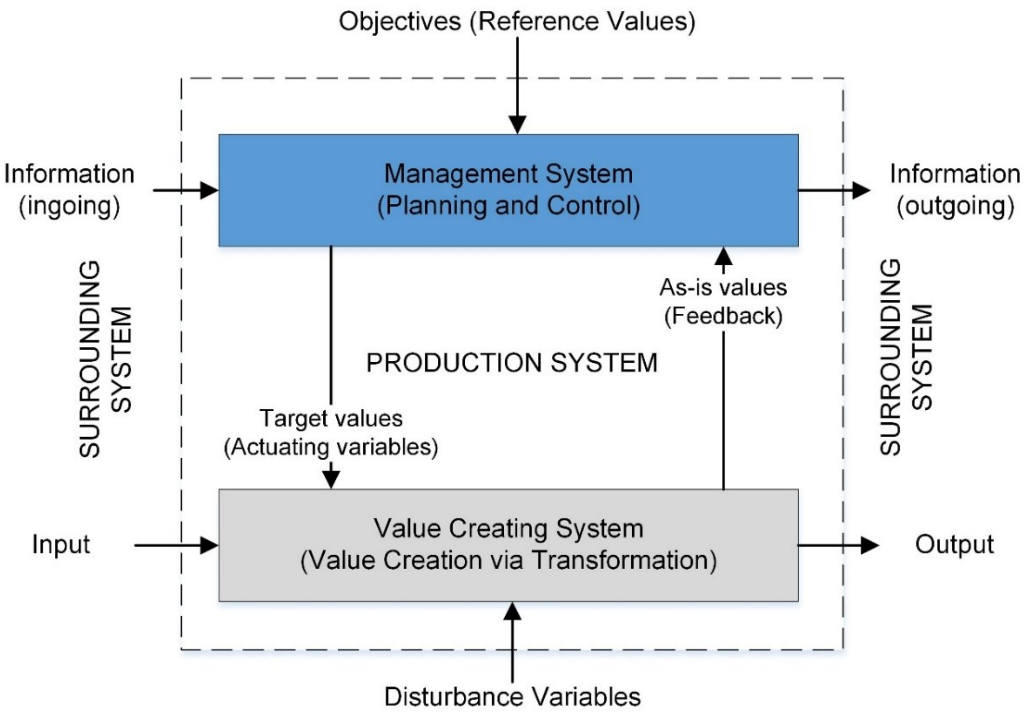


Figure 2-29: Control loop of production management, translated from [Dyc-10]

Customer-oriented production processes further divide the product families in business types by using a market-oriented segmentation based on demand frequencies as well as market opportunities and attractiveness of products. Resources are then allocated in a combination of both product families and business types [Erl-13]. The difference between the objectives defined and the results of the production system is due to the disturbance variables, which may not be planned in advance. The importance of production control systems is represented in the form of a loop in Figure 2-29.

2.3.3 Quality control

In early 20th century, Henry Ford introduced simple quality control mechanisms to sort out defective products. Since then, Quality Management (QM) has continued to evolve. First, quality planning methods demonstrated the advantage of preventive over reactive methods. The inclusion of customer satisfaction and the use of statistical data resulted in quality management methods such as Six Sigma in the 1980s. The two main standards for quality assurance are ISO 9001 and ISO 9004. These two standards complement each other: while ISO 9001 specifies requirements for a quality management system that can be used for internal application by organizations or for certification, or for contractual purposes [ISO-15b], ISO 9004 provides guidance to support the achievement of sustained success for any organization in a complex, demanding, and ever-changing environment, by a quality management approach with the implementation of a Total Quality Management (TQM) [ISO-18]. This approach can avoid many of the most typical causes for failure of collaborative ventures [Zhe-02]. TQM is a process which collects all the interests of the individual participating parties and that balances them to suit one another. As quality management is the bases of all successful collaboration between companies the TQM is important for the implementation of production networks, as the basis of Modern quality management (TQM) principles [Pfe-05, Pfe-14].

QM is the key for an organization to differentiate between producers within saturated markets with high competition. In such an environment, companies have to demonstrate advantages of their products to ensure business growth. According to ISO 9001:2015 standard, quality is the degree to which a set of inherent characteristics fulfils requirements [ISO-15b]. In consequence, a degree of fulfilment of inherent characteristics equals the level of requirements met from internal or external stakeholders, according to the nature of the process in question. Improving process and product quality serves to decrease costs due to a lowering of defect rates, product returns, or customer losses, but also helps in managing processes and products [Kam-13]. In other words, a holistic QM system determines the quality policy, goals, assurance, planning, and control as well as continuous quality improvement [Pfe-14].

Quality policy determines the intentions and directions of the top management of the organization with regard to quality. Top management ensure a realistic policy according to values and goals and organize their implementation and measure implementation success by steering quality goals. Quality goals must be specific, measurable, achievable, relevant, and timely (SMART) and are often customized to each department according to the specificities of their function. Quality planning ensures that resources are available for the implementation of quality goals. It organizes resources by target goals, actions, and lifespan and assigns responsibilities for the implementation. Quality control monitors the completion of actions from quality planning. Quality assurance builds trust toward the fulfilment of an organization´s quality planning. For example, quality certificates can be designed to gain trust among customers and other stakeholders. Continuous quality improvement sustains the fulfilment of quality goals. For example, companies benchmarking the respective products and processes can achieve best practices and see continuous improvement [Pfe-14]. A thorough QM leads to a balanced load, shorter throughput times, lower inventory, fewer defects, less rework, improved customer satisfaction and, all in all, improved productivity [Kam-13].

The QM actions fields can be instantiated in implementing the Plan, Do, Check, and Act Cycle (PDCA) cycle. In the first stage, Plan, an improvement project is begun with Quality Planning by setting Quality Goals as indicators using metrics, and conceiving the necessary steps, methods, and boundaries. Execution of the steps follows using Quality Control with Do. In Check, effectiveness of actions is evaluated according to the set indicators as suggested in Quality Assurance. In Act, experience gained in current project defines Continuous Quality Improvement [Kam-13, Pfe-14]. Lean and QM literature provide many tools and methods for different purposes and circumstances. KANJI AND KAMISKE list the 13 most popular and valuable QM methods that can be embedded in the PDCA-cycle. After a short description of QM tools, an adaptation to the remanufacturing environment is suggested [Kan-96, Kam-13].

The 8D report is a process model that employs an eight-step problem-solving process in QM. Sustainable problem solving is achieved, and immediate actions are presented to prevent further disruptions. This tool is often used to handle customer complaints [VDA-09]. Guidelines are detailed regarding actors, responsibilities, actions, and implementation follow-up [Kam-13].

The Seven Quality Tools (Q7) are a combination of methods for supporting the troubleshooting processes. They aim at identifying and investigating failures in a systematic way. Failures are initially detected by check sheets, run charts, and histograms. Next, these failures are analysed using Pareto diagrams, scatter diagrams, brainstorming, or cause-and-effect diagrams [Kan-96, Kam-13].

In contrast to the Q7, the Seven Management Tools (M7) are seven graphical tools that classify and illustrate the problem-solving process rather than detecting or analysing the failures which occur. The major M7 fields are data analysis, solution finding, and solution implementation. M7 are primarily used within the first stages of the product development process [Kan-96, Kam-13].

Failure Mode and Effects Analysis (FMEA) is a systematic and well-structured approach for finding potential failure stages within the product or process planning phase, by adapted Product FMEA or Process FMEA frameworks. FMEA includes the planning of preventive, detective, or corrective actions. Beyond prevention, FMEA ensures a high reliability level during the entire product lifecycle. The origins of failures and their effects on the product or process are evaluated for each key assembly of the product. Using a risk analysis, the occurrence (O), severity (S), and detection (D) of failures on a scale of 1 to 10 is established according to standard data [Kam-13] or sector specific data [VDA-12], and the risk priority number (RPN) is assigned based on the O, S, and D grades. As a high RPN calls for immediate preventive actions, this indicator acts as a priority list.

The Fault Tree Analysis (FTA) is directed at the analysis of complex systems in a quantitative and qualitative way [Kan-96]. Critical system components and operational conditions of a predefined failure are interrelated using logical gates and events. Then, the probability of a breakdown is calculated to indicate the overall probability of default for the investigated top-level entry. This tool is particularly useful for a systematic understanding of root causes [VDA-03a].

Quality Function Deployment (QFD) is a systematic method used in the Quality Planning phase for designing a new product [VDA-03b]. The House of Quality (HoQ) depicts a house with several levels that illustrate the steps for technical requirements to answer customer requirements and includes representation of competitors. QFD gives a precise input for the prioritization of new functions in a future new product [Kam-13].

The Design of Experiments (DoE) QM tool is used to plan and statistically evaluate experiments for robust products and processes and is employed during the Quality Planning phase. The entire process should be seen as a system with ingoing and outgoing values. The overall goal of the DoE is to identify the most important quality feature/output variable M and to adjust the control factors z in such a way that the product or process becomes insensitive toward the disturbance factor x [Kam-13].

Statistical Process Control (SPC) is an operational QM tool that monitors production processes via the use of statistical analytics. To guarantee the constant quality of a product, the process must be capable, with predictable parameters, steady occurrence, and causes without influences. First, a Machine Capability Analysis (MCA) verifies if machines can manufacture within tolerances and minimum requirements. Second, the Process Capability Analysis (PCA) determines if a predefined process is capable of achieving minimum product quality requirements. Once requirements are secured, SPC is performed on test samples using statistical parameters, such as arithmetic average or erratic value, and compared to tolerances in a quality control chart [Kam-13].

The ABC analysis is devoted to focusing Quality Planning on the most important measures. It aims at classifying the relevance of value generated by investments in quality into three categories: A, B, and C. Based on the Pareto principle, it proves statistically that 5-15% of A-class measures ensure 60-85% of value, whereas 20-40% of B-Class measures represent 10-25% of value, and 50-75% of C-class measures secure 5-15% of value [Kam-13].

A Strength Weaknesses Opportunities Threat (SWOT) Analysis is used to identify strengths and weaknesses of a product and opportunities and threats for its future evolution. It is an investigation of the current performance within the destination market of the product as compared to products from competitors. The tool outlines necessary changes to sustain the success of the products [Kam-13].

Stakeholder Analysis identifies the most valuable stakeholders for the company, by a graphical analysis of the interrelations between all relevant stakeholders to uncover interferences and contrasts. Stakeholders may include governments, customers, suppliers, shareholders, staff, or individuals who have interests or claims toward the organization. The result of this analysis is that the organization is better able to orientate their goals toward their most valuable stakeholders [Kam-13].

Benchmarking is performed to identify best practices using a comparison of measurable performance criteria to assess a selection of internal or external products, processes, or strategies. Internal benchmarking applications can concern departments of a company or organizations associated within a concern. External applications include competition benchmarks for several manufacturers of a same product to uncover success factors, sector-based benchmarks to detect upcoming trends in a specific market, or sector-independent benchmarks to identify new approaches to an issue [Kam-13].

The Theory of Inventive Problem Solving (TRIZ) is a systematic approach for innovative problem solving for technical and scientific issues. The method offers 39 physical and technical parameters for defining requirements and suggests an interrelation of these parameters to define an innovative method according to 40 innovative principles. First, a problem analysis ensures a guided abstract description. Analogies between similar abstracts are identified, allowing listing of previously developed solutions to provide inspiration for the current problem through inverse transformation. However, TRIZ requires intense training [Kam-13].

2.3.4 Time Data Management

Time Data Management (TDM) can be defined as a set of activities to determine, pre-process, apply, and administrate time data within a company [Tsc-00, Kuh-14b]. TDM is primarily used in manufacturing companies to specify time values for strictly identified work content.

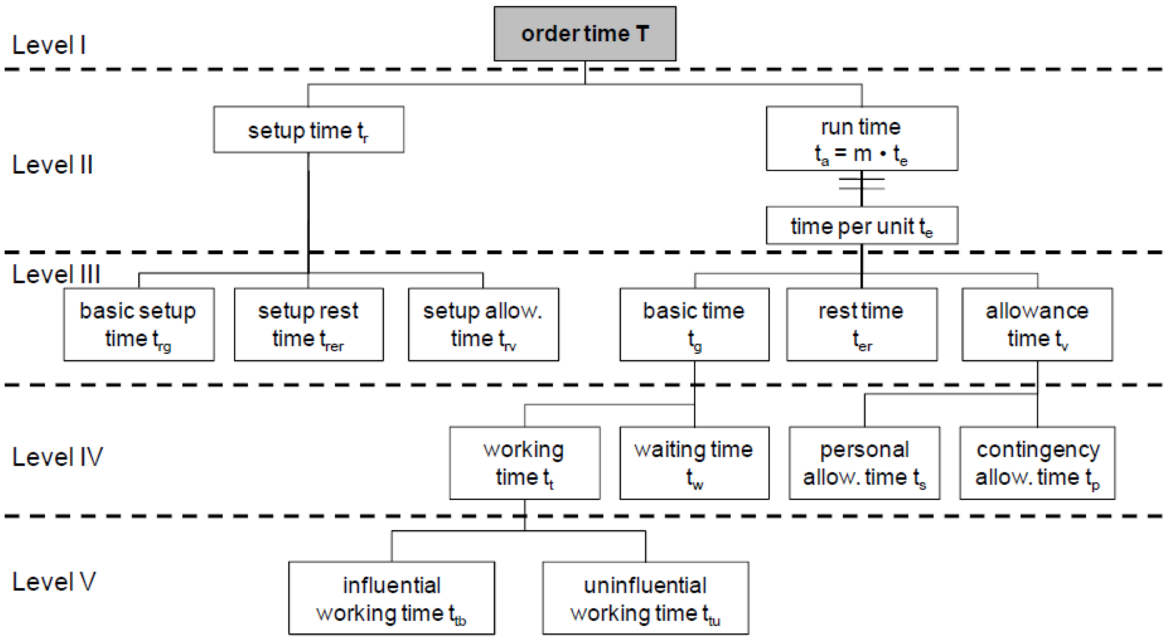


Figure 2-30: Hierarchy of time categories for human work measurement [REF-02]

Time data is used during the product design phase to assess the effects of product design on the assembly-related production costs [Boo-11], and during the production planning phase for the design or work systems and for the monitoring of production output and worker productivity [Zül-96, Wie-96]. Hence, TDM serves as a basis for decision making in strategic and operative planning in industrial engineering for its contributions to labour flexibility, process organization, or performance assessment by industry experts [Dom-10, IFA-15, Pet-11].

TDM provides relevant information for the analysis, design, modelling, and simulation of production systems and of human work conditions [Gro-07, Wie-10]. However, TDM is only partially used in industry because of a lack of competences for its application or the fear of additional costs and time necessary for its adequate application [Kuh-14b]. Although many authors recommend the use of TDM in production or supply chain management [Dom-10, Pet-11], they do not consider the method for acquiring the time data [Dua-12, Sor-12]. The German Association for Work Design, Industrial Organization and Company Development (REFA) focused on developing knowledge and experience for TDM since 1924 [REF-16]. REFA developed a structured hierarchy of time categories for human work measurement according to the nature of the activities effectuated, as illustrated in Figure 2-30. Level I represents the order time for a defined work activity, which is composed of setup time and run time per order or time per unit produced at level II. Both run times and setup times are further divided in level III into basic time at the workstation, rest time for workers to recuperate outside of working hours, and allowance time for pauses during the work day. In level IV, the basic time is categorized into effective working time and time spent waiting for performing the next operation; and allowance time, which is distinguished between personal pauses and collegial pauses when all workers stop working together. Level V serves for a further separation of working time according to the value-added character of the operator work sequence from the viewpoint of the customer [REF-02].

To provide a holistic view of systematic factors underlying TDM approaches, KUHLANG ET AL. developed a morphological analysis based on methods and procedure for each relevant process related to TDM activities [Kuh-14b]. Attributes from this work are selected to describe the TDM types and constitution of time values, as they provide an overview about the variety of methods available. HEINZ AND OLBRICH suggest a segmentation of the methods available for TDM into two categories, based on whether the objective is determination of actual times or target times [Hei-89]. Actual times are based on the observation and measurement of activities at the workplace using stop watch time studies, through external or self-inquiry to the worker, in sampling of standard work processes or via machines for an automatic data collection [Gro-07]. Target times aim at deriving time value for a series of movements by the statistical aggregation of time values and influencing factors [REF-02, Pet-10] and can be obtained by calculation, comparing and estimating, or with predetermined methods for time study (PMTS) [Hei-89]. To constitute a database of standard time values for a reliable description of work methods, actual times need to be processed prior to their integration, when target times can be instantly integrated. The association of standard time values using a system of building blocks allows an accurate estimation of the time of work methods and their effective and efficient reproduction in other contexts, provided that the TDM chosen provides trustworthy data [Bok-06, Kuh-14b].

The widest application of PMTS is Methods-Time Measurement (MTM), named after the declaration that the method defines the time necessary for performing a specific activity. The underlying principle of MTM is the division of work philosophy developed by Taylor and the development made by Gilbreth, who described in 1911 that the run time of a manual process is controlled by a person's skill, qualification, effort, and method [Gil-11]. This standard was developed in the 1940s and published by Maynard et al. in an eponym book in 1948 in New York, U.S. [May-48]. MTM was the precursor of all PMS. The goal of MTM is "First Time Right". The flagship company asserted that the main advantage of MTM compared to other techniques for work process management is the ability to plan and improve the methods in the planning development phase of the factory planning phase model [MTM-08, VDI-11].

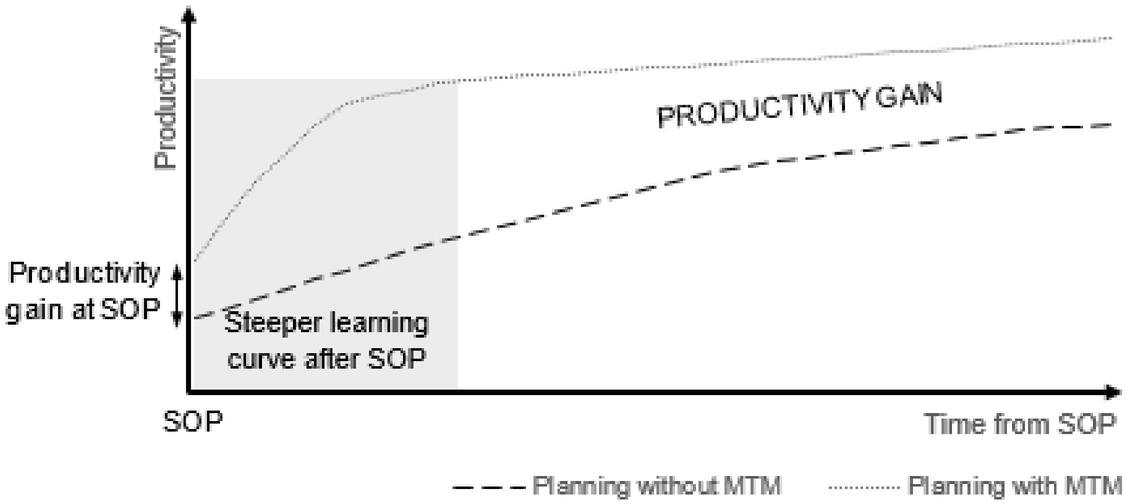


Figure 2-31: Productivity comparison with and without MTM [MTM-08]

MTM has the advantage for work process organization of fulfilling four essential criteria for TDM. First, the method is reproducible within entities of an organization, as it is described with a standard codification. Second, it preserves a unique method-time relationship, as the times suggested are a direct result of the combination of codes for describing a work process. Third, it offers an advanced planning of methods and time, as its application is possible both in the planning phase before the Start of Production (SOP) as well as in the improvement phase when the processes are applied, as illustrated in Figure 2-31. Finally, it represents the only internationally recognized time standard for the breadth of its industrial customers and national offices, coordinated by the International MTM Directorate (IMD). MTM diversifies its application using a system of building blocks statistically constructed on the basic MTM1 system originally developed by Maynard et al. MTM is organized according to the production type defined by the frequency of repetition based on the typical lot size to be manufactured. MTM also has the advantage of a wide array of methods directed to the improvement of psychical and physical ergonomics with the Holistic Ergonomic Index (HEI) and the improvement of assembly friendly products from MTM analysis with the ProKon software [MTM-08]. The more repetitive the process is, the higher the level of detail that is considered and the more accurate but more time-consuming the analysis results [Bok-06, MTM-08]. Similar PMS proprietary methods exist: examples include Accenture Consulting's Maynard Operation Sequence Technique (MOST) [Acc-16] and activity-specific applications needs in the apparel industry such as the SawEasy system [Saw-16].

2.3.5 Simulation of production systems

Manufacturing companies are under pressure by global competition to continuously increase the efficiency of their production systems. In new manufacturing, the organization in global production networks also leads to an internal competition between production units of the same manufacturer. In parallel, product complexity increases to match increasing requirements of customers, who can choose from a broader product offering, as the liberalization of international trade led to a direct competition between manufacturers [Ban-10].

To provide factory management teams with an adequate tool to aid in decision-making for the implementation of production systems, Digital Factory emerged as a widely accepted science. Its principle lies in the modification of production processes using IT tools with an object oriented method including relevant production, storage, and transport activities. The simulation tool is used in any hierarchical level of production management, for purposes such as the choice of a factory for a new product, optimization of resources, and assessing the extent of potential flexibility in product variety, variance, or lot sizes [Ban-10]. Simulation of production systems became an important field of research and offered various IT-based applications, with the example of the Siemens Manufacturing Operations Management (MOM) software suite customized to various levels of customer requirements [Sie-16a]. A simulation study starts by the formulation of a problem, followed by the definition of a conceptual model populated by data collected within the entities concerned. The simulation model is then implemented, validated, verified, and accredited using simulation experiments. Thus, results of the simulation are documented and analysed in the form of reports. As methods and rules are defined in software, the validity of simulation results depends on the accuracy of the data entered [Cim-10].

The most developed simulation technology is called Discrete Event Simulation (DES). It conceptualizes reality as a world where a system consists of discrete mobile units of traffic that flow with the aim of making transactions with scarce and scattered resources; the system is known as transaction-flow world view [Sch-09]. SCHRIBER describes a discrete-event simulation as one in which the state of a model changes at only a discrete, but possibly random, set of simulated time points, called event times. Often, two or more traffic units are manipulated at the same time point and are serially considered based on a predetermined order [Sch-09].

The person in charge of the information input in the simulation model is called the modeller, and the developer of the modelling language is called the designer.

Simulation software identifies discrete events based on specific software rules and logic for simulation time and events management [Cim-10]. The term entity names a unit of traffic or transaction that can react to events in the simulation. A distinction is made between external entities explicitly expected by the modeller and internal entities generated by the simulation software [Sch-09]. DES models use entities, resource control elements, and operations as object categories. Separation is made between dynamic entities that flow into the simulation model, as work pieces in the case of material flows, and static entities which represent resources influencing the dynamic entities, such as operators or machines. The control elements are the variables in the code that define the rules of simulation and support logical alternatives based on the system status, defined by simulation parameters. The operations represent the events happening to the entities during their flow in the simulation model [Sch-98].

A simulation model aims to design a virtual prototype of reality to predict, anticipate and improve potential efficiency issues by combining descriptive elements and logical alternatives of their behaviour. These alternatives consist of several replications producing unique statistical results of a unique set of numbers by means of simulation. The cycle of replications initializes the model by performing the simulation until target conditions are met; the result, called a run, is reported in the system database. During a run, the simulation internal clock reports the simulation time for discrete steps of unequal size in the Entity Movement Phase (EMP). Once all the possible discrete steps are performed, the clock is advanced to the next event in the Clock Update Phase (CUP) before the two-step cycle repeats [Sch-09]. Entities are given five possible states, according to their position in the simulation model and the interaction with static entities. They can be ready to be processed, active as currently processed, time-delayed until a determined simulation time, condition-delayed until a specific condition is met, and dormant as the condition for release is specified by the simulation modeller. According to their state, in the context of manufacturing systems, simulated workstations can either be working when they are in operation, waiting when ready but without work pieces to process, or blocked when waiting for a next workstation to be ready before being again ready to work [Sch-98].

Data is managed inside the simulation software by a system of lists that organizes entities in their five states. The Active Entity consists of one ready entity being currently processed until it changes to another state, defining the action undertaken in the EMP. Further ready entities are stored in the Current Event List (CEL) and managed according to the First-In First-Out (FIFO) principle. The Future Events List (FEL) stores all time-delayed entities according to their move time, and orders their priority to be transferred to the CEL. The time evolution in the FEL is determined by the time value advanced in the CUP. The Delay List (DL) is composed of all condition-delayed entities waiting for their source of delay to be achieved. If the delay is easy to relate to a condition, it is automatically released into the CEL using a related waiting system. Should the condition be too complex to identify, the poll waiting system allows the system to perform routine checks implying specific computations, whose results decide if the entity can be released to the CEL. The modeller decides which logic will allow dormant entities to enter or exit the User Managed Lists (UML).

Designers use many programming languages for supporting simulation models. General purpose languages like C++ are normally used when the programming logic is specific or when the simulation results are given a higher importance than the graphical user interface. The advantage of general software is the potential degree of freedom for adapting the simulation objects to reflect the real situation to simulate. Domain-specific simulation languages (DSL) are languages based on the discrete event simulation; they can be used when the programmer does not have a deep knowledge of this simulation technology [Fis-01]. Identified limits of DES software are the handling difficulty for inexpert users [Ban-98], the choice of the software fitting the application characteristics by offering the right functionalities and potentials [Swa-07], and the complexity of the model to be simulated [Cim-10]. Moreover, the simulation of complex models involves a significant amount of entities to be simulated and directly impacts the time needed by the software for the execution of the simulation run [Cim-10]. To succeed in matching criteria able to offer a realistic simulation of the real environment, simulation models should offer flexibility in setting simulation parameters, offer an acceptable execution time, and have a scalable architecture to reuse data [Lon-08].

2.3.6 Remanufacturing systems

The characteristics of remanufacturing processes are different from manufacturing due to additional management of core returns, disassembly, inspection and sorting, cleaning, and reconditioning processes [Ste-98]. Most remanufacturers have to manage diverse product lines to achieve an economy of scales [Ayr-97]. Furthermore, PPC in remanufacturing operations is further complicated by small batch sizes with an increased variance in operation times required due to endemic core quality and product variance and variety issues [Gui-00, Ste-98]. In addition to an increased pressure to reduce remanufacturing lead times induced from increased competition between remanufacturers, remanufacturing systems lack formal systems such as Enterprise Resource Planning (ERP) to achieve effective production management.

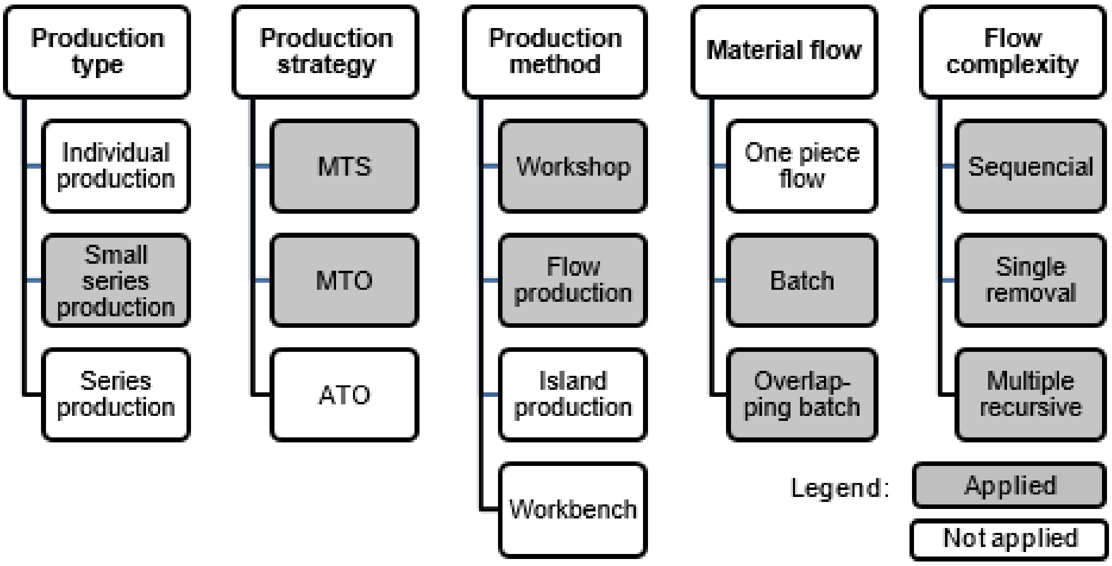


Figure 2-32: Production design in remanufacturing firms, adapted from [Lun-10]

GUIDE mentions seven characteristics that specifically complicate production planning and control in remanufacturing: uncertain core timing, the balance between return and demand, variance in disassembly, uncertainty of recovered materials, reverse logistics management, stochastic material matching issues, and variable processing time [Gui-00]. Remanufacturing companies are characterized by a high variance in products for serving niche markets and complying with customer requirements. Depending on the company strategy, operations are organized in a combination of make-to-stock (MTS), make-to-order (MTO) and assemble-to-order (ATO). MTS stands for a production without current customer order, made in anticipation of future needs. MTO is customer specific and indicates that production only starts when an order actual is communicated to the remanufacturing facility. ATO is a hybrid solution in which assemblies are produced and stored before the final assembly process is performed upon a customer request. Remanufacturers use techniques for production planning and control purposes such as Just-in-Time (JIT), Theory of Constraints, or classic inventory control techniques [Gui-00]. Hauser analyses remanufacturing companies with regard to their production design, as illustrated in Figure 2-17. In most companies, small series production processes are organized in single workshop units and partly connected through flow production. The material flow is organized as batch production, when parts transfer between workstations only when all parts of the batch are processed. Overlapping batch production is the most common practice. In many companies a sequential material flow is implemented. The main challenge is the multiple reprocessing of products due to a high variance in core quality and uncoordinated process steps [Lun-10].

LUNDMARK ET AL. summarize the main issues in PPC as uncertainty and complexity. For core collection, a large number of suppliers demands a complex management. Core forecasting uncertainties in demand and in supply require an increased amount of flexibility in production.

An unknown balance in demand and supply by using inventory management automatically increases costs as well as production planning and control complexity. Uncertain supply further results in quality uncertainties, which in turn results in a need for stochastic routing for the remanufacturing processes. Complicated disassembly due to core variety and variance leads to variable processing times and a rise of production planning. Matching small batch sizes in manual disassembly with automated cleaning and manual inspection and sorting will often result in inefficiencies. Within the redistribution phase, an uncertain demand and an increased complexity are caused by immature markets, the perceived lower quality of a product, niche markets, and product offerings. The influence of new product innovations by OEMs can also suddenly impact the price or the demand for remanufactured products [Lun-09]. Material matching restrictions mean that the identity of the assemblies of a product must be matched before a core arrives at its final stage as a remanufactured product. Mixing parts and components must be avoided during processing and can represent a real challenge with high product variety of similar product families, as in the case of alternators. This restriction strongly depends on product characteristics [Mäh-07]. STEINHILPER illustrates material and information flows between processes, material sourcing and product distribution in Figure 2-33.

A prerequisite for remanufacturing planning and control is the accuracy in planning product returns through determination of the quantity and quality of the cores as well as the time they will be available on the market. Such information is necessary for the design of reverse logistics networks, resource allocation, and inventory planning [Clo-12]. Approaches to solving the issue of core return forecasting can be classified into two categories: estimation of the length of use phase based on sales record or time-series analysis of historical collection data. The first method was developed using simulation and fuzzy-logic models [Mar-02], fuzzy-coloured Petri-nets [Han-07], grey systems theory [Ayv-14], and extrapolation of product, sales, and consumer behaviour historical data [Ume-06, Tak-09]. Results show promise concerning the evaluation of product return quantity over time but bring few estimations concerning quality characterization. The second methodology was applied in the context of IRs without access to sales data in the sector of automotive parts remanufacturing. Theoretical and effective results were compared over a period of time to examine the origins of the error rate and further refine prediction models [Mat-15a, Mat-15b, Mat-16]. Practical methods for improving the effectiveness of core forecasting employ reinforcement of the relationship between core supplier and remanufacturer, or alternatively to consider the integration of both activities. As discussed in section 2.2.2, OEMs develop guidelines, web-services, logistic platforms, and financial incentives to motivate post-use collectors to increase quality and to inform forecasts of cores [Wei-15].

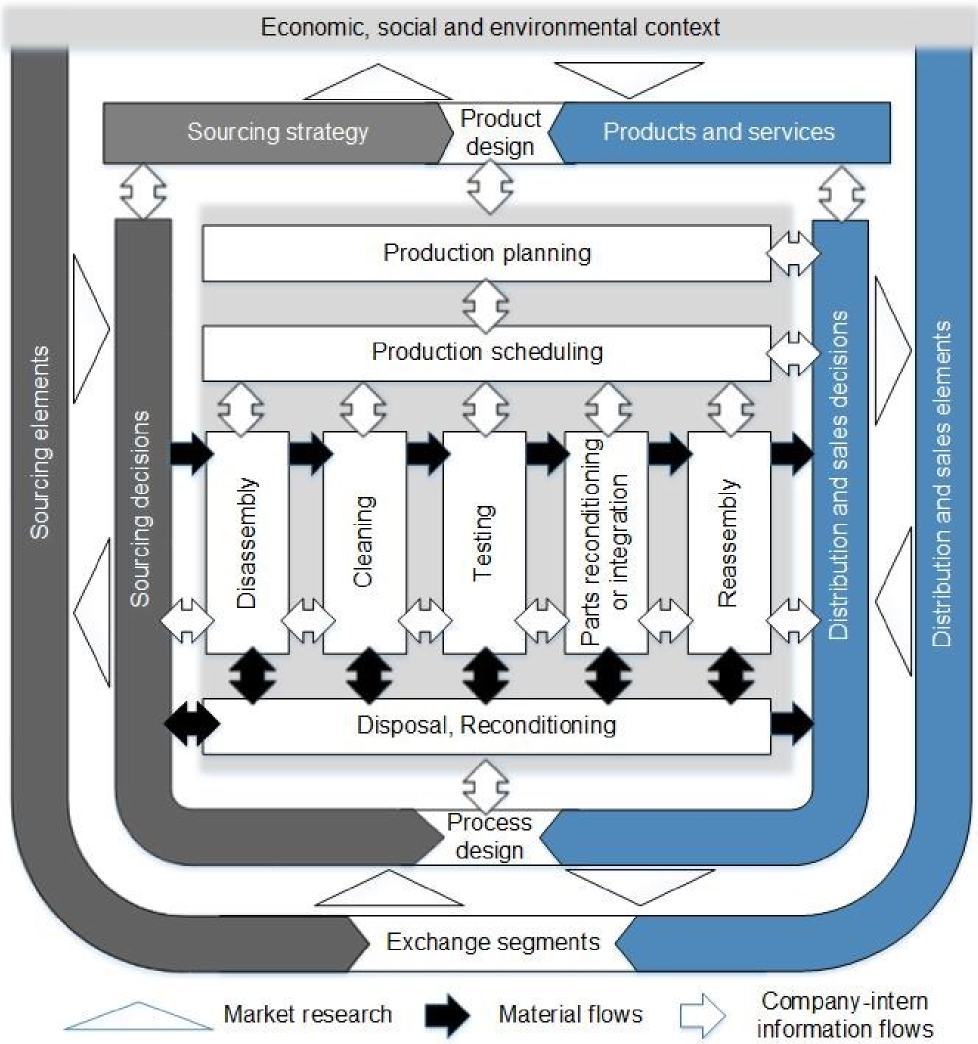


Figure 2-33: Remanufacturing systems interactions, adapted from [Ste-93]

Useful information for the construction of a remanufacturing process are the technical specifications of the new product as well as the definition of defaults causing the core to be dysfunctional. Depending on their level of digitalization, OEMs may have direct access to the product digital model and to the main failure causes through FMEA product establishment, giving them a decisive advantage over IRs. Reverse engineering approaches have been developed to provide a guideline for retrieving necessary information for documenting automotive mechatronics remanufacturing processes [Fre-11]. Other research works concern the development of decision-support systems for the establishment of remanufacturing strategies and can be classified upon the availability of monitoring systems to collect product use data. When no information is available, pre-defined core quality classes can be determined [Wei-15, Zik-08], provided that the effort and complexity of their determination of a preliminary inspection phase [Teu-11] does not offset the productivity gain in customizing the remanufacturing process [Von-13b]. Preliminary tests can be performed by the core supplier or before processing at the remanufacturing facility and can be motivated by an incentive system [Gui-06]. Core quality assessment studies have been conducted to quantify the economic impact on the remanufacturing process [Gal-06, Fer-09, Was-10,] or on process adaptation to core quality classes and required inspection technologies [Col-16]. When a monitoring system is in place, assessment of product quality can be expressed in more detail using the definition of residual useful life (RUI) of a component [Kar-04]. The physical lifetime is obtained by computing the difference between the Usage life and the operating life of a component, and is compared with the technology lifetime for the minimum of both values predicting the RUI [Kar-08, Kar-10]. Should the RUI be greater than the average product service life, components have potential to be re-used.

Design methodologies for reconfigurable and flexible automation consider product family variance [Egu-11] or information exchange between product assemblies and modular tools and fixtures [Wie-01]. System management solutions have been researched using online genetic algorithms [ElS-12], ontology-based frameworks [Mer-10], and information systems combining data from product design and from the Usage phase, while adapting to changing environments [Sch-03]. Remanufacturing system engineering considers the allocation of resources in discrete part manufacturing and test performance using DES and analytical methods. Optimization methods are tested on various workstation designs such as U-shaped [Bou-11], cell, and job-shop layouts and present improvements in variability and cost [Gam-13]. High-level models are conceived as frameworks for investment evaluation of facility concepts [Ijo-08], [Kaf-15], but they fail to provide a reliable connection between the specific system issues described here. Therefore, further research is needed to adequately connect research efforts on remanufacturing system improvement.

2.4 Perspectives of lean remanufacturing

Remanufacturing items involves the use of cores with high variance in product nature, condition, and quantities. However, it must be ensured that product with the expected standards of quality is issued once the remanufacturing process is completed. Therefore, quality management is a central challenge in remanufacturing and aims at standardizing quality level while considering the production capability. Applying TPS principles can lead to a smoother and slimmer remanufacturing process with enhanced customer focus and continuous improvement of products and processes. Costs for the operational remanufacturing process can be reduced by limiting the inventory level, preventing failures, reducing waste in every aspect, as well as setting stable and standardized processes. A focus on customer satisfaction will result in a wider acceptance in the quality of remanufactured goods within end users. After a brief summary of terms and a definition of the scope for the application of Lean in manufacturing activities, a review of Lean methods and techniques is suggested. A discussion on methods selection and potentials for their adaptation is suggested to guide exemplary application of Lean in a remanufacturing environment.

2.4.1 Toyota Production System

The expression, Lean Production, refers to a production philosophy aimed at raising efficiency by creating value and avoiding waste in production processes. Lean Production includes a wide array of methodologies for the optimization of production; it originated within the automotive producer Toyota. The origins of Lean go back to the end years of 1880. It is based on the Scientific Management research performed by Taylor, who developed methods to optimize work processes. The basic idea was to break down work processes to elementary steps to reduce work task complexity and to increase performance of operators [Sch-13, Wes-06]. Also known as division of labour, this work process standardization led to increased productivity in production processes. In 1913, Henry Ford introduced assembly line production and combined it with division of labour: the result was an efficient and modern production system, named the Ford Production System (FPS). The system contributed to a reduction in the price of cars and led to the commercial success of Ford. FPS was copied extensively and implemented globally by other car manufacturers, except the Japanese company, Toyota [Bec-06].

After the Second World War, market conditions in Japan attributed more power to consumers and resulted in an increased demand for product variants. At the same time, a shortage of resources and a decrease in product demand represented a challenge for manufacturers. Moreover, Toyota could not invest in modern production facilities due a reduced access to capital. In consequence, the market conditions in Japan and the U.S. led to the adoption of alternative solutions. OHNO, who was the manager responsible for the development and implementation of a new production system at Toyota, realized that the FPS was not suitable for Toyota due to the decrease in flexibility it induced. He was convinced that the solution was a demand-oriented production system, able to answer specific customer requirements. As production facilities at Toyota could not be modified, they were to be used more efficiently, and focus was set on a waste-free production [Ohn-78]. OHNO'S methods were continuously implemented with great success in Toyota factories and finally led to the Toyota Production System (TPS) [Bec-06, Sch-13]. Toyota's success was not acknowledged by American and European automotive manufacturers until WOMACK ET AL. revealed the reasons for the increasing market share of Japanese automotive manufacturers with their International Motor Vehicle Program (IMVP) studies [Wom-91]. Since then, manufacturers from various sectors have been inspired by Lean Production and TPS [Sch-13]. In contrast with the Four Goals of Production, described in section 2.4.1, the goals of Lean Production are ranked in a specific order and separated into logistic and production goals. In Lean Production, quality has the highest priority to fulfil customer requirements and avoid measurement defects and failures. Second, the speed goal aims at reducing lead times and increasing machine availability. The goal of economy ranks third, as it is achieved indirectly by reducing rejections, breakdowns, and inventories while maintaining a high utilization capacity and high employee productivity. The last goal aims at a high variability of products and high machine flexibility [Erl-13].

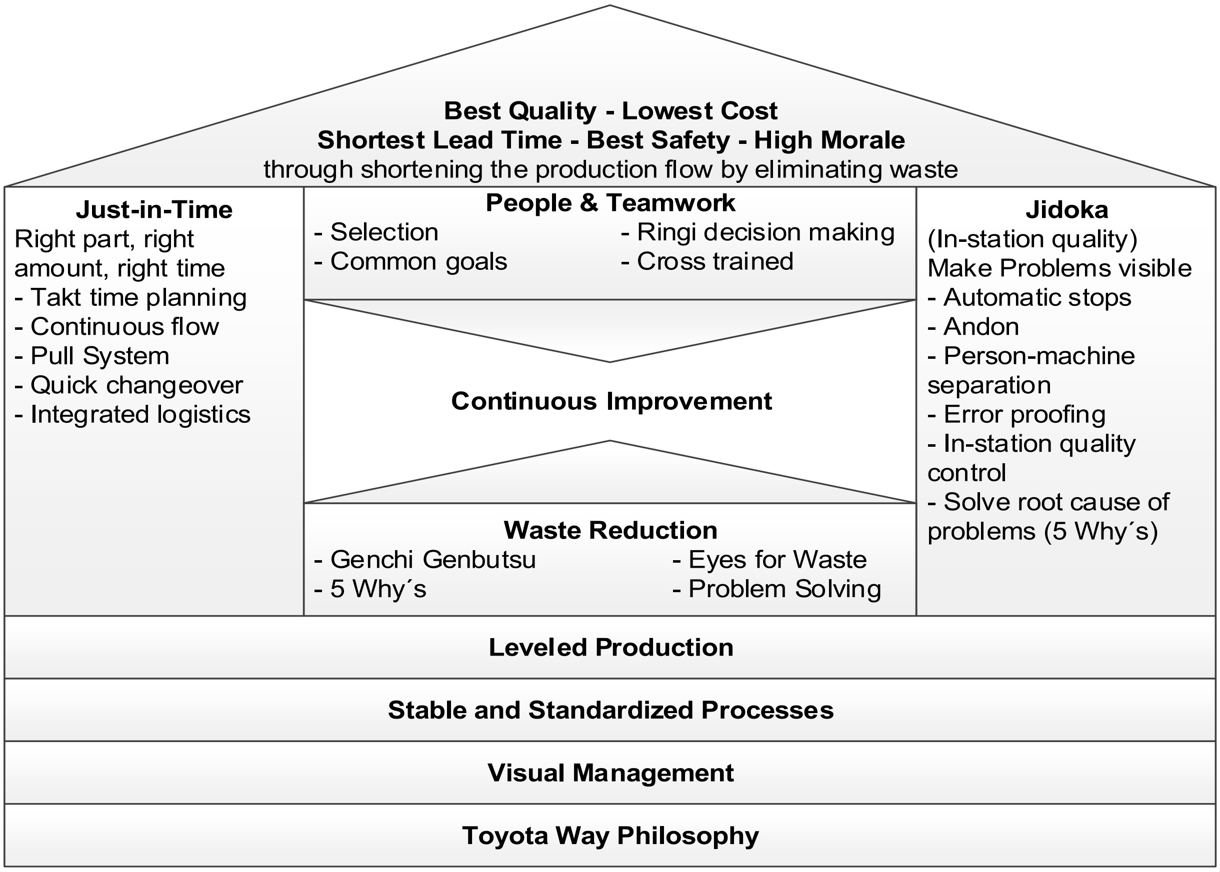


Figure 2-34: Toyota Production System (TPS) House, according to [Lik-04]

TPS is represented graphically as a house, where the foundation represents the basic principles, and the two pillars on the foundation represent JIT and quality as pathways to building a roof symbolizing perfection as the objective, as represented in Figure 2-34. In the centre of the house, methods of waste reduction indicate that people and teamwork are central to continuous improvement. The success of the TPS is driven largely by people empowerment. Just-in-Time ensures that only the right material, in the right amount, at the right time, is processed to avoid time losses and insufficient transport and handling. A continuous flow of materials, pulled by demand in applying takt time planning as well as quick changeovers and integrated logistics, are the key principles of a Lean Production process where cost gains are expected by lower levels of inventory and work in progress (WIP).

Jidoka is the Japanese word for in-station quality; it signifies that no error passes to the next workstation. Focusing on making problems visible to effectively resolve them, workers are empowered to stop the line, call for assistance, and solve the problem (Andon). The operators' sense of initiative is valorised and separated from the operation of the machines. The operators act as guardians of the production quality through in-station controls through error-proofing methods. Continuous improvement is reached by people empowered as managers of the waste reduction. Genchi Genbutsu refers to understanding where value-adding processes take place by observation. The 5 Why method allows fast problem solving by identifying the root cause of the problem. The fundamental underlying principle of TPS is the Toyota Way Philosophy, which summarizes the basic principles shared in the company. Further methods such as a levelled production, stable and standardized processes, and visual management must be thoroughly implemented [Lik-04]. A glossary of lean terms is provided in Annex A-1.

2.4.2 Methodologies

The definition of success according to Lean Production is to reduce waste in production processes using five principles: value, value stream, flow, pull, and perfection. The application of the five principles is recommended for use in the proposed sequence, but should not be applied as a procedure, rather as the basic principles for continuous improvement [Bic-09]. Beyond its philosophy and its specific vocabulary, Lean manufacturing can be applied with the following set of specific methods. The JIT principle is one of the cornerstones of the TPS-house and describes an approach of delivering the right items at the right time in the right amount. To facilitate this, several methodologies have been developed [Lik-04, Ohn-78, Ols-14]:

Continuous and One-Piece Flow (OPF) aims to reduce the eight types of waste, one key process is to set up a continuous flow according to the manufacturing sequence of the product. Rather than implementing a functional layout in which manufacturing technologies are combined into fixed stations, focus should be placed on arranging them in a flow. In this way, waiting times created by unnecessary transport and excessive inventory can be limited. In Lean Production, the ideal batch size is always one that keeps the WIP as low as possible, although it is rarely attained in practice. In reality, only parts of the production process, such as cells, use the OPF approach.

Pull System indicates to base the manufacturing organization on customer demand to lower WIP and inventory needs. The pull system is a replenishment system, in opposition with push systems driven by a blind maximization of the production output. As implemented in the Kanban system, pull production begins only once a signal from the demanding station has been received. Kanban cards include product and process data emitted by downstream workstations to inform upstream workstations of the amount of material needed for production so that a continuous process can be guaranteed and triggered when a safety stock is attained. As a result, the Kanban system ensures the replenishment of goods at upstream workstations; production is commenced only when the Kanban card is triggered, thus avoiding overproduction.

Value Steam Mapping (VSM) is a tool designed to visualize the information, process, and material flow inside the factory to identify waste inside the system. A partly standardized format is used to depicted activities. Processes are represented as boxes and inventory as triangles. Values for WIP, buffer sizes, processing, and changeover times give a first impression regarding potential waste. Supplies, activities, and demand complete the information entered. Elements are linked using arrows to provide a holistic view of the material flow. VSM are employed for planning to compare future state to basic state; changes are suggested to reduce waste and guarantee a constant flow of information, processes, and material.

Single Minute Exchange of Die (SMED) is a systematic approach for minimizing setup times inside the production process. Data is divided into internal setup times, occurring when the machine is stopped to change equipment, and in external setup times for the time needed before and after setup. To maintain high utilization levels for the machines, internal setup times must be transferred to external ones whenever possible. Focus can then be shifted to reducing the remaining internal time by using standardized tools and pre-loading and reducing the external time by pre-adjusting fixtures and jigs.

The Japanese term Jidoka stands for the practice of increasing in-station quality by stopping the line when failures occur and then taking immediate actions to counteract such failures, instead of eliminating the defect at the end of production. Due to the OPF concept, buffer, WIP, and inventory are drastically reduced and supply compensation is limited, in such sense that high quality is essential. Jidoka also leads to empowerment of people, as operators are responsible for stopping the line. Toyota researched several tools to help ensure immediate failure detection:

The Andon method uses a visual signal for line-stopping. When an error occurs, the worker stops the workstation and calls the team leader for assistance. Should correction happen within the CT, the operational status is resumed. Otherwise, the segment or even the entire line must be stopped until the cause has been found. Standardized parameters are provided for the team leaders for deciding whether to stop a workstation. Andon application is recommended within the process planning phase.

Embedded in workstation design, Poka-Yoke is a device to ensure that errors or mistakes cannot occur during the manufacturing process. These devices are used in workstation fixtures and work by only allowing a defined position for a component to be handled. Defects are avoided before their inception. Poka-Yoke is also embedded in product design. Products are designed to avoid the consequences of false handling by customers.

One of the TPS fundamentals is the reduction of the eight types of waste to achieve a constant flow. The 5 Why problem solving method is designed to eliminate failures by identifying the root causes of the error. The question “Why” is asked five times along a standardized seven-step problem-solving process to get a thorough understanding of elimination of failures. After the initial problem description and clarification of the problem, the “real” problem is defined and its location identified using Genchi Genbutso philosophy. Next, the root causes are analysed in more detail and solutions are sought for their elimination. Adequate countermeasures are developed, evaluated, and implemented as new standards to prevent further failures.

Optimization toward OPF requires sequential production according to incoming customer orders. Heijunka is described as the levelling of production by both volume and product mix to overcome deficits. This ensures adequate planning of a predictable sequence of orders with different product types in a fixed time. Problems from an unlevelled production, such as the consequences from demand uncertainty, changeovers after each order, built up inventory, uneven resource use, or demand on upstream processes, are reduced. A thorough Heijunka promises flexibility through JIT, reduces risk of unsold goods, balances utilization of machines and labour, and reduces logistic costs.

Stable and Standardized Processes are key objectives for continuous improvement. Process standardization must first enable ease of reproduction, resulting in production stabilization. Processes fluctuation must be avoided. Standardized processes are necessary for quality maintenance as well as the continuous improvement of products, processes, or performances.

Visual Management is the second core principle and is instantiated by the 5S principle, a guideline for cleaning through visualization. The aim is to make errors visible so that a quick response can take place. 5S stands for sort, straighten, shine, standardize, and sustain. Workplace sorting aims to retain only inventories necessary to perform the work instructions. A straightened inventory is an organized place where materials are at their designed location. A shiny inventory ensures that pre-failure conditions can be inspected and machine failure reduced. Standardized processes are to be established to sort, straighten, and shine. Workplace improvements are always sustained in their current condition. By its circular nature, 5S continuously improves the original state.

2.4.3 Guidelines for application of Lean Production

Observing the growing interest in Lean Production and the difficulties in its implementation, several authors examined the topic of facilitating the implementation of lean [Erl-13, Rot-99, Wom-91,Wom-03]. ROTHER AND SCHOOK introduced the first seven detailed guidelines to ensure a qualitative and sequential implementation of Lean Production [Rot-99]. ERLACH validated these seven guidelines and suggested the inclusion of three additional guidelines and focused on improving the practical application environment and providing an improved production efficiency. This approach has been proven in large-scale manufacturers as well as in SMEs.

Table 2-5: Guidelines for the application of Lean Production [Erl-13]

Step	Description	Objective
1: Adjustment to TT	Adjust PT to the customer TT.	Reach a balanced capacity profile of the value stream.
2: Process integration	Integrate processes in workstation, by technological or organizational means through line balancing, to 95% of the TT.	Allow a continuous production flow, reduce WIP and decrease the lead time.
3: FIFO coupling	Determine buffers with finite inventory levels where the parts first stored flow first to the downstream workstation with constant work in progress system (ConWIP).	Set the maximum stock quantity in the FIFO buffer and trigger next orders upstream, while the number and variant of the order is already defined.
4: Kanban control	Represents a buffer system for several processes, by using supermarkets. The system is composed of production, signal and supplier Kanban.	Removal of parts triggers the process upstream for the exact same quantity, therefore generating complete orders.
5: Pacemaker process	Workstation where the customer order paces the production line. The choice is a subjective decision between delivery time to the customer and inventory level.	Determine the production types to be realized, such as make-to-order, assembly-to-order or make-to-stock.
6: Definition of release units (RU) or pitch	Define standardized lot sizes triggered by the pacemaker workstation, which has a small enough size to keep the takt time visible.	Ensure a smooth production flow, by multiplying container quantity by the TT.
7: Levelling the production mix	Consider different variant after each RU.	Keep flexibility to demand and the workload homogenized.
8: Bottleneck control	Restriction of the maximum volume and should ideally be the pacemaker.	Avoid overproduction if the RU quantities are superior to the bottleneck restrictions.
9: Separate production and material flows	Distinguish and handle production and logistics separately.	Raise value-added proportion by focusing on production.
10: Flow-oriented ideal layout	Place the production equipment by relative position on value stream as close from each other as possible.	Reduces transportation time and occupied space.

The advantage of this work is the great transparency of the material and information flow in the factory brought about simply by showing the relation between information flow and production process. Moreover, the approach offers a basis for current and future state of a value stream mapping (VSM) [Erl-13]. The guidelines are further described in the form of 10 steps, which are illustrated in Table 2-5.

DUNKEL designed guidelines for Lean Remanufacturing and tested applicability in an industrial context to confirm that the adjustment to takt time can be applied. As the number of defective products is higher when handling cores as raw material, rejections have to be included in computing the operation time of a workstation when comparing it to the takt time in the line balancing chart, as suggested by ERLACH [Dun-08, Erl-13]. MÄHL suggests the use of a carrier for every component of a product in reaching a OPF disassembly process to avoid the sorting effort in disassembly operations and to address the problem of material matching restrictions. The disadvantage of having to use a sequential process flow is noted [Mäh-07]. DUNKEL does not recommend OPF in disassembly, as One-Set-Flow (OSF) allows the operator to perform one work task on multiple parts before starting the next step. Improvements are expected through increasing the value-added part of the disassembly process and improving productivity by approximately 55% compared to OPF [Dun-08]. However, OSF is contrary to the Lean Principles, and advantages such as flow oriented work distribution or capacity flexibility are not discussed. The combination of disassembly task with the restrictions of the cleaning process, such as machine cycle time and batch capacity, is advised to reduce excess capacities and allow adjustment to the customer takt time [Dun-08].

The FIFO logic also can be used between processes that cannot be integrated in a continuous production flow in remanufacturing. However, methods for the determination of buffer capacity, such as ConWIP, were not tested [Dun-08]. The Kanban system can be used to decouple process steps according to the specific production objective, as between component remanufacturing and reassembly, if the objective is to decrease costs, or between reassembly and shipping, if delivery time is prioritized [Dun-08, Hau-11, Kan-10]. In both cases, Production Kanban are sent to the disassembly process to refill the respective supermarkets.

Lean Production offers a set of effective and efficient techniques that can be designed as a guideline for completing production objectives. Lean Remanufacturing refers to the adaptation of Lean Production to meet the characteristics of remanufacturing and identifies major improvements opportunities in processes, lead time, and inventory [Dun-08, Hun-07, Sun-06]. Several researchers developed approaches for Lean Remanufacturing [Bou-12, Far-06, Hun-07, Kur-14, Kur-15, Mäh-07, Öst-07, Sun-06], and KURILOVA PALISAITIENE summarized challenges and opportunities of Lean Remanufacturing [Kur-13]. Some research can be applied for virulally all remanufacturing processes, as when DUNKEL further suggests the line and the U-shaped layout for reducing walking distance for the operator as well as the factory space needed [Dun-08]. However, recommendations for Lean remanufacturing are often divergent as they focus into specific remanufacturing activities with different products, process, stakeholder network and business model characteristics. HAUMANN advises not to place the pacemaker upstream from the reassembly process, as parts should only be stored with quality warranty in supermarkets to avoid inventory costs for potentially defective parts [Hau-11]. KANIKULA ET AL. further suggests seven more alternatives for application of buffers in remanufacturing processes [Kan-10]. KURILOVA PALISAITIENE ET AL. suggest another solution for integrating buffers by suggesting the implementation of supermarkets after every process excluding shipping. They argue that the low core value will not lead to high inventory costs. Disassembly is advised to be organized as a push production process to balance issues linked to core quality [Kur-15]. It can be concluded that approaches to Lean remanufacturing should be developed in a context where contextual information is fully available and considered.

As it provides an overall vision of the current state of a production system, the VSM methodology plays a central role in the concrete definition of target conditions, which leads to the definition of an action plan [Erl-13, Ohn-78, Rot-99, Rot-06]. The notion of an ideal state is essential to complete the application of a target VSM, as it orients the definition of achievable objectives to the direction of perfect, yet impossible to reach, ideal conditions [Kuh-14a]. MTM and VSM are both dedicated to the identification, reduction, and elimination of waste but provide a complementary approach generated from radically opposed perspectives. VSM contributes to the increase of productivity by the flow-oriented organization of work and focuses on single processes, industrial activities, and workplaces to accomplish this. MTM objectives are the definition and application of an ideal method for the accomplishment of a work task by planning, measuring, and comparing several options and deciding which is the most productive [Kuh-14a]. Both methods allow the simulation of virtual methods to determine target and ideal states, allow a simple yet easily understandable documentation, and their broad industrial application allow results to be transferred to other organizations [Kuh-11]. A practical application of the combination of MTM and VSM can be found in the determination of the waste type for each of the basic motions of a method, at the scale of the MTM codes [Kuh-14a].

3 Research gap

This chapter describes the gap in research identified by the author, potential solutions, and an evaluation scheme for the continuous improvement of remanufacturing practice. Section 3.1 suggests potentials for the development of a guideline for planning and improving process chain design of remanufactured products and suggests requirements for the methodology development. Next, section 3.2 describes a selection of methods with similar focus, which are evaluated in section 3.3 regarding the need for innovation of a new methodology based on specific requirement sets adapted from Lean Production principles.

3.1 Need for action

Although remanufacturing is a relatively old practice in some industries, it has long suffered from a lack of attention by public authorities and by the academic research community. Some precursors, such as HAUSER AND LUND in the U.S. and STEINHILPER in Europe identified the potential of remanufacturing before 1990, and triggered a now intensive international research community focused on this specific topic. To organize the research efforts of a growing research community, GUNGOR AND GUPTA suggested a classification of issues in environmentally conscious manufacturing and product recovery (ECMPRO) in 1999, and ILGIN AND GUPTA updated it in 2010. Four main research areas are suggested: product design, reverse and closed loop supply chains, remanufacturing, and disassembly. The remanufacturing focus distinguishes forecasting, production planning, capacity planning, inventory management, and effect of uncertainty [Gun-99, Ilg-10]. As concluded by GUIDE in 2000 and JUNIOR AND FILHO in 2012, there is consensus that effective and efficient remanufacturing depends on specific complication factors, no research addresses all of these identified barriers simultaneously [Gui-00, Jun-12]. MATSUMOTO ET AL. identified in 2016 several trends in remanufacturing research in product design, additive manufacturing, operations management, and business models. This research confirmed the need for collaboration between strategic, tactical, and operational visions of remanufacturing research for effective remanufacturing promotion [Mat-16]. This observation reveals the need for cooperation in research for designing appropriate private and public policies for supporting the remanufacturing industry. A complementary, but only scarcely developed, vision to promote remanufacturing practice is to focus on the products already distributed in the market to assess the potential for them to be immediately remanufactured. This consideration would enable a direct application of new remanufacturing ventures even if OEM companies are reluctant to implement DfRem measures. In the automotive parts or ink cartridge industry, for example, OEM remanufacturing practice has been triggered by independent companies that find a lucrative activity in the remanufacturing of specific products [ERN-15].

Operations management has the potential to become a cornerstone for connecting remanufacturing research, as it relates to business models and product design through the supply/demand balance and to the choice of adequate remanufacturing technologies. Comprehensive methods supporting remanufacturing operations management primarily focus on DfRem) and provide feedback to OEM companies on how to reduce process costs by analysing computer-assisted drawing (CAD) data with assessment metrics for disassemblability, accessibility, complexity, and recoverability [Fan-14, Fan-15, Soh-15]. However, although these methods provide a reliable assessment of technical product-based constraints, they do not address remanufacturing factory planning issues and only cover some of economic feasibility factors. Furthermore, this approach is reserved for OEM or contracted remanufacturers with full access to product design, which may present numerous barriers for remanufacturing [Gui-13a, Wid-14]. Economic effects and the integration of constraints in remanufacturing process planning are combined in the use of linear programming of Enterprise Resource Planning (ERP) information though a graphical user interface (GUI) [Ker-09a, Ker-09b, Sel-06]. Other methods focus on specific aspects in optimizing variability [Li-13], reliability, and costs [Jia-16] or uncertainty [Li-11] in remanufacturing process-chain planning. The assessment of a technology portfolio based on a multi-criteria, multi-level approach is conducted to assist in the choice of equipment for remanufacturing operations [Jia-11].

As a result of the observations from the state of the art, innovation is needed to find ways to categorize, connect, and evaluate best practices in a multi-level, multi-criteria, and standardized representation of a remanufacturing environment. Remanufacturing practice remains limited to specific product categories with an intensity ratio of less than 5% of newly produced goods, demonstrating an untapped potential for the remanufacturing of new products. Therefore, the ambition is to match specific knowledge generated in technological and organizational improvements of remanufacturing operations with an economically efficient practice. An integrated guideline for a modular creation and continuous improvement of remanufacturing processes while ensuring economic feasibility is suggested. Lean Production is the driver for ordering steps for continuous process improvement to gather experience with its intensive industrial use and for the breadth of topics addressed. The use of MTM for precisely describing human interactions in the process allows a consideration of workforce costs, ergonomics, and workstation design. The replicability of the methods based on a building block system has the potential for a reliable connection of macro, meso, and micro levels as strategic, tactical and operational remanufacturing production planning and control. Further, MTM has the unique advantage of enabling the design of remanufacturing processes in the planning phase to allow applications for products not yet remanufactured. Combining MTM with Lean Production is recommended to improve productivity [Kuh-11].

3.2 Requirements

To define requirements for the development of the methodology, six categories must be considered according to current research. First, the company strategy helps in shaping the company objectives and the context in which to optimize production. Second, the four goals of production represent the four first categories with respect to their order in the Lean Production guidelines: quality, speed, economy, and variability. A sixth requirement set is added to set a standard for teaching remanufacturing engineering using a platform adapted for creation of a systematic remanufacturing process.

The first requirement for the guidelines is to formulate the objectives of the remanufacturing process while considering the strategic decisions of the company to be analysed. To this aim, a thorough analysis of both internal and external influence factors of strategy definition is necessary. Internal influence factors are characterized by top management decisions concerning the business model of the company and define the expected profits and associated costs needed to reach the objectives defined. They are also essential to determine the proportion of value-added that the company will capture in their activities, the investments that will be needed to provide these services, and the objectives of production planning and control activities to be established. External influence factors are defined by the targeted market as well as the country-specific factors where the activities of the company occur. This category influences the expected operation revenues and costs by their interaction with the market, as well as the effectiveness of core sourcing operations.

Quality is the key word in differentiating the remanufacturing definition from the other EOL strategies. To guarantee that products remanufactured offer a function which is at least equivalent compared to the original part and are given the same warranty as a new part, quality is to be considered from the inception of the remanufacturing process [APR-16]. To assess to which extent the quality management is incorporated, the five essential steps of quality management are considered. The methodology to be developed should ensure quality policy, quality goals, quality assurance, quality planning and control, as well as continuous quality improvement.

The process chain definition translates the requirements of production planning and control on needs for work methods and workstation organization to be organized on the factory layout. It predefines the order in which distinctive operations will take place, the productivity of the entire process, and the effective distinction of the value-added nature of operators actions. Speed requirements are derived from the need for productivity management according to the Lean Manufacturing principles. To assess the extent to which a methodology offers the specific guidance for the process to be continuously improved, the five principles of Lean are suggested: namely, separation of value and waste, value stream management, material flows management, application of pull principles, and continuous speed improvement towards perfection.

A prerequisite for implementation is that economic profitability must be ensured when planning the remanufacturing process of a product. In production planning, assessment of the balance between profits and costs of a manufacturing process is the main quantitative aspect for its validation. Revenues are characterized by the sale of product or services to customer or value chain network partners. Several categories of costs should be included to allow a reliable representation. Investment is necessary when purchasing buildings, equipment or intellectual capital necessary for the launch of a venture and occur only when the investment decision is taken. Process costs are resulting from a combination of product, organization, equipment and human variables, as defined by the object-oriented classification of factory planning defined by SELIGER, described in chapter 2.3.2. Product costs are grouping the material costs of a product, such as core acquisition, and new parts. and operating costs for the buildings and equipment necessary to run the production process. Human costs are characterized by the salaries of operators and line production management required for running the remanufacturing process. Organization costs are grouping the cost of logistics, inventory, and support functions. Finally, equipment costs are summarized in cost of machinery, their consumables, and related maintenance.

The evaluation of process variability concerns the capacity of the methodology to integrate the product quality variance and the product model variety inherent to the remanufacturing production environment, as developed in chapter 2.2.4 and 2.3.6. First, core condition variance should be considered to identify the influence of core quality to the efficiency of the process, as it generates fluctuation in the treatment time and success of testing or reconditioning operations. Second, the product variety is represented by the extent of the product portfolio to be handled in a single remanufacturing facility. Third, material matching variance considers the estimation of new parts to be acquired to replace defective parts in the remanufacturing process. Fourth, process variance is defined by the versatile nature of a remanufacturing process, as additional process steps can be needed when products are tested or sorted.

The developed guidelines concern design efforts to allow users to employ the full functionality and to be able to use the results directly in the context of their activities. In the context of this work, the guideline is structured to allow the development of project-oriented courses targeting industrial engineering master students; requirements are derived from the ability for the guidelines to suit application in an educational context. Further detail about the course development are detailed in chapter 4.4. First, the scope of application reflects the width of product choice and flexibility in selection of parameters. Second, the scalability of results includes the choice of popular result format, their capacity for integration in a real company process, and the ease to extract information for decision making or for reuse. Third, ergonomics evaluates the quality of tutorials and documentation, the freedom of access to the tool, and the use of the capacities of a prototypical interface. Fourth, the logic transparency checks if the logics and mechanisms underlying the methodology are accessible and sufficient for students to understand the challenges in remanufacturing production planning. Finally, the evolutionary format regards the suitability of the methodology to be further developed in reaching higher quality results.

Presented in Table 2-6, the evaluation criteria reflect an ideal state of a methodology for production planning and control in setting target conditions for its integration as a framework for structuring research and knowledge with regard to remanufacturing. In this sense, it can serve as an evaluation of the needs for future research and can provide adequate goal setting in the development or improvement of methodologies.

Table 2-6: Requirement sets for the methodology development

4.3.2 Strategy	**4.3.3 Quality**
• Business model representation • Stakeholder network representation • Country specific production factors • Core procurement and quality • Product sales and customer acceptance	• Quality policy • Quality goals • Quality assurance • Quality planning and control • Continuous quality improvement
4.3.4 Speed	**4.3.5 Economy**
• Separation of value and waste • Value stream management • Material flow management • Application of pull principles • Continuous speed improvement	• Product costs • Organization costs • Human costs • Equipment costs • Sale revenues
4.3.6 Variability	**4.4 Education for remanufacturing engineering**
• Cores condition variance • Product variety • Material matching variance • Process variance	• Scope of application • Scalability of results • Ergonomics • Logic transparency • Evolutionary format

3.3 Current methods and improvement needs

With respect to the research gap definition, methods for (1) evaluating the technical-economic feasibility of remanufacturing, (2) considering external and internal aspects of production strategy, planning, and control, (3) focusing on the evaluation of current products in opposition to design of new products, and (4) in the form of a guideline are selected. The following three methods are identified in literature to match the scope described by the four criteria.

Remanufacturing Opportunity Tool (ReOpT) was developed and published as an online application of the website from the Centre of Remanufacturing and Reuse (CRR). The function of this tool is to evaluate the potential for a product to be remanufactured by using a questionnaire based on the characteristics of a product and its industrial environment. Divided in six categories, namely product, customer, market, customer service, environment, and required resources, the application automatically generates a customized report based on the answers to 39 questions. The report suggests an individual assessment per category expressed as the “low”, “good”, or “excellent” chances for the product to be remanufactured; defines barriers; and suggests recommendations for overcoming the barriers [CRR-13]. ReOpT is particularly directed to a rapid screening to identify remanufacturing potential, and consequently, it does not allow an in-depth analysis of the concrete actions to be taken for establishing a remanufacturing process. The tool does not provide assistance for the further implementation steps in case a product is recognized to have high potential. Further, as the logic behind the application is not explained, the knowledge gain for the user remains limited, and the user may have difficulty in gaining a global understanding of the causal influence between categories. The tool is no longer available online.

DUNKEL developed a Methodology for the Development for Lean Remanufacturing (MDLR) by ensuring the application of every single method by considering the specificities of the remanufacturing environment. The development of a guideline in the form of 14 steps is proposed, and the focus is on the improvement of the production planning of currently existing remanufacturing facilities. The Monetary Failure Analysis (MFA) tool is a method for measuring the economic impact of quality improvement and testing equipment. An innovative assessment of the economic feasibility of parts in the remanufacturing process is instantiated by the determination of a maximum remanufacturing time per part. Application of the guidelines was tested in three different German automotive parts remanufacturers by the author as an external consultant, and the result was a time reduction from 20% to 67% as well as a productivity improvement from 7% to 20% [Dun-08].

PARKINSON AND THOMPSON developed Systematic Approach to the Planning and Execution of Product Remanufacture (SAPEPR) with the concept of basing the first assessment to ensure the quality of a product to be as good as new. With this objective, their approach starts with a product risk assessment consisting of the identification of assemblies as critical items based on the result of a FMEA Process analysis. The resolution of failures of critical items serves as a basis for the tentative establishment of a remanufacturing process, which is improved by the execution of a FMEA Process before its costs are determined. The validation of the tentative process depends on the assessment from the RPN / Cost ratio as a cost-benefit analysis. Negative results lead to review of the process and positive results lead to implementation [Par-04]. Although the approach is demonstrated as able to improve process efficiency for the remanufacturing of air conditioners and turbochargers, as shown in case studies, several drawbacks were observed. The approach does not state in detail how to apply the different steps of the process and only considers the remanufacturing processes. Details are lacking for guiding users on the link between critical items and process steps, and no advice is given for improvement of the process in the case of negative results. Important factors for determination of the cost-benefit analysis, such as market price, discard rates, and determination of waste in the process, are not addressed.

Evaluation of the current guidelines shows that they only consider a partial representation of the context in which remanufacturing process planning should be established. First, current methods only have a partial consideration of the company strategy and its position within the stakeholders' network when determining how the process should be constructed. Despite the fact that ReOpt ergonomics are carefully developed through an online application, the relationship between the user choices and the appraisal of the system remains unclear and may be misleading. Moreover, the absence of consideration of quality and speed of the production system lowers the application potential of the results. The tool considers certain aspects of the strategical definition, but remains on a high level and the level of advice provided to the user fails to target specific actions allowing the continuous improvement of the process. MDLR provides a complete explanation of its development and gives thorough advice based on Lean Production rules, but the application of these guidelines does not consider the influence of strategical decisions. Moreover, the relationship between process and quality is not addressed as the focus of the work is solely to improve productivity. Product variability is only partially addressed by MDLR, while both other methods disregard it. The conclusion of the analysis is that an effort of integration of several advantages posed by the different methods is necessary to reach comprehensive results. On one hand, SAPEPR initiates process steps from the identification of critical quality factors, so that users can define the process flow of remanufacturing operations rapidly. On the other, it does not provide advice for the definition and continuous improvement of the process speed; neither does the method justifies considering all remanufacturing costs, which may be generating misleading results. Another limitation is that the method does not mention the problematics of material flow, which is decisive to justify investment decisions such as technology choice, remanufacturing location or inventory management. Further, the impact of strategical decisions on the system efficiency cannot be addressed by a sole focus on remanufacturing quality.

This analysis confirms the need for an integration of methods issued from different viewpoints, so that the appraisal of remanufacturing in all the breadth of its system is made possible. Above methods are valuable contributions to the state of the art, but may provide only a partial analysis of the issues to be solved, impairing the validity of their results. Next chapter presents a methodology for the appraisal of economic feasibility of remanufacturing systems through the implementation of Lean and MTM as exemplary supports for their definition from the investment planning phase.

Table 2-7: Evaluation of current methods

Requirement sets	Requirements	Methods		
		ReOpt	MDLR	SAPEPR
Strategy	Business models representation	◐	○	○
	Stakeholders network representation	○	○	○
	Country specific production factors	○	○	○
	Cores procurement and quality	◐	○	○
	Customer acceptance	◐	○	○
Quality	Quality policy	○	○	◐
	Quality goals	○	○	●
	Quality assurance	◐	○	●
	Quality planning and control	○	○	●
	Continuous quality improvement	○	○	◐
Speed	Separation of value and waste	○	◐	○
	Value stream management	○	●	○
	Material flows management	○	●	○
	Application of pull principles	○	●	○
	Continuous speed improvement	○	●	○
Economy	Product costs	◐	●	◐
	Process costs	◐	◐	◐
	Human costs	○	◐	◐
	Organization costs	◐	◐	◐
	Equipment costs	◐	○	◐
	Sales revenues	●	●	○
Variability	Cores conditions variance	◐	◐	○
	Product variety	○	●	○
	Material matching variance	○	○	○
	Process variance	○	○	○
Engineering Education	Scope of application	●	●	●
	Scalability of results	◐	○	●
	Ergonomics	●	○	○
	Logic transparency	○	●	◐
	Evolutionary format	○	◐	○

4 Methodology for guideline development

In this chapter, the steps undertaken for the construction of guidelines are detailed. Section 4.1 lists the scope and define four categories of elements in the guideline model, classified in financial, strategic, tactical and operational categories. Methods for quality and productivity management are selected to be used in the context and the scope of this analysis in section 4.2. Information input. As the order in which information is presented to the user is essential for the success of a guideline, section 4.3 explains the order in which the guideline elements were integrated and details the activities undertaken in each step. Based on the results obtained, the guideline is evaluated based on economy and variability requirements sets. Finally, the use of the guideline as a medium for project-based engineering education course is discussed in section 4.5.

4.1 Scope definition and guideline elements

The approach for the creation of a comprehensive guideline requires consideration of several dimensions of production organization and a definition of the interrelation of these elements. The company strategy is represented by the company's internal objective setting summarized in its business models as well as the company's position in the stakeholders' network forming its business environment. Consequences on cost, revenues, sourcing of old products, and delivery of new ones can be deduced from attributes characterizing these strategic elements. Strategic elements are defining the context in which the production planning activities should be established. Production planning and control is represented by the consideration of value creation elements able to describe the formation of the remanufacturing processes and should be performed while considering the economic feasibility of the remanufacturing operations. This level is tactical and should represent the degree of freedom with which the factory is able to fulfil the company objectives. Production scheduling is the implementation of the process in the factory layout at the highest level of detail. This contains the choice of work methods, and workstations and equipment for performing the remanufacturing operation. The result of the interaction of the three elements are represented by the financial management tool, which consists of collecting the investment, the fixed and the variable costs of each element of the three dimensions to represent the result of the user-defined remanufacturing strategy. Elements are used to classify all influence factors to consider the financial consequence of operating the remanufacturing activity over a period of time in a circular material flow system. Figure 4-1 summarizes interactions between levels and indicates the information input and output for each level.

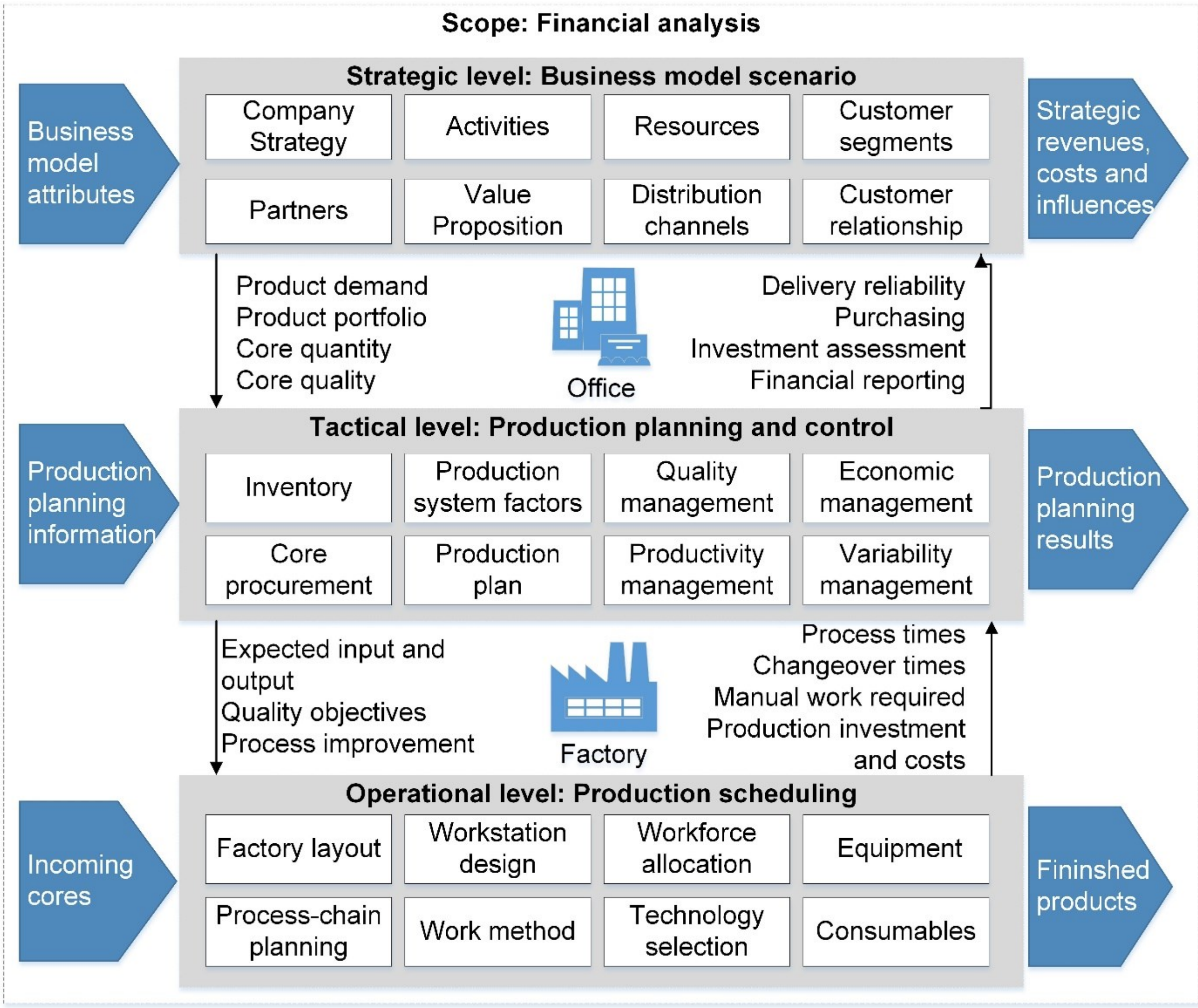


Figure 4-1: Strategic, tactical, and operational level activities

4.1.1 Finance

Because the main objective of the guidelines is the determination of the economic feasibility of remanufacturing operations, the financial elements are determined to ensure consideration of the major financial consequences of the elements previously described. In the frame of the guidelines, each quantitative monetary influence is classified within one category. Four types of financial elements are distinguished:

- Investment costs represent the finances needed for one asset to be purchased and represent the necessary investment for the remanufacturing production strategy to be applied. The application is limited to direct investment in factory and operations management. For the sake of simplicity, investment related to activities integrated in the strategy aspect are considered to be leased and therefore registered as fixed costs.
- Fixed costs are independent from the level of activity occurring in the factory and therefore are formatted as a fixed monthly value. They include financial costs which represent the interest from bank loans to be paid at the end of each period.
- Variable costs depend on one or several elements of the production description and are for a given period of time in the context of national production factors. Computation

of variable costs is done through analysis of the complete process chain and considers human, equipment, and product-related costs according to the decisions in production planning and scheduling. Inventory costs are considered only for their variable components, including logistics and purchasing price deduced from the product element and the inventory management cost as a percentage of the stock value at the end of the month.

- The main revenue source is the sale of remanufactured products or assemblies resulting from the process developed and embedded in the business model defined in the strategy. Revenues depend on the current market price during the month in which the products are remanufactured.

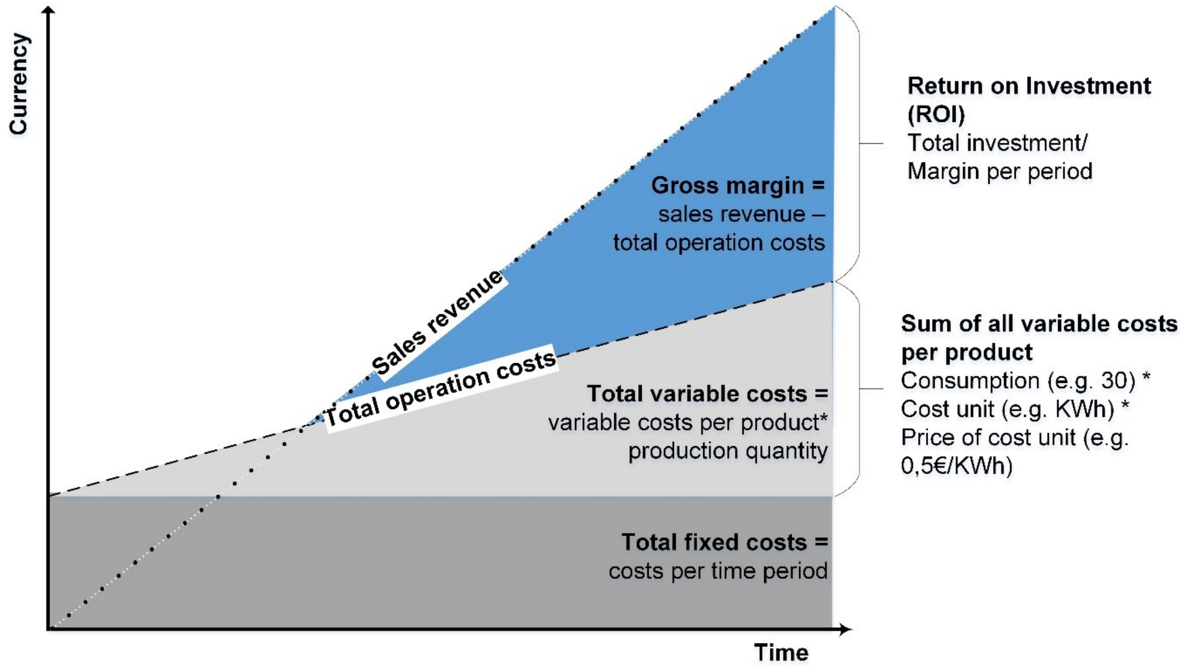


Figure 4-2: Model for the calculation of financial influence

To allow the computation of variable costs from the source information expressed in a specific unit, as for example the work hours, the principle of cost units and price of cost unit is suggested. This enables consideration of variable levels of prices for the same cost units, as the activity is exerted in specified countries or factories with their own production factors. The principle selected to compute costs is explained in Figure 4-2.

Further, financial elements are gathered into a monthly profit and loss statement, which computes the balance between revenues, and variable, fixed, and financial costs to determine the profit or loss from the activity. The availability of funds required for the payment of costs as well as investments are summarized in a cash flow analysis, which determines when a bank loan is needed. The main indicators to assess the financial health of the company are the Break-Even Point (BEP) and the Return on Investment (ROI). These popular indicators are useful to compare different production strategies and to determine the minimum activity levels to be achieved to cover the fixed costs by the difference between revenues and variable costs.

4.1.2 Strategy

In this work, the strategy definition is suggested by the examination of the value creation activities of a single company. The first step is to set a qualitative description of the value proposition offered to the customers and the effects on the company's high-level organization and on product variability such as core quality or sales seasonality. Second, strategy defines the price to which the cores are collected as well as the revenues to be expected from product sales, considering external logistic and customs costs.

The Canvas Business Model was developed using an extensive investigation of business models and represents the viewpoint of a large group of academy and industry experts. Moreover, a detailed method to use Canvas is proposed to assist the creation of business models. It has been applied successfully by many organizations, such as IBM and Ericsson. Using the action-research method, interviews were designed with companies active in the field of remanufacturing to adapt the Canvas Business Model dimensions to a business model framework. Table 4-1 describes the results obtained and the required input per dimension [Gui-13a].

Table 4-1: Adaptation of Canvas Business Model dimensions

Framework dimension	Corresponding Canvas dimensions	Main type of information	Examples of required content
Strategy	None	Qualitative	Profitability, market, environmental and legal drivers
Customer segments	Customer segments	Qualitative	Customer type, profile and price sensitivity
Value proposition	Value proposition	Qualitative	Type of services associated, product ownership policies
Customer relationship	Customer relationship	Qualitative	Customer proximity and participation within products' lifecycles
Network	Channels, Key partners, Key activities	Qualitative	Actors involved in distribution and remanufacturing processes
Resources	Key resources	Qualitative and quantitative	Valuation of needed resources to perform remanufacturing
Revenue	Revenue streams	Quantitative	Estimation of sales over a 5 year period
Costs	Cost structure	Quantitative	Estimation of workforce and infrastructure costs
Business case	Revenue streams, cost structure	Quantitative	Profit and loss statement, investment

Once the business model is described in a qualitative manner, the material flow must be defined to obtain the period in which to operate the remanufacturing activity. As the essence of the remanufacturing process relies on the availability of cores, this step is essential. The definition of the strategy phase allows determination of several factors describing the scenario in which the remanufacturing activity will be embedded. The information determined during this phase concerns the quality, quantity, and price of products throughout the main steps of their lifecycle. Figure 4-3 shows variables that describe the represented system at the strategic level are suggested to represent the material flow quantities to be assumed:

n Lifecycle number, starting with new manufacturing
U_n Use phase, lifecycle n
C_n Collection phase, lifecycle n
R_n Remanufacturing phase, lifecycle n
D_n Distribution phase, lifecycle n
PF_{Un} Product flow toward Un
PF_{Cn} Product flow toward Cn
PF_{Rn} Product flow toward R_n
PF_{Dn} Product flow toward D_n
LF_{Un} Lost flow from U_n
RF_{Cn} Recycling flow from C_n
RF_{Rn} Recycling flow from R_n
LF_{Dn} Lost flow from D_n

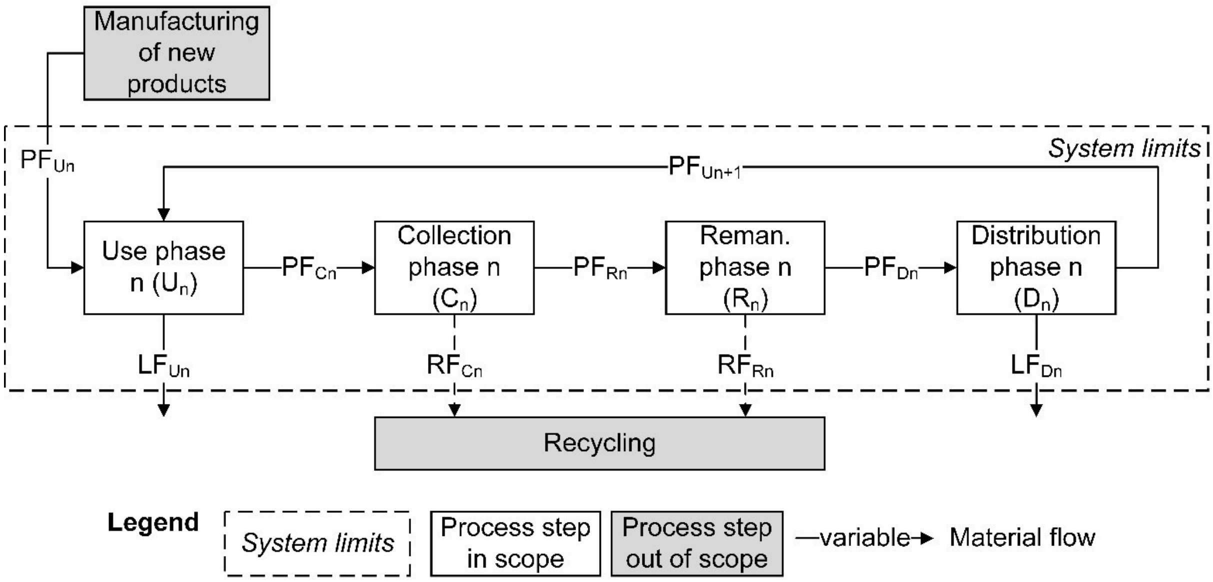


Figure 4-3: Circular material flow model, adapted from [Stö-06]

From the viewpoint of the remanufacturer, many variables can be computed in the strategy phase. PF_{Un} represents the sales amount of new products from the OEM. PF_{Cn} gives the amount of products effectively collected after the use phase, and can be computed by applying a factor representing the collection intensity ratio as a percentage of all new products. LF_{Un} represents the flow leaving the control of the designed remanufacturer, as for example to competitors processing the same product family. The collected products are in turn identified at the collection stage to estimate their quality class, so that PF_{Rn} represents the amount of acceptable products and RF_{Cn} the flow of products to be recycled. During remanufacturing, a certain amount of products RF_{Rn} are considered as defects when operations prove unsuccessful, so the amount of remanufactured products sales to the distributor PF_{Dn} represents only a fraction of RF_{Cn}. LF_{Un} represents the products getting out of the control of the distributors by the fate of theft or damage, which cannot be valorised through recycling. The amount of sales of remanufactured goods from the distributor is characterized by PF_{Un+1}.

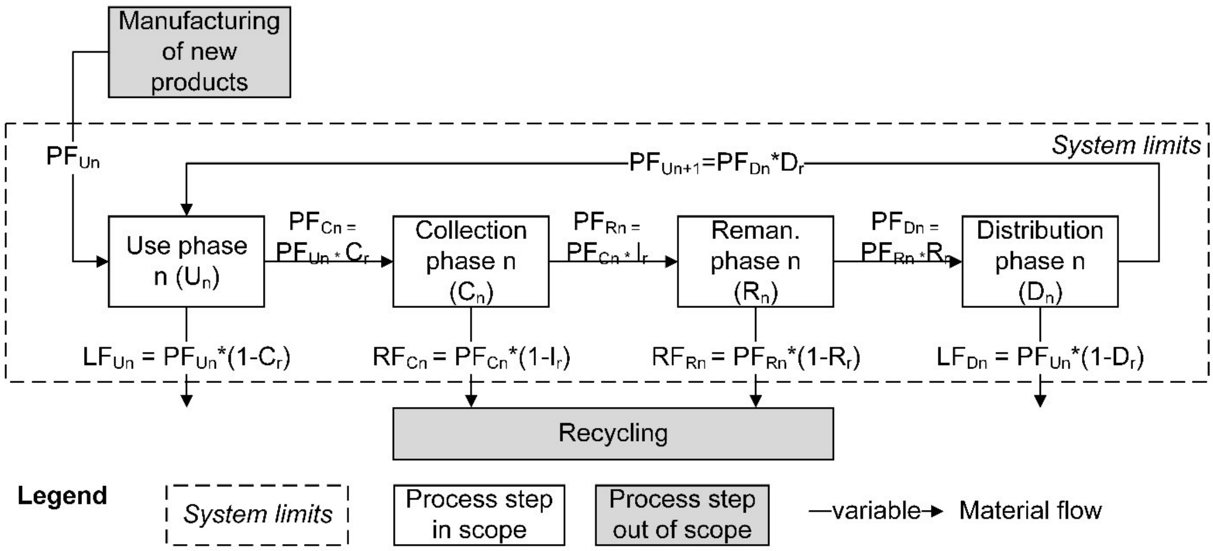


Figure 4-4: Strategic efficiency ratios affecting material flows

To determine the material flows to be expected, influence factors are derived from the efficiency of core collection, the percentages of cores with minimum quality requirements to be remanufactured, and the success ratio of the remanufacturing process. This information can be summarized in four ratios, as illustrated in Figure 4-4:

C_r Collection success ratio from all collectors selected by the remanufacturing company

I_r Identification success ratio for products considered for remanufacturing by the collector

S_r Success ratio of cores being remanufactured to the expected standards

D_r Distribution success ratio for remanufactured products entering the market

The influence factors are used to determine the structure of the company organization, costs, and product price to be expected under the scenario described in the Canvas Business Model. It is important for determination of the remanufacturing economic feasibility to determine the core price and the remanufactured product price in its strategic context. However, sales price and costs depend on the value chain integration ratio according to the activities performed by the company in question and the partner network considered. Every external stakeholder applies his own internal margin to the price at which he sells the service to the next stakeholder. Further, the exchange between partners in a network implies costs for allowing the transfer to happen in the context of national or international exchanges.

Therefore, the price announced by the supplier of a product or service may not comprise a fraction of logistics, administrative, tariff, or non-tariff cost factors that should be financed by the buyer, which are represented as transfer costs. To consider the hidden costs in the computation of costs and prices, the definition of a value chain integration ratio is suggested for both costs and prices from the viewpoint of the remanufacturer. First, the sales price of the product to the end user must be determined:

$$S_t^x = P_t^x * MP \tag{4-1}$$

with

x Product in consideration (units)

t Period in consideration (months)

S_t^x Sales price for product x at the period t

P_t^x Market price for the product x at the period t

MP Market premium ratio

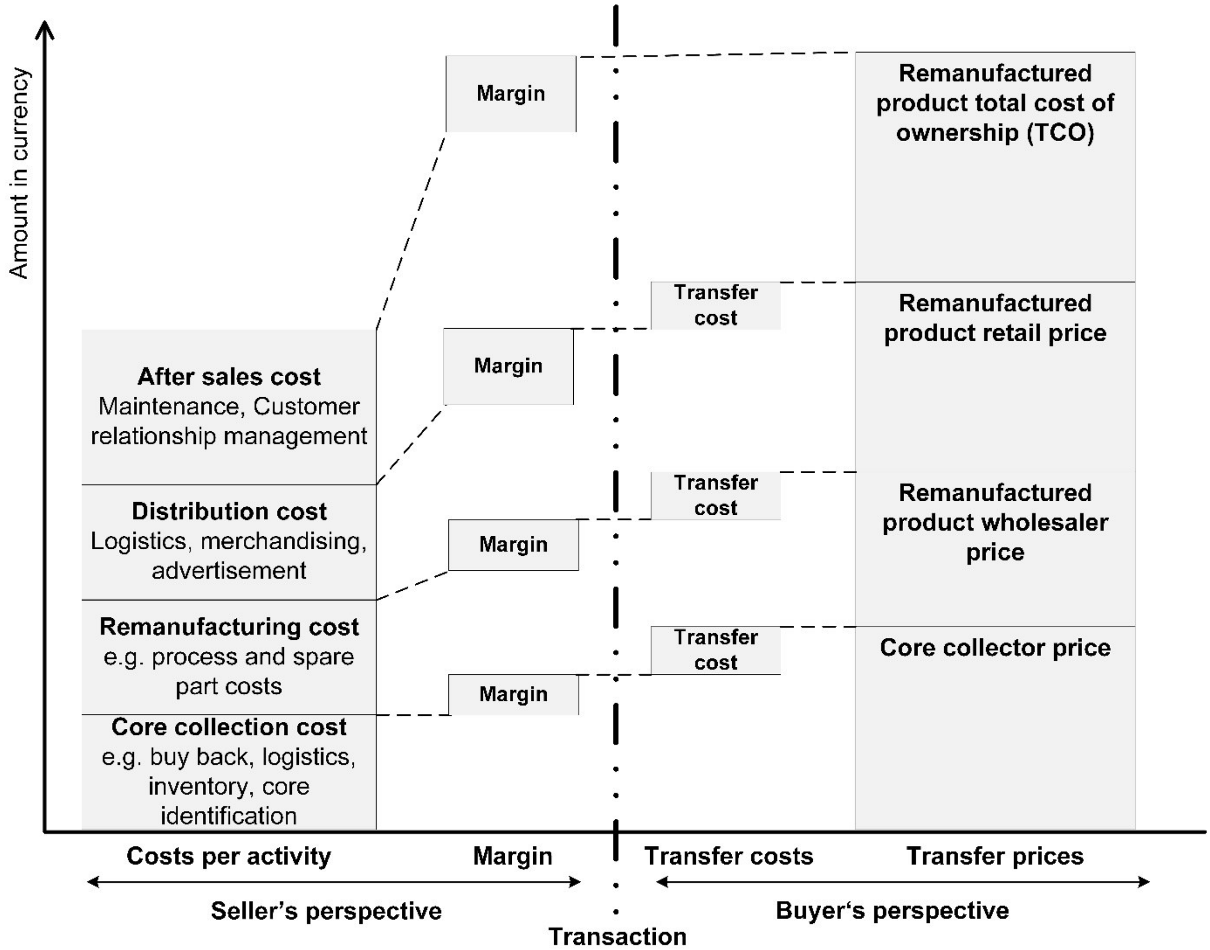


Figure 40 Representation of the strategic ratios affecting material flows

To determine the value chain ratio of sales, the final sales price is compared to the transfer price resulting from the sales of the remanufacturing company to the next value chain actor:

$$VS_{x,t}^p = \frac{S_t^x}{TP_t^x} \tag{4-2}$$

with

VS_t^x Value chain ratio for sales

x Product in consideration (units)

t Period in consideration (months)

S_t^x: Sales price for product x at the period t (currency)

TP_t^x Transfer price of the remanufacturing company (currency)

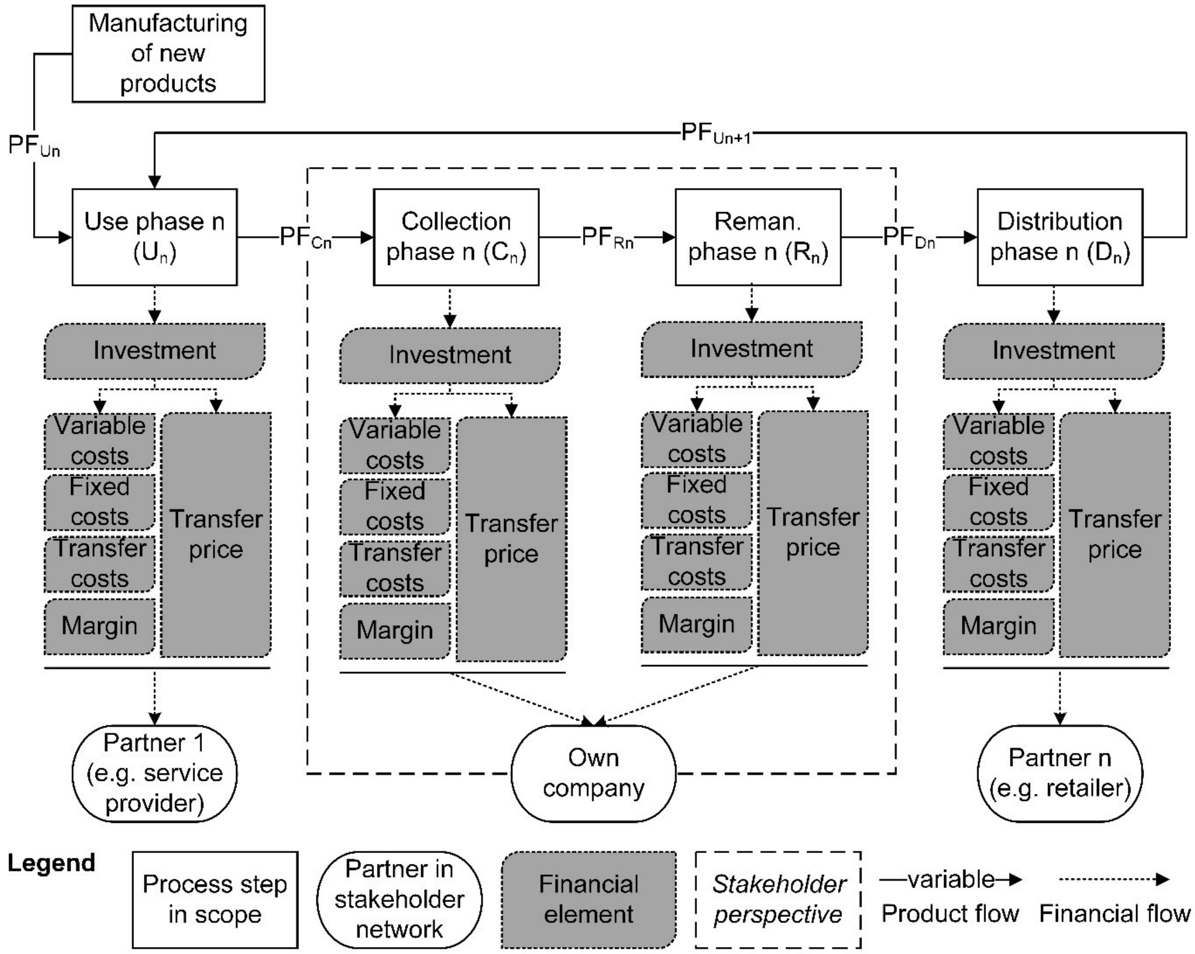


Figure 4-5: Financial consequences of the stakeholder's network design

The quantities of flows from several lifecycles can be accumulated, as they represent the same products and have been selected to be candidates for remanufacturing with the same quality criteria. The accumulated amount of cores collected must be considered to determine the core cost at the period t resulting from the business model decisions. The cost for the acquisition of cores depends on the integration of activities from the remanufacturing company and from the partners' network involved in case several sources of cores are used. To determine the value chain ratio of costs, an analysis of the integration at a determined phase of the process is suggested:

$$VC_t^x = \frac{C_t^x}{TC_t^x} \tag{4-3}$$

with

VC_t^x Value chain ratio for collection costs

x Product x in consideration

t Period t in consideration

$C_{p,t}^x$ Total internal costs occurring before the core collection

TC_t^x Transfer costs of upstream externalized activities

The purchase cost of the cores from the viewpoint of the remanufacturer can be calculated:

$$CP_t^x = \frac{C_t^x}{VC_t^x} * I_r \tag{4-4}$$

with

CP_t^x .... Core sourcing price for product x at the period t

VC_t^x Value chain ratio for costs

C_t^x Total costs occurring before the core collection

I_r Identification ratio for products considered for remanufacturing by the collector

Business model effects on influence ratios

The exact value for the strategic influence factors is computed as follows. WIDERA analysed the company-specific business model influences on the barriers and challenges for remanufacturing [Wid-14]. The influence of 130 attributes classified in the nine dimensions of the Canvas Business Model are evaluated on a scale from -2 to +2 using the degree to which a strategic ratio can be facilitated or lessened by the business model attribute.

The strategic ratios are collection, identification, remanufacturing and distribution success; core quality and control; transaction efficiency; product acceptance and value trend; and business model premium as represented in table 9. The influence trend of each strategic ratio is shown by the balance between positive and negative influence, which are proper to the type of business model. The business model attributes as well as the identified barriers for remanufacturing are listed in Annex A-2. The average influence of each strategic ratio is computed as follows:

$$\bar{E}_d = \frac{\sum_{i=-2}^{2} n_i * i}{\sum_{i=-2}^{2} n_i} \tag{4-5}$$

with

n_i Number of influence for the corresponding rate i

i Value of the corresponding rate

The trend of each strategic ratio can be determined by computing the influence strength as a quantitative value to determine the absolute effect of business model attributes on each strategic ratio. Based on the formula (4-5), the ratio influence strength E_s is obtained by summing the influences of business model elements for each strategic ratios identified, with:

$$E_s = \sum_{i=-2}^{2} n_i * i \qquad (4\text{-}6)$$

Table 9 Summary of strategic ratios

Strategic ratio	Canvas dimensions	Description of effects	Influence effects	Effect range
Collection success ratio	Customer relationships, Network	Indicates strategic influence over the product collection success	Defines C_r	0,8-1
Identification success ratio	Value proposition, Resources	Indicates strategic influence over the product identification success	Defines I_r	0,8-1
Remanufacturing success	Resources	Indicates strategic influence over the product remanufacturing success	Defines R_r	0,8-1
Distribution success	Canals	Indicates strategic influence over the product remanufacturing success	Defines D_r	0,8-1
Transaction efficiency	Network	Translates the fraction of transfer costs between companies in a network	Defines TC_t^x	1%-5%
Cores quality	Customer relationships, Network	Cores quality categories influence disassembly time and discard rates in reconditioning operations	Defect rates, Disassembly time	0,8 - 1
Cores control	Customer relationships, Network	Indicates the level of control of the company over the product returns as a % of product life	Returned cores distribution	1%-5%
Product value trend	Value proposition	Indicates the evolution of a current market price for a product, considering the technological or market-driven obsolescence	Market price evolution per month	0% to - 2%
Market premium	Value proposition, customer segments	Indicate the effect of the company business model on product sales price, taking into account customer acceptance	Market premium ratio	0,7 - 1,2

Absolute influences of each strategic ratio are determined by evaluating the selection of answers options characterizing the company business model within the potential answers, by using to following formula:

$$E_d \begin{cases} \dfrac{(\sum_{i=-2}^{2} n_i * i)}{\sum_{i=-2}^{2} n_i} \; for \; \sum_{i=-2}^{2} n_i * i \geq 0 \\ -\dfrac{(\sum_{i=-2}^{2} n_i * i)}{\sum_{i=-2}^{2} n_i} \; for \; \sum_{i=-2}^{2} n_i * i < 0 \end{cases} \qquad (4\text{-}7)$$

The absolute value of the strategic influences is computed by evaluating company-specific, absolute influence factor E_d on the material flow qualitative and quantitative characteristics. The influence of business model on the ratios is used to determine the company-specific level per business model type through the value influence factor ratio IFx by dividing absolute value by their strength. The proportion of positive and negative barrier influence factors by the grading of their impact on the strategic ratios. Value ranges are defined to represent the minimum and maximum impacts of business model types on a scale from 0 to 2 based on the expected success of business model types for remanufacturing. If the value of the barrier is closer to 2, it will influence the grading positively, and vice versa. The values for the business model range are estimated as follows:

$$IFx = \frac{E_s}{E_d} \tag{4-8}$$

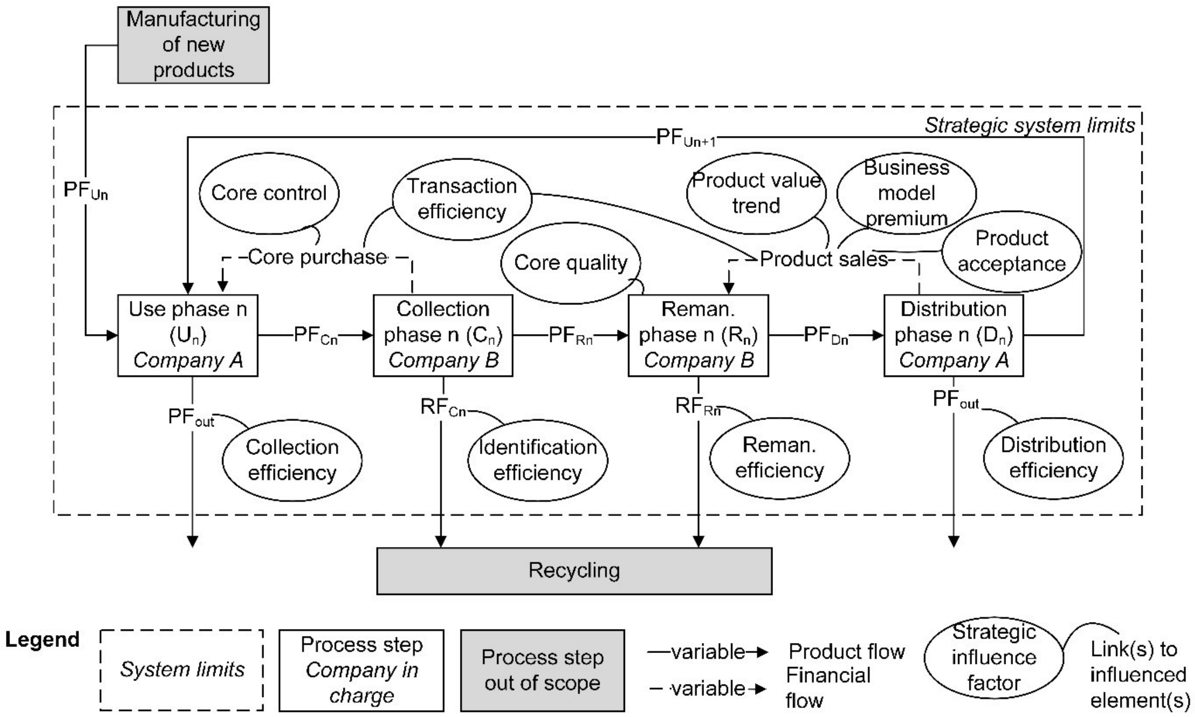


Figure 4-6: Strategic ratios affecting material or financial flows

The combination of strategic influence ratios and material flow estimation allows the definition of the quantity of cores by the application of percentage defining the collection, identification, remanufacturing and distribution success rates. In addition, core control determines the distribution of core returns as a consequence of the level of efforts provided to monitor products held by the customer. Core quality is considered to determines the influence of normally distributed good, normal and bad core quality classes on the disassembly time. The sales price of the products to be remanufactured is determined by the country-specific market price, which is gradually decreasing due to changing relationship of offer and demand for remanufactured products. The rate to which the market price is evolving with time is determined by the product value trend, considering perceived and technological obsolescence according to the product nature. According to the level of services coined in the company, a business model premium reflects if the product is sold higher or lower than the market price. The transaction efficiency shows the level of transfer costs between two possible actors of a remanufacturing network, such as between the collector and the remanufacturer. Further input for the strategy concerning the core price, logistic costs for the core delivery and assembly, and spare part price are considered as estimation data derived from the business model chosen in the strategy level.

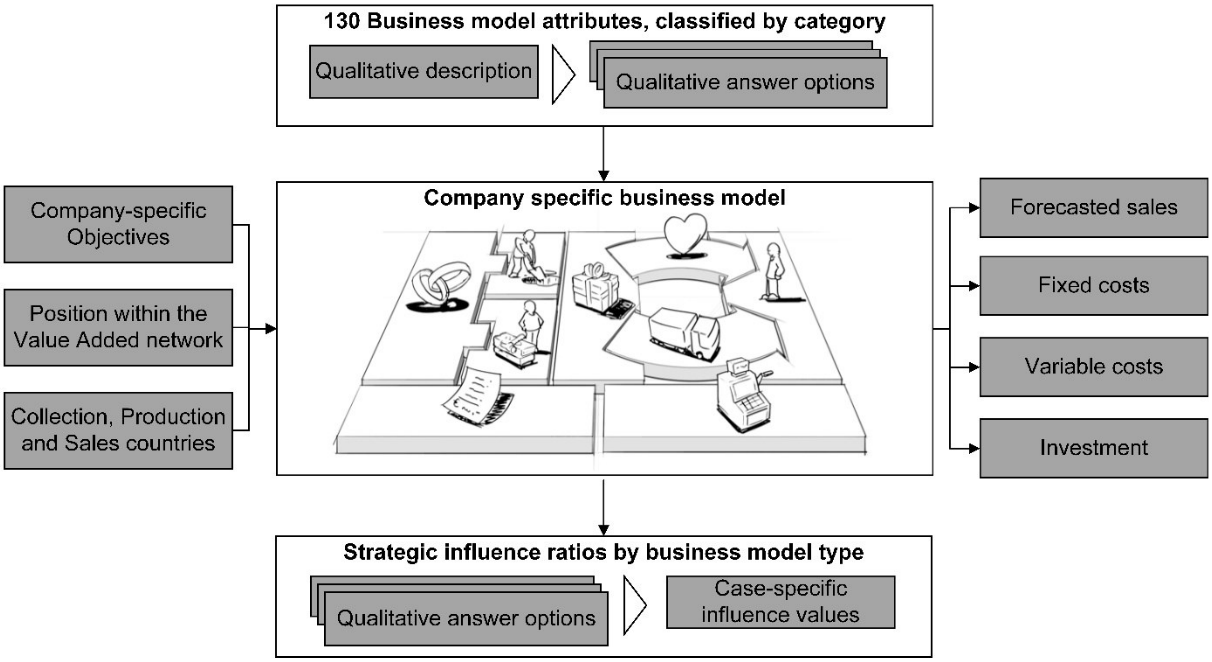


Figure 4-7: Methodology to determine strategic ratios affecting material flows

The prices of cores and products are listed per country, to represent the local conditions of transactions, supply, and demand of products. In this thesis, the prices and costs are defined though the determination of country-specific activity factors together with their influence on costs or revenues of an activity. Factors can either be depending solely from the location, such as for the valorisation of workforce and energy costs or be product and location specific for the evaluation of products, cores or recycled material market prices. In order to determine the right prices and cores, and to allow the representation of international remanufacturing networks, three locations are determined for the determination of a company strategy with core collection, remanufacturing operation and distribution locations, as illustrated in Figure 4-8.

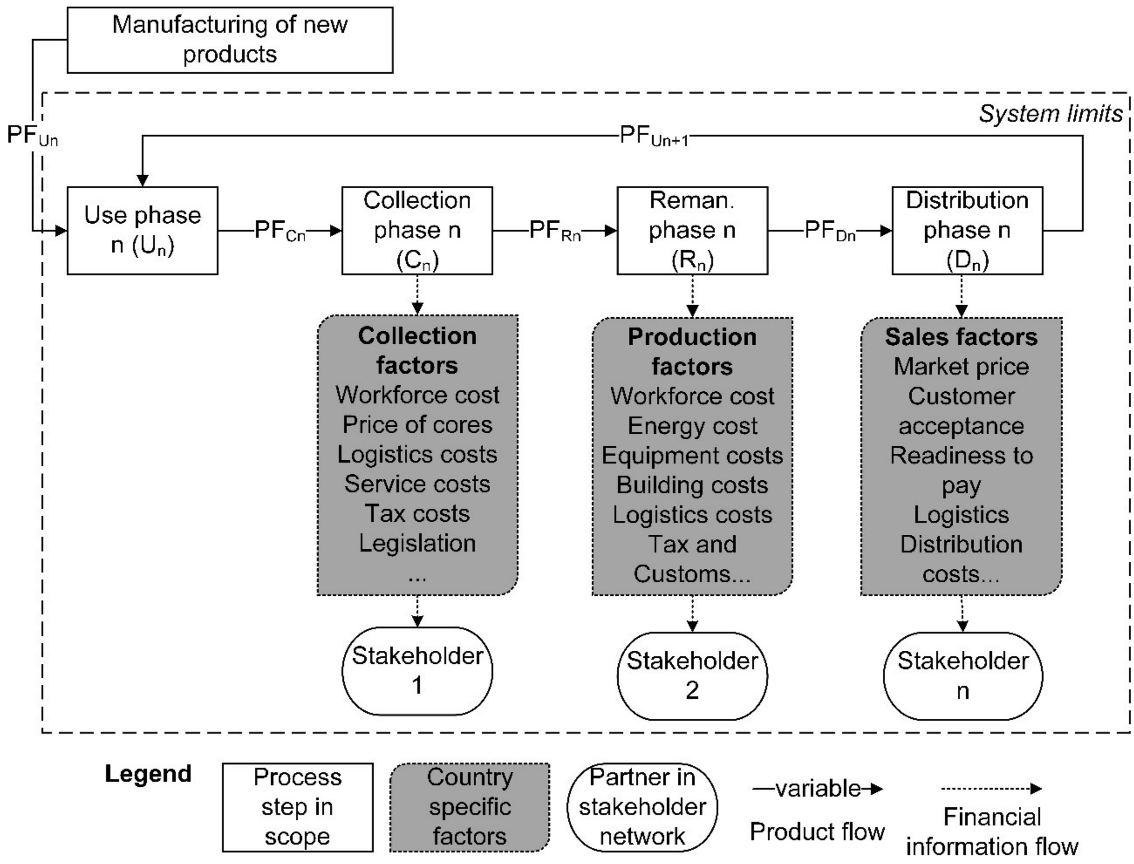


Figure 4-8: Country-specific influence factors

As a summary of this chapter, the elements of the strategic dimension as well as their contents are presented in graphical from in Figure 4-9.

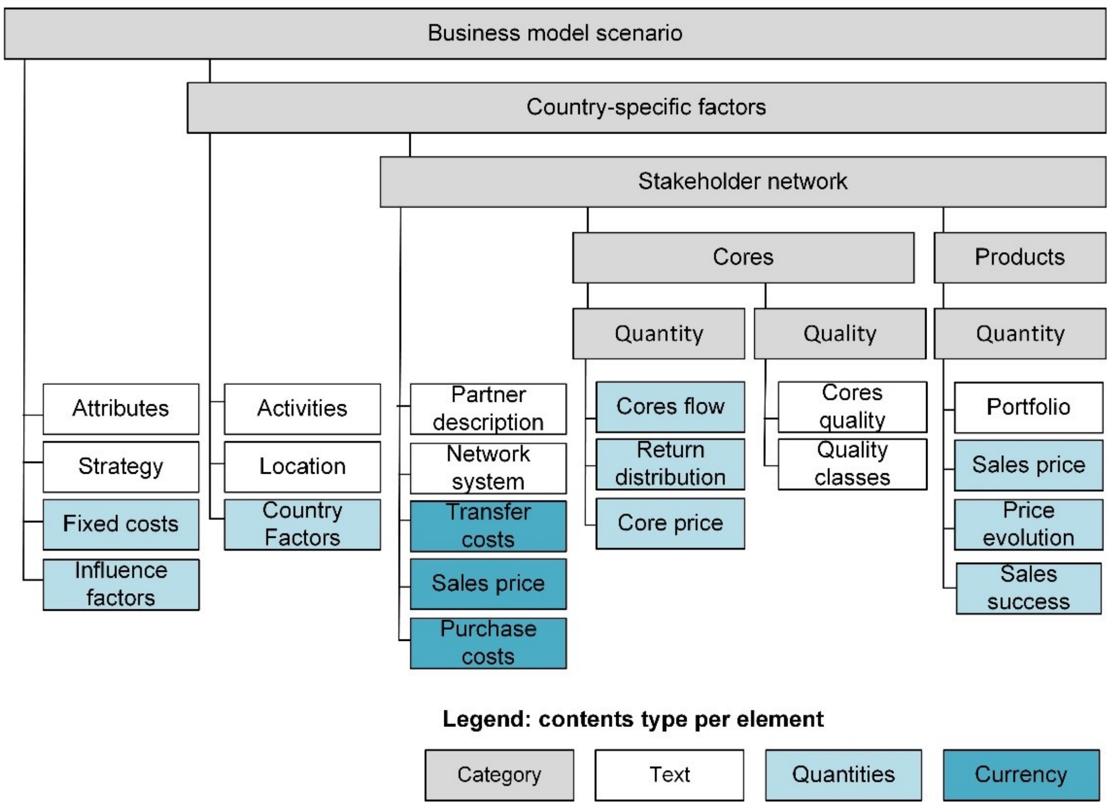


Figure 4-9: Strategic guideline elements

4.1.3 Tactics

Once the strategic elements are described and implemented, the tactical dimension can be approached. This dimension is relevant for the field of PPC and is represented by the tactical definition of the ideal method to organize the remanufacturing process to achieve the objectives in terms of quality, productivity, economic, and variability performance. Input information as well as output requirements are defined within the strategy phase and communicated to the production planning team to realize the defined objectives. Typically, the tasks to be realized are to ensure customer satisfaction through the delivery of products at the right time, of the right quantity, and with the best quality. This is performed by the definition of a production plan, which defines the order in which the products will be produced before each production shift begins.

The material flow characterizes a major input to the remanufacturing process and embodies the causal relationship between a company strategy and its production planning and control operations. The influence factors of product material flow are those described during the strategy definition based on the production and sales pattern from the previous lifecycle and from the execution of the remanufacturing company business model. The formula to determine the incoming material flow RF_{Rn} in the context of the company strategy is inspired from the works of UMEDA ET AL. that define the core return distribution [Ume-06]. To determine the time in which the flow is incoming in the factory, the distribution of sales of new products during the period n-1 is represented as a normal distribution, considering μ_d as the mean and σ_d as the standard deviation for the period *t*.

$$D(t) = PF^{x}_{Un-1} * NDist(\mu_d, \sigma_d, t) \tag{4-9}$$

$$NDist(\mu, \sigma, t) = \frac{1}{\sqrt{2\pi\sigma}} \exp(\frac{-(t-\mu)}{2\sigma^2}) \tag{4-10}$$

with

PF^{x}_{Un-1} Amount of product x sold in the lifecycle n-1

The second step is to determine the time when the products are reaching the end of the use phase, so that they can be ready to be collected. The amount of products distributed at the time between τ and $\tau + \Delta\tau$ is represented as $D(\tau)\Delta\tau$; assume the same normal distribution as for the previous product sales period PF^{x}_{Un-1}. Therefore, it can be assumed that the material flow RF^{x}_{Rn} for all time periods ($\tau = n \ldots \infty$) can be represented as follows:

$$S(\tau, t) = D(\tau)\Delta\tau * NDist\ (\tau + \mu_s, \sigma_s, t) \tag{4-11}$$

$$S(t) = \sum_{n=1}^{\infty} S(\tau, t) = \int_{\tau=0}^{\infty} D(\tau) * \ NDist\ (\tau + \mu_s, \sigma_s, t) d\tau \tag{4-12}$$

The model can be used to approximate the relative distribution between the product sales and the estimation of core return distribution. Two other indicators influence this distribution: namely, the standard deviation σ_s to which the cores are returned and the collection efficiency CE_n^x:

$$\mu_s = L_x \tag{4-13}$$

$$\sigma_s = L_x * CQ_t^x \tag{4-14}$$

$$CQ_t^x = Cr_t^x * Ir_t^x \tag{4-15}$$

with

CQ_t^x Core quantity control ratio

RF_{Rn}^x Amount of incoming cores of product x in the lifecycle n

Cr_n^x Average collection intensity ratio for product x in lifecycle n

Ir_n^x Average identification success ratio for product x in lifecycle n

L_x Average product lifetime

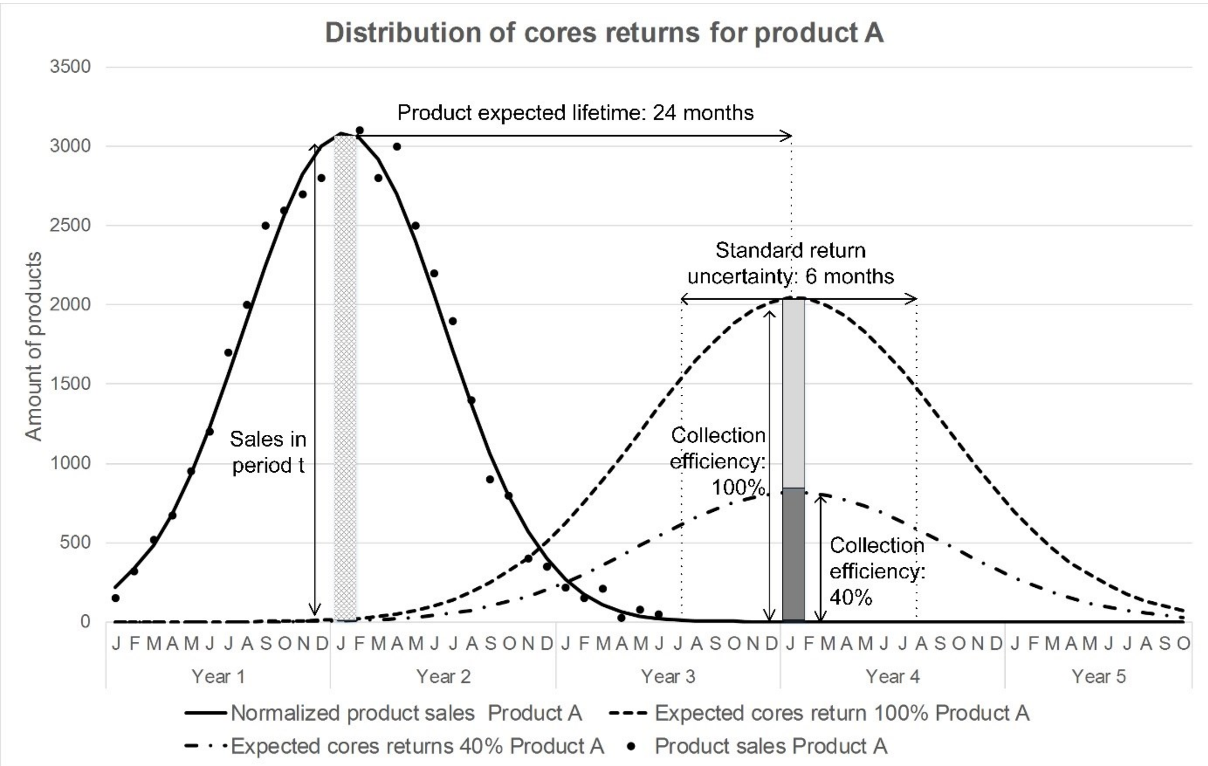


Figure 4-10: Core return distribution

The result of the core return distribution can be summarized in Figure 4-12, for a product A having an expected lifetime of 24 months, a standard return uncertainty of 6 months, and a collection efficiency rate of 40%. Core distribution allows the computation of the total numbers of cores on the market for the product studied. As the cores are the raw material of remanufacturing companies, they are either stored at the warehouses of the collector company or those of the remanufacturer before being processed and distributed for another lifecycle. The analysis of the core returns RF_{Rn}^x in the lifecycle n+1 can therefore be computed with the same formula as for computing the core return distribution from new products, as remanufactured products have the same quality requirements as in manufacturing. However, the strategy of the company should not change between the lifecycles. If the market price determination is computed in the strategy part, its evolution over time should be considered at the tactical level to determine the actual price at which the remanufactured products are sold. Figure 4-11 shows an example of the decision factors for the remanufacturing period with product price and core availability.

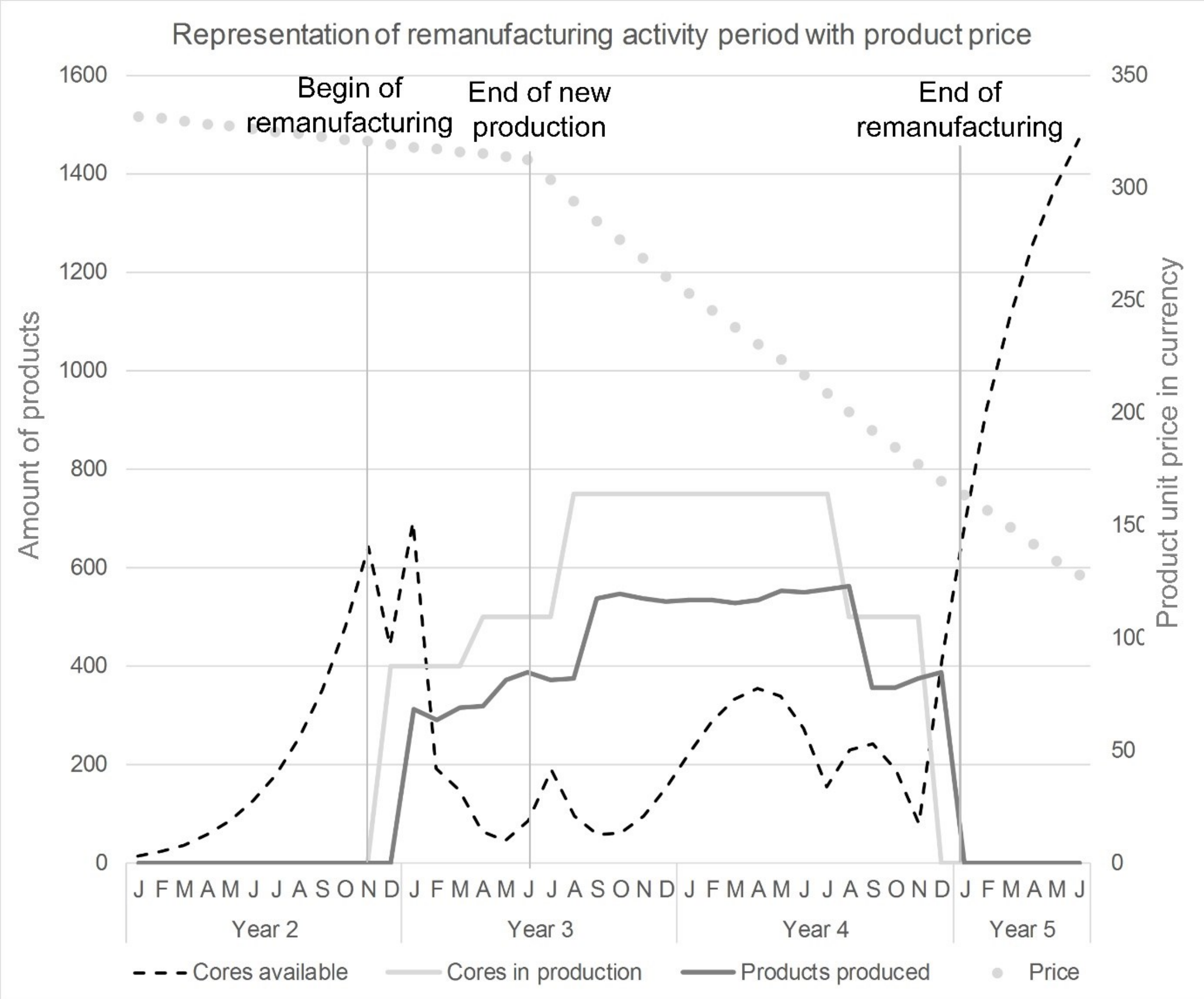


Figure 4-11: Remanufacturing activity period per product

A representation of the PPC activities and information flows for a typical remanufacturing process is suggested in Figure 4-12. Cores and products arriving at the factory location are considered to be immediately stored in an inventory. Material, assemblies, and core deliveries are considered to be effectuated at the beginning of the month; the products are shipped at the end of the month, in a quantity which is a multiple of their container size. The inventory gives flexibility in production planning to proceed to sourcing in previous months, in anticipation of future high sales level.

The product element represents the first information which is necessary to design the material flow entering a remanufacturing process, and for the allocation of the related costs. The element characteristics are classified in two categories: the product structure and technical specifications describing the quality standards of a new product, and the product material flow regarding the quality, quantity, and value of cores and remanufactured products.

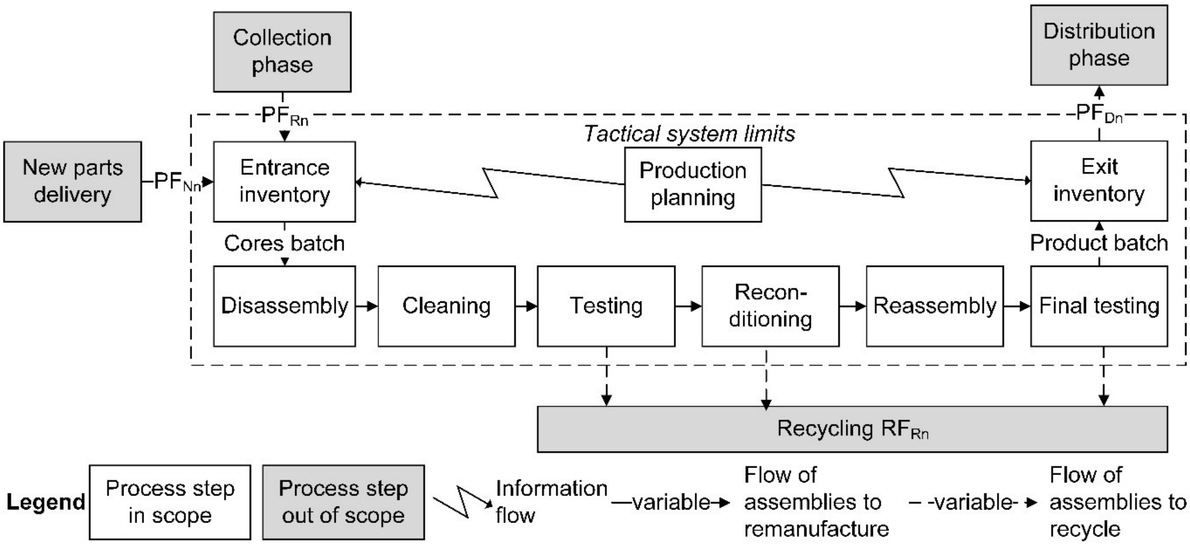


Figure 4-12: Tactical dimension of PPC activities

The first objective of the product description is to identify which groups of components must be disassembled for the adequate operation of the remanufacturing process; this defines the level to which the product must be disassembled. These modules are referred to as "Assemblies" in the guideline process and are expected to be attributed discrete processes at the remanufacturing facility. Assemblies are distinguished from the parts which have to be systematically replaced by new components because of their shorter life time, low price or the difficulty to recondition them.

In case of high levels of standardization between different products of the same family, identical assemblies can belong to more than one product. The functional, safety, and usability requirements are described at the assembly level and linked to every potential failure that prevents a core from being functional and which is corrected in the reconditioning phase of the remanufacturing process. This means that the assemblies can follow different paths through the remanufacturing facility to detect and correct failures which are linked to one assembly. Therefore, the information concerning the product should be detailed to allow an analysis of the effects of the remanufacturing process proper to each assembly, as represented in Figure 4-13. The information can be summarized in four categories: product structure, quality, quantity, and price. The product structure details the nature, number, requirements, and specifications of each assembly. The product quality concerns the potential causes and effects of failures that should be handled during the remanufacturing process.

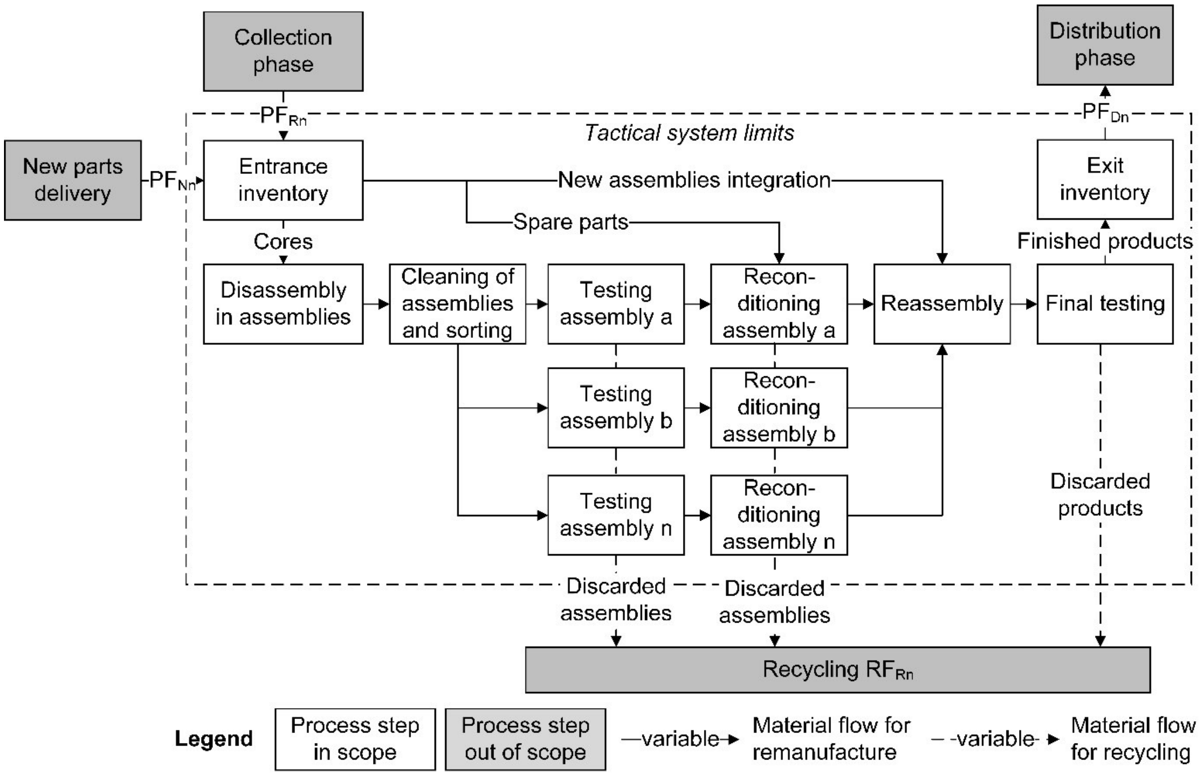


Figure 4-13: Tactical dimension of cores, assemblies, and product flows

Quantitative figures concerning the amount of cores, assemblies, spare parts, and products must be incorporated in the production plan for each period. Finally, price for core, assemblies, spare parts, and products are important elements of the economic feasibility analysis, as illustrated in Figure 4-14.

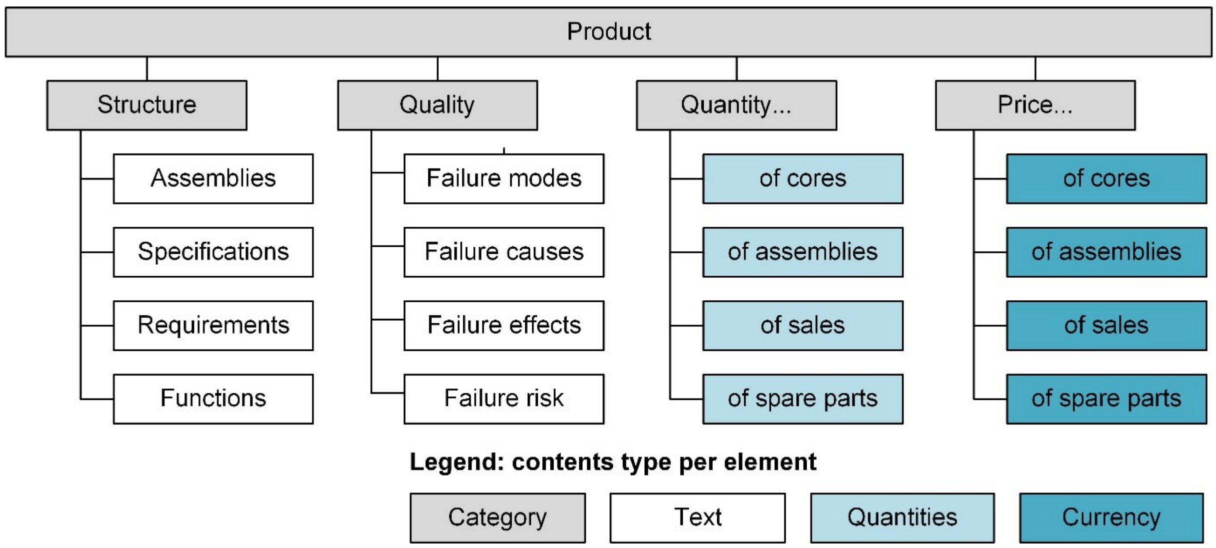


Figure 4-14: Tactical guideline elements

4.1.4 Operations

The last element type to describe a remanufacturing process concerns the work methods defined for each workstation in the industrial layout to ensure the remanufacturing of each product considered. In production scheduling, the operations are defined by the process chain forming the factory layout, the manual work methods used at each workstation to handle products or to operate machinery, and the equipment used during the process.

The first organizational level for operations management is the production scheduling; it determines the rules of work organisation within the factory, according to requirements from the production plan. Production scheduling comprise the working conditions from operators, the factory and workstations characteristics as well as the work methods, which are represented in subordinated organizational levels.

The second organizational level is considered with the factory layout. The factory represents the building in which the remanufacturing operations are performed and is characterized by the initial investment costs and the country in which the factory is placed. The factory layout determines the organization of the workstations used in the process and describes in which order the workstations handle the material flow through the factory.

Once the layout is defined, a third organizational level concerns the workstations characteristics. It determines the characteristics for each workstation to ideally handle the process planned to be performed. Following information is necessary to define a workstation:

- Type: Indicates the type of operations executed in the workstation, such as disassembly, cleaning, or reconditioning
- Changeover: Time to change the workstation setup after each product change
- Batch size: Number of assemblies handled per operation in the workstation
- Max capacity: Maximum storage capacity in the workstation to continue processing new operations
- Workstation price: Initial investment per workstation
- Number parallel: Number of parallel workstations in the layout

The next organizational level element concerns the work method used by the operators when processing the material flow in the workstations. These elements employ the MTM technique to define the time needed for the product to be processed in the workstation. The MTM analysis must belong to the one workstation where the action that is described occurs. One workstation can contain more than one MTM analysis; analyses can be performed in parallel by several operators or sequentially. To be accurate, the MTM analysis not only depends on the workstation layout but also on the product elements; therefore, the analysis is product-specific. Creation of the MTM analysis necessitates determination of the following variables:

- Description: Summarizes the work method contained in the MTM analysis
- Start: Indicates the precise moment when the work method starts
- Contents: Details the work steps contained in the method

- Finish: Indicates the precise moment the method stops
- Limitations: Optionally indicates if more products are treated jointly in the method
- Discard rate: Indicates the average failure percentage for a typical core

MTM codes represent the highest level of detail in this model, as they are used to describe the combination of single moves necessary for the completion of a work method. As remanufacturing is typically processed using product batches, the MTM building block Universal Analysis System (UAS) is suggested. Each MTM code represent a movement from an operator and is described using the following criteria:

- MTM code: Refers to the UAS codification in short names,
- Description: Allows the description of the movement in the context of the work method to ensure understanding amongst process designers,
- Type: Shows if the process concerns a manual or automatized operation,
- Time TMU: Describes the time necessary for the operation to be performed in TMU,
- Parallel: Indicates if the move is done in parallel from another longer move, in which case only the time of the longest move is considered.

Depending on the work method, a last equipment used to perform tasks in the process. This step establishes the specific machinery employed within workstation to perform the operations according to the batch size and operating time. Cost for equipment operation depends on the place in which the factory operates according to the local production factors.

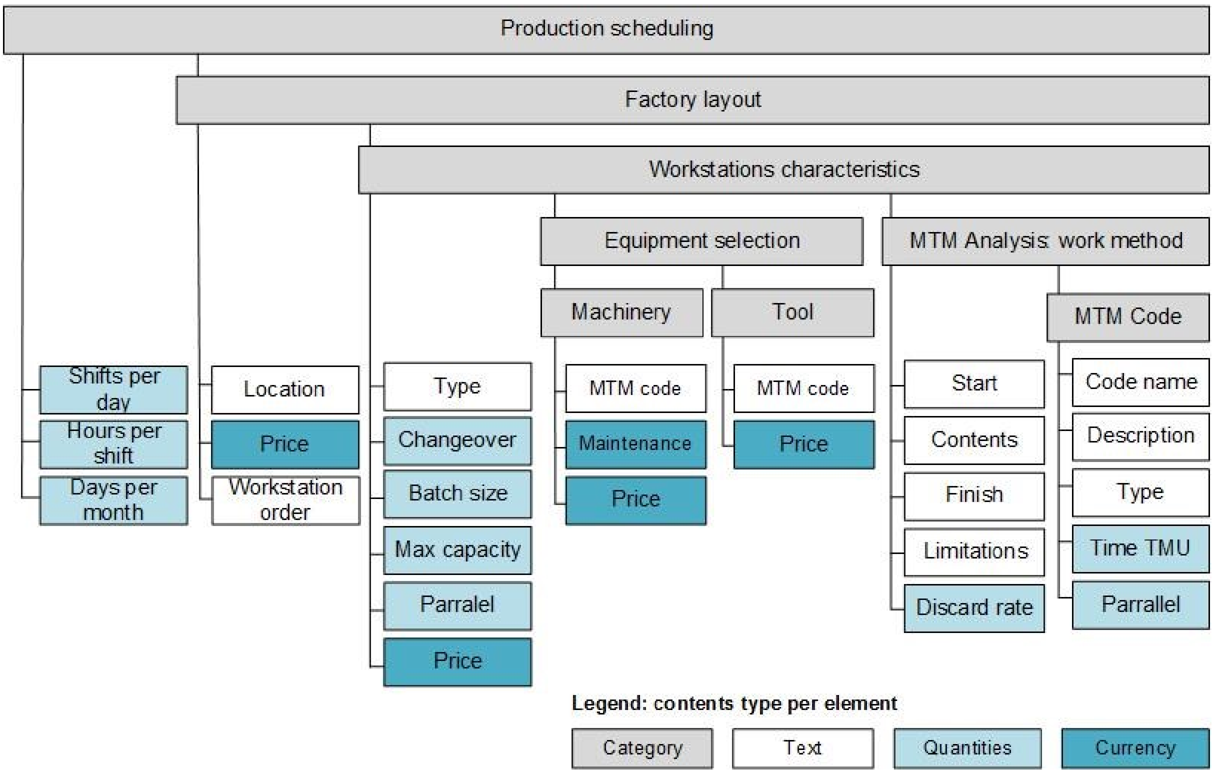


Figure 4-15: Operational guideline elements

The machinery is a group of all machines which perform automatic tasks to be configured and activated by the operator. In opposition, the tools are the artefacts which require an action of the operator to ensure the operation of a task. The difference between machinery and tool is essential to consider the parallel time an operator can dispose of when an automatic process is running. In addition, only the machinery has maintenance costs. Machinery and tools depend on one workstation from one factory; their linkage is fixed per layout. The equipment process time duration is represented in a customized MTM code. The summary of the operational element is represented in Figure 4-15.

The human element of the process considers the personnel count on three levels inside a factory: factory operators, factory management, and support functions. The number of operators is obtained from the production scheduling activities established when designing and optimizing the process-chain at the scheduling level. The need for factory management and for support functions is estimated at the production planning stage, according to the activity levels determined to ensure the satisfaction of the demand for remanufactured products or assemblies; it depends on the value chain integration activities decided. The use of MTM also allow the consideration of ergonomics in the workstation design by using the tools designed for this function, although this functionality will not be considered in the scope of the methodology to establish the guidelines.

4.2 Method selection

Evaluation criteria based on scope and on requirements set from chapter 4.1 are suggested to evaluate the integration potential of productivity and quality management methods identified in the state of the art. The objectives of the guidelines are manifold and should be achieved through a systematic approach to characterize production planning decisions in remanufacturing. Based on the objectives of Lean Management for production planning and using strategic, tactical, and operational elements previously described, methods targeted on quality, productivity, economy, and variability management are evaluated, and the choice for integration is justified.

Scope requirements are suggested to decide if the methods can fit in the scope of application. Requirements are to be applied for the selection of both quality and productivity methods, and their compliance to the requirements sets validated. Three major requirements help to choose which method can be implemented in the guideline. If the method does not comply with a major criterion, it is automatically eliminated and will not be implemented. The first requirement, operation focus, verifies if the method input and output information can be used in the context of production planning and control. The second requirement, planning ability, indicates if the method can be used without the need to implement a process. The third requirement is remanufacturing ability; it verifies that no counter indications exist for the method to be used in the context of remanufacturing.

To allow a detailed analysis, the users of the guideline must be informed about strategy, product structure, product cost, product quality issues and their treatment, as well as the equipment needed for the application of quality treatment. If the tool is perfectly suitable for OEM production management, it could also be used by contacted or independent remanufacturers informed about a product's technical specifications. In the context of a linear production planning methodology according to VDI 5200, the guidelines can be employed for concept planning, fine planning, and in preparation for a remanufacturing factory.

4.2.1 Quality

The evaluation process is defined by the scope of application and the guideline objectives.

Table 4-2: Evaluation of quality management methods for guideline integration

Quality management methods	Scope			Quality requirement set				
	Operation focus	Planning ability	Reman. ability	A1	A2	A3	A4	A5
5 Why	Yes	No	Yes	○	○	◐	◐	●
8D	No	No	Yes	○	◐	◐	●	○
ABC	No	No	Yes	◐	●	○	○	◐
Benchmarking	No	Yes	Yes	●	●	○	○	○
DoE	Yes	No	Yes	○	○	●	●	●
FMEA Product	Yes	Yes	Yes	◐	●	●	●	●
FMEA Process	Yes	Yes	Yes	○	○	●	●	●
FTA	Yes	No	Yes	○	○	●	●	○
M7	Yes	No	Yes	◐	●	●	○	○
Q7	Yes	No	Yes	○	◐	◐	●	○
QFD	Yes	No	Yes	●	●	◐	○	○
SPC	Yes	No	Yes	○	○	●	●	●
Stakeholder Analysis	No	Yes	Yes	●	○	○	○	○
SWOT	No	Yes	Yes	●	◐	○	○	○
TRIZ	No	No	Yes	◐	●	○	○	○

Legend

A1: quality policy / A2: quality goals / A3: quality assurance / A4: quality planning and control A5: continuous quality improvement

Evaluation: ○ No contribution ◐ Partial contribution ● Dedicated

To verify the achievement of the guideline objectives, the methods identified in chapter 2.3.3 are validated by their compliance with quality management requirement sets. The evaluation for each requirement is either qualitative and comprehensive, partial, or no contribution to quality improvement. An overview of the breadth of coverage of quality by the selected tools, to confirm that the guideline will fulfil the given requirements, is illustrated in Table 4-2. After the application of the selection criteria, methods such as 8D, Q7, M7, FTA, and ABC are used situationally. Therefore, it is not possible to implement them for planning of remanufacturing operations. However, the methods recommended after the SOP, if a structured approach to negative customer complaints must be established, if quality focus is to be adjusted to a specific topic, or if failures and their defect rates are to be analysed. The 5 Why method is used to identify the root cause of the problem and can be employed during operation of the remanufacturing process. FMEA Product and Process can be implemented in the guideline and have the advantage of covering most of the requirement sets. The only requirement that is not fully covered by the selected method is quality policy, as FMEA Product requires the indication of the level of quality by the user in selecting an acceptable level of RPN.

4.2.2 Productivity

The productivity methods identified in the state of the art are selected using the application of major criteria and validated by the speed requirement set, given the proximity of the objectives. The results of the evaluation are presented in Table 4-3. Many productivity management methods are selected to be integrated in the guideline; they cover the entire set of speed requirements. The application of most of the Lean Production methods can be ensured by the integration of methods such as Heijunka, Kanban, OPF, Pacemaker Process, SMED, and VSM. However, situational methods are not included, as for Andon, Go Gemba, People Empowerment, Poka Yoke, and the 5S method, as their implementation is not possible or is highly inefficient in the planning phase of a remanufacturing process. MTM is chosen over other TDM methods, as it is a PMS with open source time data that offers a statically proven target for determining the time of operations before the start of production.

4.3 Guideline structure

Elements and methods are ordered according to the development of a strategic, tactical and operational dimensions explained in chapter 4.1, on the result of the works of ERLACH and DUNKEL for the design of the integration of Lean Production summarized in chapter 2.4.3. The economy and variability requirement sets are considered as objectives to improve the coherence of the remanufacturing system developed and are evaluated at the of the guideline description.

Table 4-3: Evaluation of productivity management methods for guideline integration

Productivity management methods	Scope			Speed requirement set				
	Operation focus	Planning ability	Reman. ability	B1	B2	B3	B4	B5
Andon	Yes	No	Yes	○	○	○	○	◐
Go Gemba	Yes	No	Yes	○	○	○	○	●
Heijunka	Yes	Yes	Yes	○	●	●	●	●
Kanban	Yes	Yes	Yes	○	○	●	●	○
MTM	Yes	Yes	Yes	●	◐	○	○	●
One-Piece flow	Yes	Yes	Yes	○	○	●	●	●
Pacemaker process	Yes	Yes	Yes	○	◐	●	●	◐
People empowerment	Yes	No	Yes	○	○	○	○	◐
Poka-Yoke	Yes	No	Yes	○	◐	◐	○	○
SMED	Yes	Yes	Yes	●	◐	○	○	●
Simulation	Yes	Yes	Yes	●	◐	●	○	◐
Standardized work	Yes	Yes	Yes	○	●	○	○	○
Stop watch	Yes	No	Yes	○	◐	○	○	◐
5S Method	Yes	No	Yes	◐	○	○	○	●
VSM	Yes	Yes	Yes	○	●	●	○	●

Legend

B1: separation of value and waste / B2: value stream management / B3: material flow management / B4: application of pull principles / B5: productivity continuous improvement

Evaluation: ○ No contribution ◐ Partial contribution ● Dedicated

4.3.1 Lean Production

Lean Production goals are ranked as quality, speed, economy, and variability. The logical structure of the guideline respects this order and adapts to the challenges of remanufacturing for the fine planning phase of the production planning process [VDI-11]. Strategic decisions influence the characteristics of material flow entering the remanufacturing process, based on the distribution of new product sales. Once strategy is defined, it is ensured that the remanufacturing process restores cores to the quality expectations of a new product. After defining which actions are necessary for quality management, the guideline defines all processes necessary aims to handle the product in the factory, using Lean and MTM principles. Models developed for the implementation of Lean Production are taken as a basis for ordering the process steps. This step provides every necessary information to proceed with a detailed economic feasibility study of a product-specific remanufacturing process, for each of the specific sub-assemblies. In the economy section, the production planning is obtained while taking decisions on parts replacement, work organisation and production planning. The final step of variability is to integrate several product variants in one factory in order to further adapt the remanufacturing system to its environment and to obtain final value for the economic feasibility assessment over a given period of time. The guideline summarizes the results in the form of a VSM and reports the quality, work methods, and economic indicators. The guideline interface ensures an adequate environment for the user to select the correct information, as presented in Figure 4-16.

For each step, the Idef0 Diagram is used as an effective illustration tool to display methods and information flow. The four parameters, input, control, methods, and output, are represented by arrows. Process steps are illustrated as chronologically numbered boxes connected by arrows to signify that the output of a process represents the input for the next one. Controls necessary to further specify the task enter the box from the top, and methods that are necessary for this activity enter the box from the bottom [AIH-07]. Control elements represent the source of information needed to use the methods prescribed, which are organized in three categories. The scenario concerns data from sources external to the production management such as business models and market conditions. Every information related to product characteristics from the second category. Finally, information about factory organization constitutes the layout category. Methods represent the tools belonging top each guideline step. The adaptation of the Idef0 diagram is summarized in Figure 4-17.

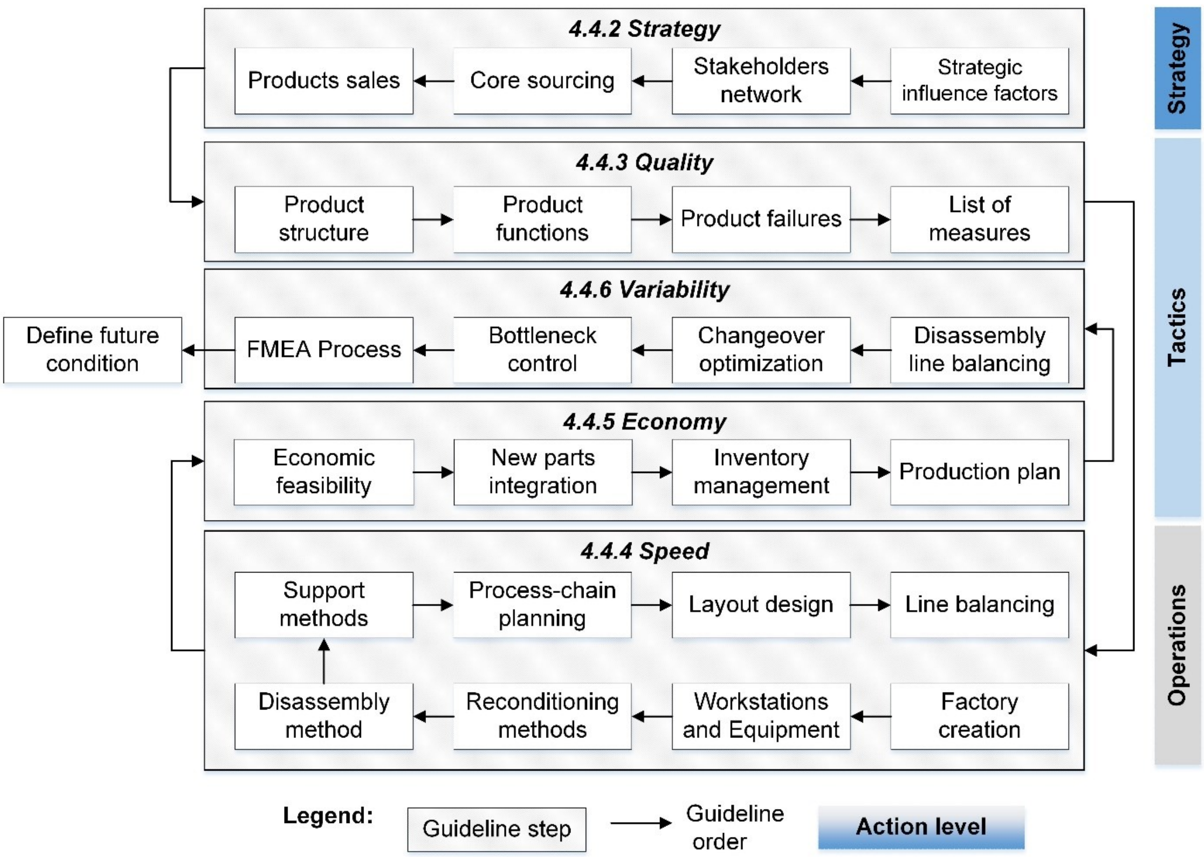


Figure 4-16: Logical structure, objectives, and scope of the guideline

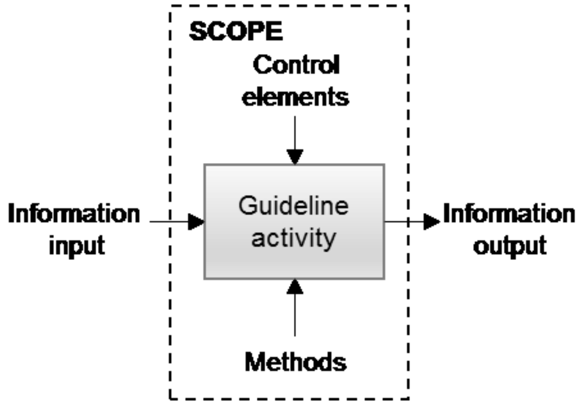


Figure 4-17: Idef0 Diagram

Then, the guideline structure is presented as a logical succession of steps classified by Lean Production objective under consideration of the order of application. Each of the steps is detailed in the form of processes, given the information flow, control elements, and methods. Steps are summarized in Figure 4-18.

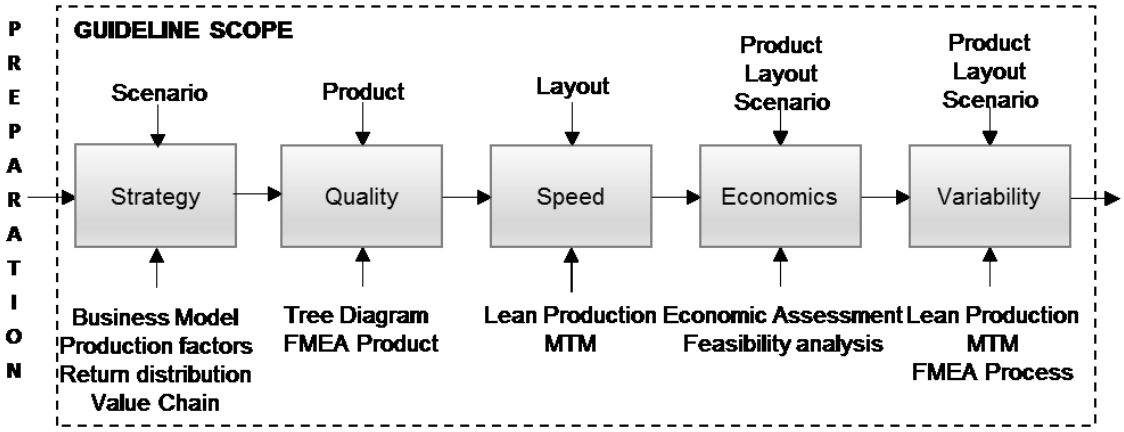


Figure 4-18: Idef0 of the guideline steps

4.3.2 Strategy

To define the context for operation of the remanufacturing activity, the strategy determination aims at defining the company’s objectives and conducting a first, preliminary evaluation of the economic feasibility of the remanufacturing activity. The first step is selection of the business model of the company within a range of patterns with pre-determined attributes, to obtain positive and negative influence factors on production planning.

Second, the stakeholders’ network indicates the activities integrated by the company within the reverse value chain that make up the remanufacturing strategy. It targets the necessary costs, revenues, and investment to realize the activity. Next, the core sourcing objectives are determined in the context of their country of origin. The final step concerns the product sales in the marketplace where the remanufactured product will be sold. The summary of the strategy part gives feedback concerning the operational margin based on the financial elements already determined. A graphical representation of the strategy determination steps is presented in Figure 4-19.

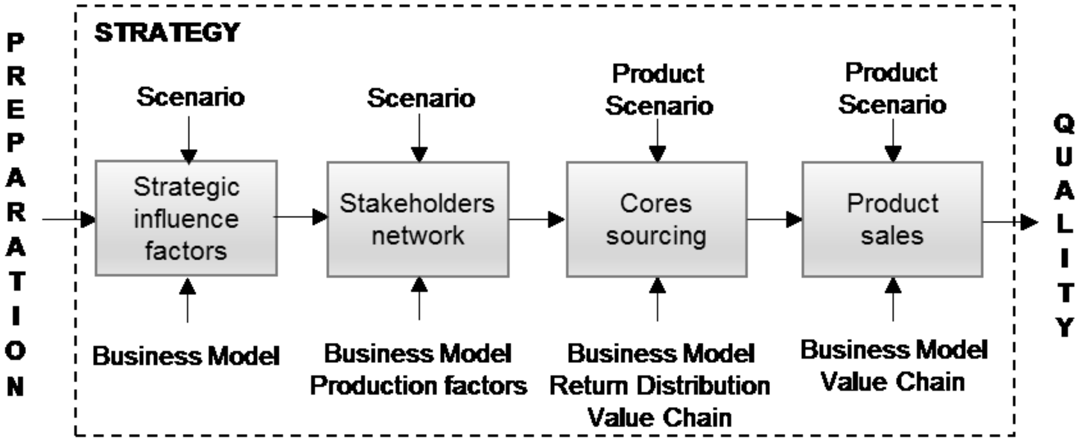


Figure 4-19: Idef0 of strategy step

In the business model step, a choice between several predefined business models with a description of the qualitative dimensions of the Canvas Business Model is suggested. The first business model suggests commercializing goods under the model of PSS, where the products are leased to the customer and remain the property of the company. In this thesis, only one example of PSS-based business model is considered. Revenue flows are fixed per product and per month but expressed as product sales for the total revenue generated in the period, and products are collected after a time agreed upon contractually. A different alternative is proposed with the aftermarket model, where the products' ownership is transferred to the customer and then collected by market-driven methods such as product swap upon availability. This model requires less services to be developed but faces issues in collection efficiency and customer acceptance. Each business model strategy has a minimum and a maximum range value in which the influence of company-specific business model is determined by the strategic influence factors, as represented in Table 4-4. Additional forms of business model can be further integrated provided that standard values can be defined.

In the case of the warranty replacement, the delivery of parts to an OEM by remanufacturing used products implies no full reassembly, a demand-driven production organization, and mitigated customer resistance. The effect of qualitative factors on the product quantity, quality, and control is represented by standard values influencing the dynamics of material flows and market value in the later steps of the process. Second, the position of the company within the stakeholders' network and its level of vertical integration is informed by the attribution of responsibilities to the activities resulting from the business model decisions. These activities can be integrated or outsourced. In the case of integration, the value added is captured by the company, but input is requested for the investment, and fixed and variable costs occurring as a consequence of the integration. If the activity is outsourced, the costs per product are planned to be higher than if done in-house; transaction costs should apply, but no additional costs will result.

Also, the stakeholders' network is used to indicate the countries where cores are sourced, where the operations are performed, and where the remanufactured product is sold, to indicate the market conditions in their local context. The third step considers the analysis per product with regard to the cores sourced. In the context of the country selected in the previous step, the average core price is entered per product. The quantity of cores per container is specified as well as the conditions of sale and the transfer costs which are not covered in the sale price, such as logistics and import customs for the location of remanufacture. In the context of the value chain integration, the total costs are integrated in the core unit.

Table 4-4: Standard values per business model type

Influence factor	Influenced element	Ranges	Standard value per business model (worst value-best value)		
			PSS	Warranty	Aftermarket
Collection success ratio	Defines C_r	0,8-1	0,9-1	0,85-0,95	0,8-0,9
Identification success ratio	Defines I_r	0,8-1	0,9-1	0,85-0,95	0,8-0,9
Remanufactu ring success	Defines R_r	0,8-1	0,9-1	0,85-0,95	0,8-0,9
Distribution success	Defines D_r	0,8-1	0,9-1	0,85-0,95	0,8-0,9
Transaction efficiency	Defines TC_t^x	1%-5%	1%-5%	1%-5%	1%-5%
Cores quality	Defect rates, Disassembly time	0,8 - 1	0,95-1	0,85-1	0,8-0,9
Cores control	Returned cores distribution	30%-1%	5%-1%	1%-20%	30%-10%
Product value trend	Market price evolution per month	0% to -2%	-0,1% to 0%	-1% to 0%	-2% to-0,5%
Market premium	Market premium ratio	0,7 - 1,2	1-1,2	0,9-1,1	0,7-0,9

The last step concerns the sale of products in the target country. At the difference of the core sourcing, where determining the core sourcing conditions to aggregate all related costs, the product price is computed as excluding all costs which must be paid by the remanufacturer. The container size is used to determine the repartition of logistics and customs costs per product sold.

As a result of the strategy phase, the information necessary for input to production planning is obtained. The difference between the product net sale price and the total core cost provides the theoretical margin remaining for the remanufacturing operations. Influence factors from the business model determine the level of variability to be handled as a requirement from the business model. The local production factors determine the level of costs to consider for workforce, energy, consumables, and machinery necessary when operating the remanufacturing process. Should the margin level be estimated as too low for pursuing the analysis, iterative adjustments can be made to each of the strategy elements.

4.3.3 Quality

The main objective for quality determination is to make sure that the process established will secure the level of quality presented as a flagship by all remanufacturing industries. After the information about product and assemblies is entered, the Product FMEA method is used to define the nature of detection and corrective actions per assembly. This step ensures that the most significant faults are recognized and reconditioned during the appropriate process steps.

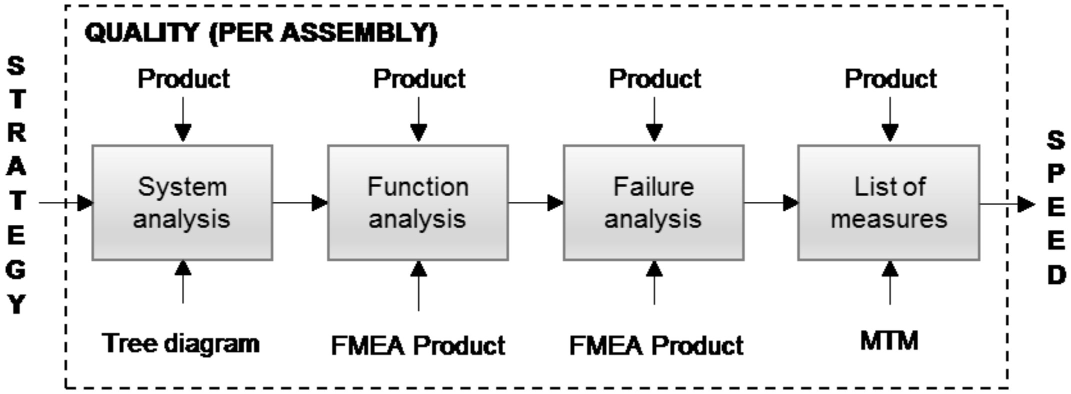


Figure 4-20: Idef0 of the systematic quality determination

The methods are explained according to the element variables processed by the guideline program represented in Figure 4-20. The first step is to describe a system analysis from the bill of material using a tree diagram detailing system, product, assemblies, and costs. The bill of material is the starting point to separate between assemblies which will be reconditioned or alternatively parts to be replaced. Major determining factors to estimate which assemblies are worth reconditioning is their market price, relative life duration within the product, and non-destructive accessibility. For simplification purpose, the parts will be changed at each remanufacturing process. The part price is determined by the following formula:

$$Price\ of\ replacement\ parts = Pp - Rp \qquad (4\text{-}16)$$

with

Pp Price of new parts sourced in the market

Rp Revenue from recycling of used parts

The second step aims at generating information on the product functional analysis. It establishes the product system specifications through the determination of functions and requirements for each assembly selected to be remanufactured. Functions can be classified in functional and non-functional requirements, which target safety, performance, and usability.

The list of functions is then related with assemblies, considering that some functions may involve several assemblies. The assemblies' functional description details the specifications which ensure their operation as target values to be tested within the remanufacturing process.

The third step is to obtain the information concerning the potential failures per assembly, while considering the fields required in the FMEA Product. The scale for rating the severity, occurrence, and detection of the failure should be specific to the product family considered for the guidelines. Severity describes the importance of the effects on customer and legal requirements regarding the system behaviour and the failure effects on humans and the environment. This category does not change when the FMEA is used for remanufacturing. Occurrence describes the frequency of a failure and should be measured by estimating the likely causes of the failure. In the case of remanufacturing, the causes of failure, such as cracks, wear, or rust, depend on the previous use phase and on eventual lack of care during the collection and reverse logistics phases. Detection concerns the current control system to detect the cause of failure and proceed to corrective actions, representing visual, mechanical, or electrical testing during the remanufacturing process. The process is very different, as in the manufacturing environment, the detection should be performed on cores which are all non-functional and reveals the critical importance of test system design. The failure modes are ranked by criticality according to the Risk Priority Number (RPN), which provides a guideline for the definition of actions to be included in the remanufacturing process.

Following the FMEA Product ranking, a provisional description of the detection and correction actions is given, based on their potential to reduce the most critical failure modes. This last step of the quality determination highlights the difference between the current and the future state of the remanufacturing process regarding its ability to solve the failure modes identified. When initially creating the process, no process steps are defined; therefore, the occurrence and detection failures should be high. The inclusion of actions should provide a drastic reduction of the RPN level per failure mode. Further instantiations of the current and future state process of the Remanufacturing Product FMEA ensure continuous improvement of the quality process.

4.3.4 Speed

Once correctives methods are considered and defined as a guarantee to maintain the quality expected for remanufactured products, the next step is to define and order the other actions needed in the process and to ensure the highest level of productivity. The process chain should be constructed to enable the detection and corrective measures per product to be instantiated and operated with the minimum waste within the remanufacturing process. To estimate the efficiency of a remanufacturing process from the planning stage, the production layout should be determined and the steps are displayed in Figure 4-21.

First, a layout is established and the actions already determined are related to the layout. This process will be unique for every product considered within the scope of the guidelines. Second, the characteristics of the remanufacturing facility are defined through its location, investment, and size. The necessary input sources such as workforce, electricity, consumables, and overhead are determined in the context of the selected country infrastructure. Further, the planned workstations are defined for their respective process step type, such as testing or cleaning, initial investment, and maximum amount of products received before being blocked.

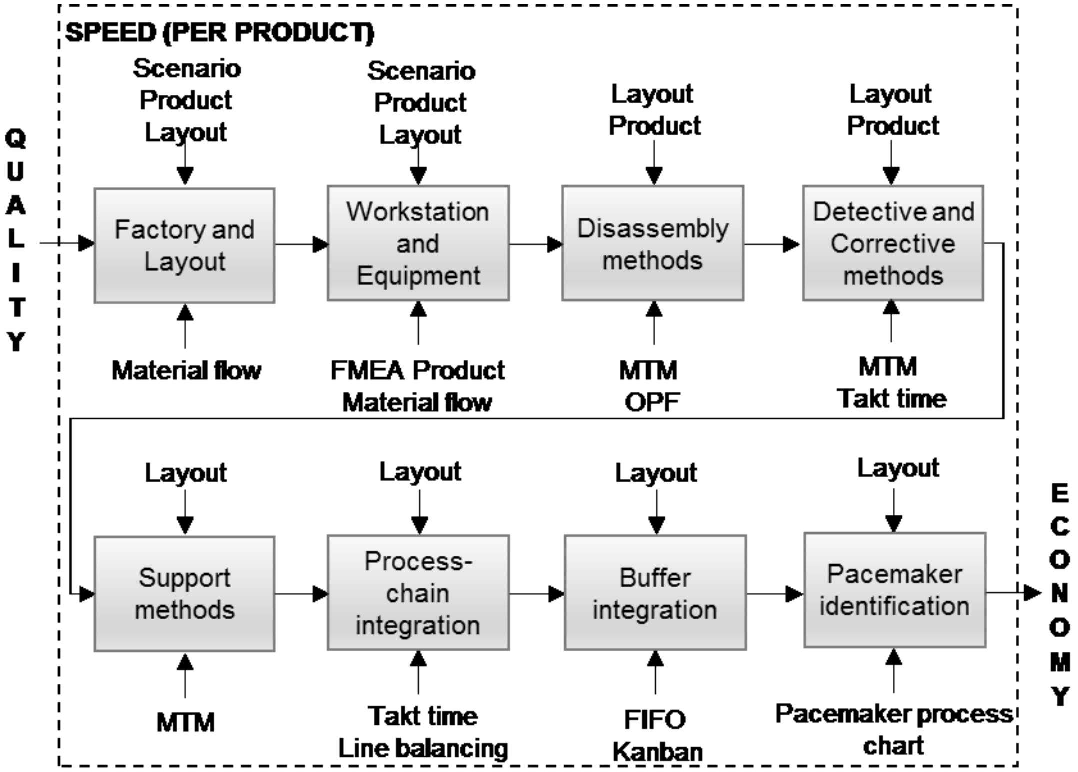


Figure 4-21: Idef0 of the optimization of process speed

Next, with respect to the assumed product quantities to be processed, technologies are selected and equipment defined for their nature as machinery or tool, workstation type, investment, consumables used per minutes of inactivity, maintenance, and size. One or several MTM codes are created for each piece of equipment, according to the different programs which can be operated and with respect to their use of consumables per minute of activity and for the action time. Then, workstations and equipment are jointly placed inside the factory, including internal logistics transport infrastructure within the process chain, to define the current factory layout design.

The next action necessary to determine the process elements is to define the manual operations within the layout previously drafted. Starting with disassembly, each production step is defined in detail using MTM analyses in the context of the workstation and layout design, adjusted to an estimated takt time, and integrated in the process. The MTM analyses are specific for each product, whereas the workstations are used for various product types upon changeover. For this reason, in addition to the operative work methods, the changeover method establishes the specific work method per workstation, including machine or tool reconfiguration, change of fixtures, and workstation reorganization.

The first step for method definition concerns optimization of disassembly process. Using product structure and layout elements, the disassembly sequence based and the disassembly method are determined. Second, detective and corrective actions are described based on the results of the quality phase and of the disassembly methodology selected. Next, the full process definition considers all remaining actions which are necessary for the execution of the process, such as reassembly, transport, or packaging. After every remanufacturing process step is entered and its method and equipment listed, the process integration can occur. Then, the takt time is computed from the user entries of the time available for a customer order quantity and price, represented as a yearly activity average for a maximum period of one shift.

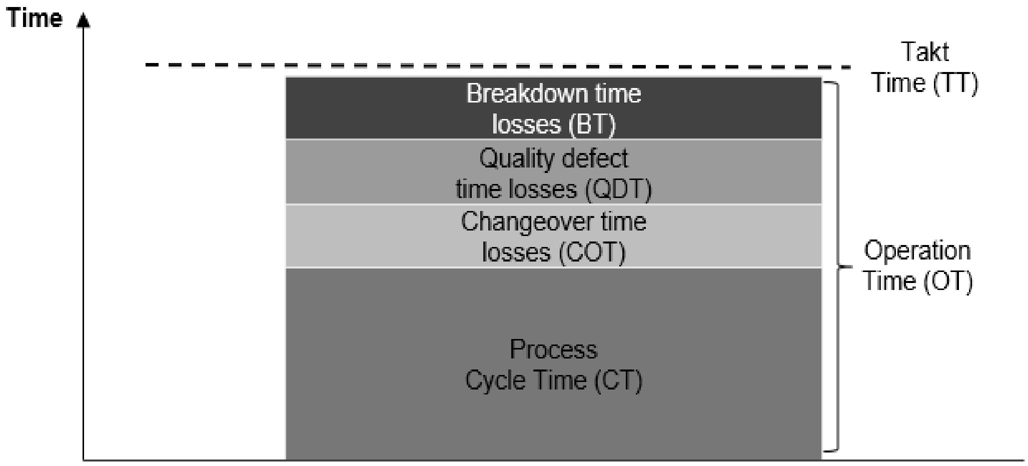


Figure 4-22: Takt time determination

Further, the process integration ensures that the MTM analyses is structured in workstations to allow comparing operation times, using takt time adjustment as represented in Figure 4-22:

$$TT = \frac{available\ working\ time\ per\ year}{customer\ demand\ per\ year} = \frac{FD \times WT}{Pcs} = \frac{WT}{DD} \qquad (4\text{-}17)$$

with

TT Takt time [time unit/work pieces]

FD Factory days [day/year]

WT Daily working time [time unit/day]

Pcs Annual piece number [work pieces/year]

DD Daily demand [work pieces/day]

If several parts are being processed simultaneously or several machines are used, CT must be calculated to obtain the time per part. The CT can be calculated as follows:

$$CT = \frac{OT \ \times \#P}{\#Res} \ or \ CT = \frac{PT \ \times \#P}{PQ \times \#Res} \tag{4-18}$$

with

CT Cycle time [time unit]

OT Operation time [time unit]

PT Processing time [time unit]

PQ Process quantity for batch or continuous processing [work pieces]

#P Number of identical parts per finished product [work pieces]

#Res Number of identical resources [work pieces]

In this step, the total processing time, discard rate, breakdown, and batch size are computed. Several MTM analyses can be assigned to one operator, or one long MTM analysis can be divided in several shorter ones to avoid disruption of the process flow. For matching capacity to customer demand, it is necessary to determine the minimum number of resources required for the production operations. The number of required resources is calculated as follows:

$$\#Res = Rounding\ up\ \left[\frac{CT}{TT \times (1 - COF) \times BTF \times (1 - QDF)}\right] \tag{4-19}$$

with

#Res Resource requirements

CT Cycle time [time unit]

TT Takt time [time unit]

COF Changeover losses factor [%]

BTF Breakdown time factor or uptime [%]

QDF Quality defects factor [%]

Using line balancing and a resource statistic chart, the amount of operators needed by workstation can be obtained. Example of choices related in this step can be to group workstations in cells, duplicate workstations or place several operators in a same workstation.

$$\#OP = Rounding\ Down\ \left[\frac{\sum OT_i}{TT \times 95\% \times \#Res}\right] \tag{4-20}$$

with

#OP Number of operators in continuous flow production

OT_i Operation time at station i [time unit]

TT Takt time [time unit]

#Res Number of parallel lines

After confirming the process integration, FIFO and Kanban methods are used for the integration of buffers, and the pacemaker station is identified. The next step concerns the integration of buffers within the process. The buffer ideal maximum capacity is suggested to the user based on the ConWIP formula. For the integration of Kanban buffers, the suggestion of ConWIP from the FIFO step is used to support the creation of buffers. As no buffers are placed, but the processes are already grouped in workstations, the user chooses the workstations from a list where a buffer can be integrated and the guideline suggests a maximum capacity size. As the same layout will be used for several products, and Kanban ensures the control of several FIFO lines, the buffers are designed to have an integrated Kanban function. In the guideline, the Kanban is represented by several FIFO buffers.

$$ConWIP = \frac{(OT_{max} - OT)}{TT} \times LS \tag{4-21}$$

with

ConWIP Limited inventory level, in units
OT Operation time at current workstation, in seconds
OT_{max} Operation time at preceding process, in seconds
TT Takt time, in seconds
LS Lot size, in units

The last step of the speed process is identification of the pacemaker workstation. The basic idea is that production is scheduled at this pacemaker, allowing it to then “pull” material to it. A key rule for selecting the pacemaker is that all processes after it must “flow” to the customer. In the context of remanufacturing, the pacemaker gives a possibility to “estimate” the cores needed to satisfy the customer demand, on the basis of the pull philosophy. As the pacemaker should be placed after the last workstation with discard rate, it can manage the remanufacturing process upstream.

4.3.5 Economics

Once the processes for every product are integrated and linked to one unique layout composed of factory, methods, and workstations, the process economics are validated by assessing the combination of estimated customer orders, as summarized in Figure 4-23. In a first step, product and process costs for remanufacturing are compared with new component prices to validate the economic advantage to remanufacture. Second, the new parts integration strategy in the remanufacturing process define the number of new components to be purchased. As a result, inventory levels for replacement components along with incoming cores are deduced. Finally, the production plan – as well as the period to perform remanufacturing operations - is defined based on the material flow of product returns, and the results of the company’s financial status are displayed using a profit and loss statement along with return on investment.

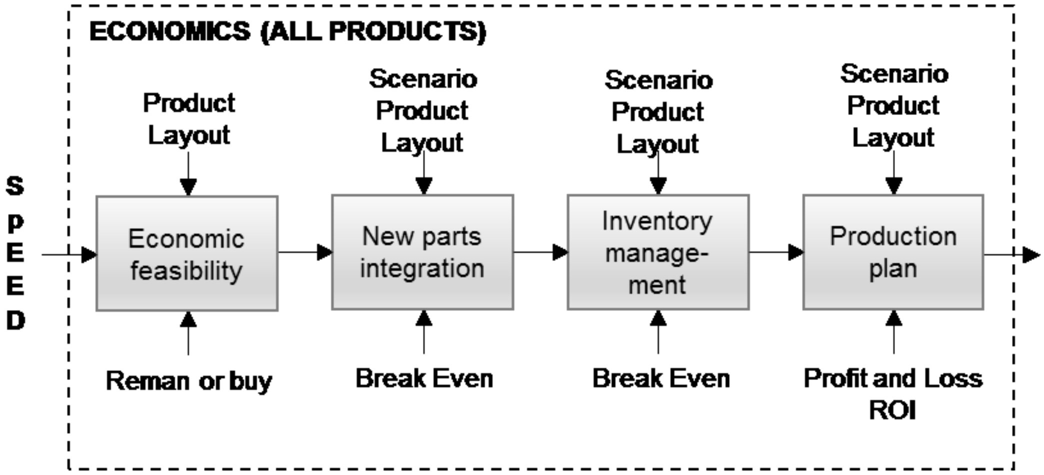


Figure 4-23: Idef0 for the validation of process economics

The first step of the process is to analyse remanufacturing feasibility per assembly. This step is essential to ensure that the user choice for the assembly to be remanufactured is economically sound, in comparison with the price of a new assembly in the spare parts' market. Then, the costs per factory are determined to ensure that the prices of consumables for all of the workstations and machinery are determined. Finally, the feasibility assessment is computed according to the equation derived from the works of DUNKEL, where it is assumed that the total cost of remanufacturing of a part must not only consider the cost of effective remanufacturing but also the total cost and effort invested in non-effective remanufacturing of parts [Dun-08]. The original equation is suggested and described using guideline element variables as follows:

$$Cer = VC + AC + ECC \tag{4-22}$$

$$Cner = D - Cer \tag{4-23}$$

$$Ctr = Cer * Per + Cner * Pner \tag{4-24}$$

$$\text{If Ctr} < \text{Assembly Price, remanufacturing is possible.}$$

with

VC Sum of all variable costs (machine and workforce)

AC Assembly of part replacement cost including discard rate

ECC Cost to replace an assembly

D Disposal revenue (+) or cost (-) for a discarded assembly

C_{ner} Cost of non-effective remanufacturing

P_{ner} Percentage of non-effective remanufacturing

P_{er} Percentage of effective remanufacturing

C_{tr} Total cost of remanufacturing

For the case in which the total cost of remanufacturing is superior to the cost of a new assembly, the process is modified to remove actions to remanufacture this assembly. If remanufacturing is cheaper than a new assembly, its economic sense is confirmed.

The economic efficiency to support the decision for the best scenario is provided by displaying the break-even chart per potential strategy, including the estimation of customer orders made at the previous step:

$$Breakeven\ point\ =\ FC\ /\ (S-VC) \quad (4\text{-}25)$$

with

FC Fixed costs per period

S Sales per period

VC Sum of all variable costs (machine and workforce together)

The strategy for the choice of new parts integration, concerning the integration of new assemblies to complement the production needs of the remanufacturing assemblies, must be defined. Three strategies are possible.

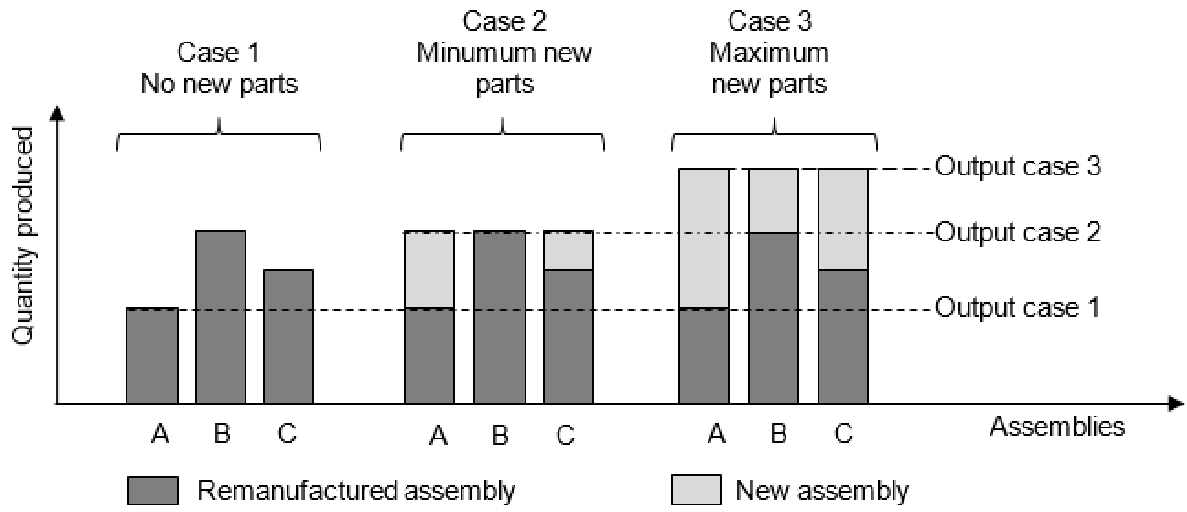


Figure 4-24: Effect of the integration of new parts on the production output [Dun-08]

The first strategy considers the sole use of cores for the production of remanufactured goods without the integration of new assemblies, in which case the finished goods amount equals the smaller amount of successfully remanufactured assembly type. The second strategy integrates remanufactured assemblies in products along with new assemblies to replace those with lower remanufacturing success. The third strategy considers the assembly of completely new goods to define a set amount of new assemblies for all types, following the principle of “hybrid” factories mixing manufacturing and remanufacturing lines. The three strategies are graphically represented in Figure 4-24. The third step concerns the inventory management, which displays the stock level at the beginning and end of each month as well as the quantities of assembly, cores, spare parts, and products produced, purchased, or sold, by multiple of container size. The inventory valuation is displayed, and the importance of inventory costs on the fixed cost repartition is computed.

The production plan provides a detailed image of the activity objectives for the future remanufacturing venture. This step relates core availability, remanufacturing process, and product sales by planning the typical production plan per shift, which is extrapolated to determine the activity targets per month. The strategy, tactical, and operational dimensions are represented to precisely compute the investment, fixed, and variable costs for the profit and loss statement and ROI per factory. The objectives are entered on a monthly basis, and the strategy for new parts integration as well as the release units can be modified. The following formula is used to compute ROI:

$$ROI = \frac{IC}{(S+D)-(FC+VC)} \tag{4-26}$$

with

IC Investment costs

FC Fixed costs per period, in value

S Sales per period, in value

D Disposal revenue (+) or cost (-) for a discarded assembly

VC Sum of all variable costs (machine and workforce)

4.3.6 Variability

The final aspect of the guidelines is aimed at adapting methods and process to the variability resulting from the product portfolio to be remanufactured. In this step, the decisions taken in the previous steps are locked. Focus is set on the disassembly line balancing, optimization of changeover times, and improvement of bottlenecks. Once all processes are optimized, the FMEA process enables the potential failures that can occur during the execution of the process to be identified, to define the future improvement potential. Finally, a VSM establishes a base for continuous improvement after the process implementation, as illustrated in Figure 4-25.

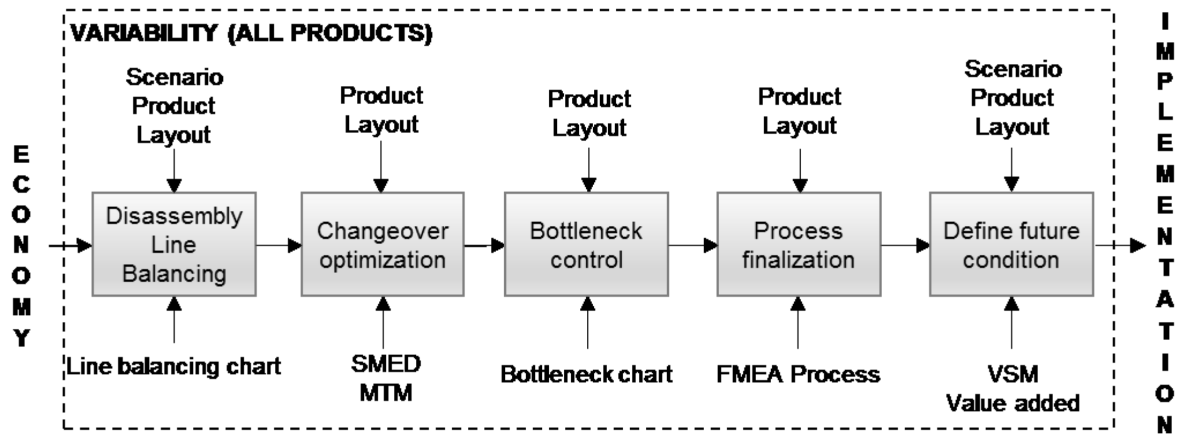


Figure 4-25: Idef0 of the adaptation of process to variability

The disassembly line balancing aims to balance the disassembly method per product to the restrictions issued from the cleaning machine situated downstream. Cores quality is determined by setting a percentage of cores with normal, poor, and worse conditions. Effects from cores quality categories on the remanufacturing operations is expressed as additional time needed for the disassembly of each category. Line balancing per workstation is established by comparing categories to the tact time with the influence of the core quality. This process compares disassembly time to processing time for each product, while considering conditions and batch size of both processes. The disassembly work method, batch size, transportation type, and the buffer are retrieved from the speed steps results, and DLBP methods can be used in the context of the product portfolio decided when making the production plan. Using the line balancing chart, the adjustment to tact time for each product is ensured. The disassembly line balancing is accomplished using the weighted average by batch size from all disassembly workstations of the process chain.

In the changeover step, the methods are detailed using MTM analysis attributed per workstation, showing the necessary moves to adapt a workstation to a new product in the production plan. External and internal changeover times are determined by the classification of each MTM code in one of the two categories, with the aim to reduce the proportion of external changeover time by improving the method. Once the methods for all workstations are confirmed to be optimized, the sum of the time values of each MTM codes determine the workstation changeover time.

The bottleneck control indicates which workstations are blocking the process flow based on the simulation of the product mix scheduled for a determined time of a shift. Taking the information on the product mix to be handled, the bottlenecks are determined for each month of activity, provided that production schedule differs for each time period to reflect core availability and demand patterns presented in the scenario. As the work method is unique for each product of the portfolio, the time per workstation is considered to reduce bottlenecks.

Once the process is fully optimized, the FMEA process allows brainstorming of failures that may occur within the work methods defined, from the viewpoint of the operator. The failures can be prioritized by severity, occurrence, and detection. In a similar fashion to the FMEA product, the RPN gives a ranking of the failure modes per workstation and establishes the actions to solve the potential issues identified. In place of the product assemblies, the process components, represented by the MTM analyses defining the manual work methods, are considered as the object of failure modes. Severity, occurrence, and detection are used in the same fashion as for the FMEA Product to describe the RPN for the current and the future situation attained after the implementation of detective and corrective measures.

As the result of the implementation of Lean and MTM methods in remanufacturing planning for ensuring quality, speed, economics, and flexibility to variability conditions, a future condition for the production system is generated using the VSM graphical representation of the data collected. The main purpose of this result is to support the implementation phase toward the implementation of remanufacturing activities by defining a step toward reaching a perfect organization. In the context of the guidelines, the VSM can be saved and compared with further iterative improvement processes which can imply the modification of strategic, tactical, or operational decisions. Along with the representations of the break-even point and ROI, as well as the profit and loss statement, decisions are taken in a reliable technical-economic context. The economic feasibility under process variability is expressed through the representation of best and worst remanufacturing success ranges as result of DES of the guideline results.

4.3.7 Economy and variability evaluation

As all the information is collected at the final step of the guideline, the economic and variability requirements can be summarized. To assess whether the guidelines meet the economic requirements suggested, the types of costs are represented according to requirements sets.

Product costs are considered according to the viewpoint of the company to be evaluated by the consideration of the real prices of services amongst the actors of a stakeholder product. They encompass the costs for cores, spare parts, new assemblies as well as recycling gain or loss. Organization costs are considered for the key phases of a product lifecycle with collection, remanufacturing, distribution and use and focus is given to the factory planning and control phase. Managerial workforce costs are integrated, although to a lesser level of detail. Using MTM allows to have a fine planning of the human and equipment costs as the remanufacturing method is described and the waiting, setup and blockade times can be computed. Revenues are considered as the sales or leasing of product and services and though the revenue or costs of recycling spare parts and cores which cannot be remanufactured. The guideline allows computation of the financial situation of the company by summarizing costs and revenues inputs from the strategic, tactical, and operational viewpoints.

Improvement can be obtained by developing the simulation of logistics costs, under a defined stakeholders' network configuration, which is provided from the results of the strategy step. Further, market studies could allow to better justify the sales forecasts as with the sole consideration of a company business model and objectives. Such a consideration is handy to quantify the capacity of secondary markets to absorb the surpluses of saturated primary markets, therefore allowing companies to use remanufacturing for export development. However, the approach has the advantage to offer a wide range of measures to improve the economic feasibility of a remanufacturing system and the consequences of such decisions can be easily identified. Table 4-5 summarizes economic evaluation.

Table 4-5: Guideline evaluation for economic requirements

Economic requirement set	Description of economic influence	Type of influence	Completion	
Product costs	Cores acquisition	Variable cost	●	●
	Replacement parts	Variable cost	◐	
	Replacement assemblies	Variable cost	●	
	Recycling of discarded parts (if cost)	Variable cost	●	
Organization costs	Factory running costs	Variable cost	●	◐
	Machinery running and standby	Variable cost	●	
	Collection logistics	Variable cost	●	
	Distribution logistics	Variable cost	●	
	Internal logistics	Variable cost	◐	
	Warranty costs	Fixed cost	●	
	Inventory cost	Fixed cost	●	
Human costs	Operator wages	Variable cost	●	◐
	Production management	Fixed cost	◐	
	Support functions	Fixed cost	◐	
Equipment costs	Factory acquisition	Investment	●	●
	Workstation acquisition	Investment	●	
	Equipment acquisition	Investment	●	
	Equipment maintenance	Fixed cost	●	
Sales revenues	Sales of products and services	Revenue	●	●
	Leasing of products and services	Revenue	●	
	Recycling of discarded parts (if revenue)	Revenue	●	
Contribution evaluation: ○ None ◐ Partial ● Dedicated				

Levelling production mix, bottleneck control and disassembly line balancing ensure an appropriate adaptation of the production system to product variety. Varying cores conditions are considered by three cores classes with influence on the disassembly time of the products. The strategic influence ratio concerning for cores quality is suggesting values for the additional time needed for the disassembly. However, more effects of the cores quality on the production line, such as their direct relation to the success of the reconditioning operations, could not be integrated. The relationship between an adequate core identification and the effective selection of the cores reaching the remanufacturing was disregarded, although it could have influenced the financial results of the remanufacturing facility. The integration of new parts to leverage different success levels for assemblies to be remanufactured is suggested and the integration of spare parts considered. The integration of new parts to leverage different success levels for assemblies to be remanufactured is suggested and the integration of spare parts considered. Material matching is however restricted to the amount of cores and of set of new parts, instead of considering each part as unique inventory entry, which would have allowed the represent the results of modular product design to cost reduction effects. Process variance is the requirement reaching the best consideration level, as the bottleneck control and the changeover optimization provide concrete recommendations for improvement of the work methods. The FMEA Process, realized after all other improvement measures, provides valuable improvement for cores conditions and process variance, as well as for product variety. Limitations are mainly caused by the focus on the process organization while separating it from the logistics, as recommended in Lean, as well as the scope of creating a planning tool, prohibiting the access to observation data. Although the logistics data is considered in the transfer costs, it does not appear separately as variable, and cannot be influenced. The methods addressing the variability are presented, and their contribution to the variability requirement set are evaluated in Table 4-6.

Table 4-6: Guideline evaluation for variability requirements

Selected steps	**Methods**	**Variability requirement set**			
		D1	**D2**	**D3**	**D4**
New parts integration	Production planning strategy	○	○	◐	○
Levelling production mix	Pitch Definition	○	●	○	○
Bottleneck control	Bottleneck chart	○	○	○	●
Disassembly Line Balancing	Line balancing chart	◐	●	○	○
Changeover optimization	SMED	○	◐	○	●
Process finalization	FMEA Process	◐	○	○	◐
Define future condition	VSM	○	◐	○	◐

Legend: D1: cores conditions variance / D2: product variety / D3: material matching variance / D4: process variance

Contribution evaluation: ○ None ◐ Partial ● Dedicated

4.4 Project-oriented course development

As described in the research gap and the state of the art, remanufacturing is a complex topic which long suffered from a lack of recognition as a specific industry by public instances. Academic research for remanufacturing retained significant attention from the 1990's and further developed into a large array of specific fields of research illustrated by ILGIN AND GUPTA with the environmentally conscious manufacturing and product recovery (ECMPRO). This framework distinguishes four main issues for research in circular manufacturing with product design, reverse and closed-loop supply chains, remanufacturing and disassembly [Ilg-10]. Research in remanufacturing production planning and scheduling presents models developed for a specific purpose, which are yet associated together for the consideration of systemic issues [Gui-00, Jun-12, Mat-16]. DES provide an appropriate methodology for appraising the behaviour of production systems and has been applied for supply chains, production planning and scheduling contexts [Li-09, Gui-06, Gui-98, Sou-02]. In order to allow the application of theoretic knowledge within practical case studies, the methodology developed within this thesis allow the applications of specific methods within a common framework for the computation of financial consequences. Beside the issue of fragmented research about remanufacturing systems, KALVERKAMP identifies the lack of tools for educating future managers in managing remanufacturing supply chains and suggests the creation of a game based learning course [Kal-15b]. IJOMAH developed a framework for providing training in remanufacturing organizations using business processes described through Idef0 models, and validated the interest of companies as addressing vital issues in the remanufacturing industry [Ijo-08]. Although the validity of results has been proved in validation sessions with companies, the tool developed was limited to the recognition of practitioner expertise on remanufacturing and disconnected form the application of academic models for improving results.

In order to allow a structured knowledge transmission through the development of a project-based course, a targeted review of didactics theory is suggested. According to the theory of situated learning, knowledge cannot be transferred without alteration from one person to another. The main reason is that the signification of knowledge within leaning processes are interpreted personally, and depends significantly of the environment in which the learner is situated [Lav-91]. The personal competence to behave within a given environment is qualified with a large range of adjectives, such as ability, aptitude, capability, competence, expertise, qualification, proficiency or skill. ERPENBECK suggests that competences are dispositions for self-organized handling, impossible to proof directly but possible to evaluate through their realizations and containing emotions and motivations from internalized values and norms [Erp-03]. Knowledge is described as "every form of representation of parts of real or theoretic worlds in a materialized transfer medium" [Bod-97]. Although the frontier is hardly defined in literature, explicit knowledge can be addressed without systemic perspective while implicit knowledge is acquired through a qualification process, being the two extremes of a same dimension [Ste-10]. In order to allow competences to be transferred through the acquisition of knowledge, the dimensions of learning and teaching should be addressed. One definition of learning, and learning to learn, is a self-defined method-in-action competence for interacting with a changing environment to "become more effective, flexible and self-organized in a variety of contexts". HOFFMANN suggests a classification of the learning model for engineering education where the process begins by the identification of a contradictory situation placing the learner in front of a problem, as illustrated in Figure 26.

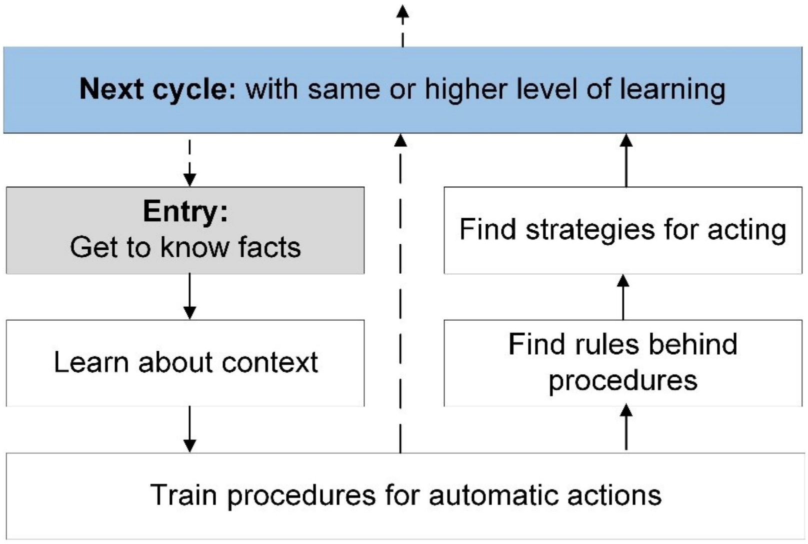


Figure 4-26: Learning cycle diagram [Hof-]

First actions are to understand the meaning of the vocabulary used, before learning which rules are structuring solution procedures, to finally apply these rules and solve the problem. The highest step in learning is to continue the learning cycle at a similar or higher knowledge perspective, as it allows to analyse facts using another set of rules and strategies [Hof-05]. Course planning concerns the analysis from methods and contents which should fit together and with the expectations from learners. SMITH AND RAGAN suggest that course planning can be divided in three phases to gain efficiency.

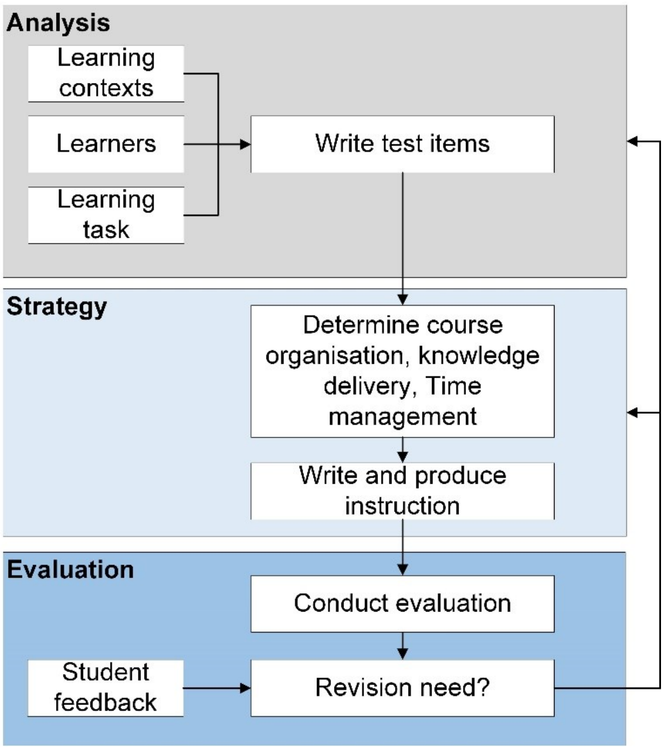


Figure 4-27: Instructional Design Process Model [Smi-05]

First, the task analysis phase defines the environment, participants background and objective of the learning course, so that a detailed list of expected achievements and related evaluation targets can be defined to fit the current group of students. Second, the strategy phase sets organization, methods and facts which will be the elements for the development of the course continuum, precisely defining its scope and boundaries with neighbouring systems. Finally, the last phase is to set the rules for the formal evaluation of knowledge gains by students based on the activities defined in the two first phases, receive feedback from the learners, and improve the course in case of need [Smi-05].

Innovation aim for the development of the course is to present students with academic methods to create and improve remanufacturing systems in a virtual industrial environment. As the learning objectives of the course are to train engineering students to specific issues in remanufacturing planning within situated learning, the course is developed with the reference model for integrated competence management developed by MEYER. This model highlights the connections between students, their educational environment, and the expectations of the labour market for future employees. The competence management logic is illustrated at the centre of the model with goal setting, planning, decision making, action and control and allows continuous improvement by running the process again and again. Further, the model embeds the course objective and elements into a broader organization of stakeholders with industries looking for qualified workforce, engineering students providing this workforce and the universities in charge of organizing competence management. Students are connected with industry by the labour market and to the university by the education market, and society is the largest perspective connecting every other stakeholder and underlying their actions [Mey-06]. Figure 4-28 illustrates how the model synthetises stakeholder needs, competence fields and knowledge resources in the context of remanufacturing production planning.

The project-oriented course is developed in the context the Global Production Engineering (GPE) Master study program offered by the Technical University of Berlin (TUB) and held remotely the Vietnamese-German University (VGU) located in Ho-Chi-Minh city, Vietnam. The course is taking place during the third of four semesters from this two-year study program alongside with other project-oriented course [VGU-18]. Knowledge requirements from the learners are to have successfully studied subjects of PPC, MTM, DES, Engineering Economics, Lean and Quality Management. Classes are designed to present industrial practices and academic research concerning business model innovation, quality and productivity management, improvement of the economic results and the adaptation of the process to variability. For each category, focus is set on understanding the specific application within remanufacturing context inducing the adaptation of common tools, which could be best illustrated by the FMEA Product tool, which necessitates different input information than in new production.

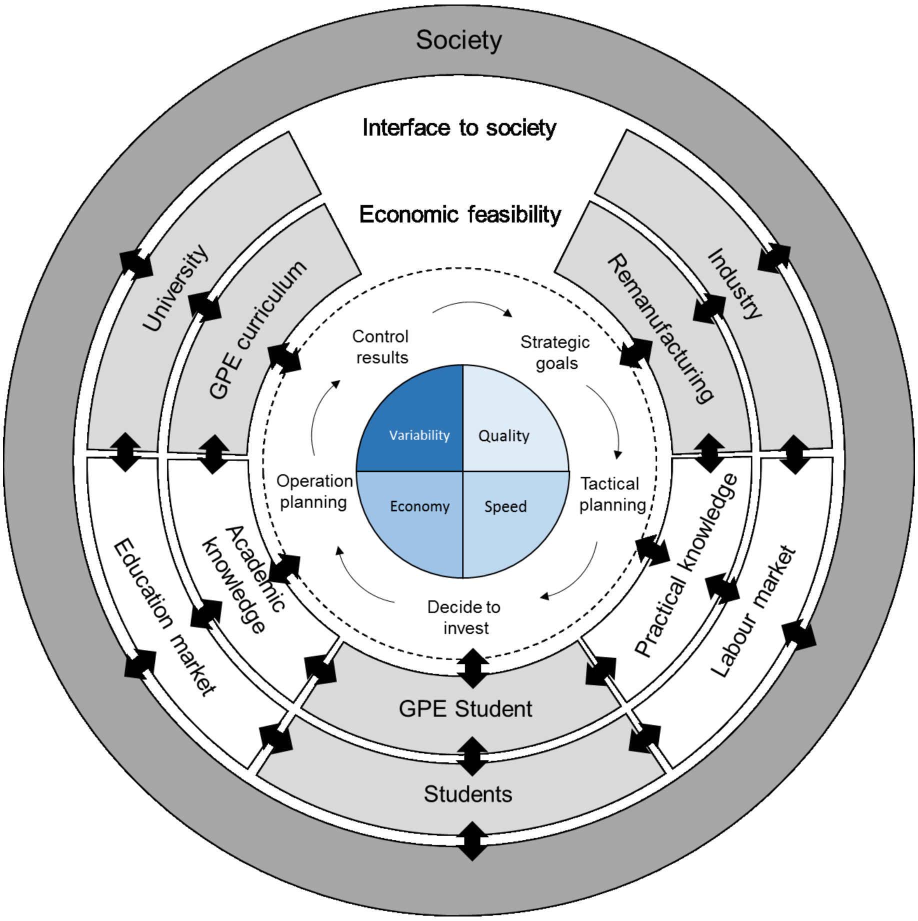


Figure 4-28: Reference model for Integrative Competence Management, adapted from [Mey-06]

After the theoretical presentation about remanufacturing, its challenges and field of application, learners are presented with the scope and structure of the guideline with a product example and learn which information should be collected. Learners are separated into groups and given exemplary product variants for which they have the develop a remanufacturing system. New product sales and country-specific production factors are obtained through market research. The learning principle for the course is illustrated in Figure 4-29.

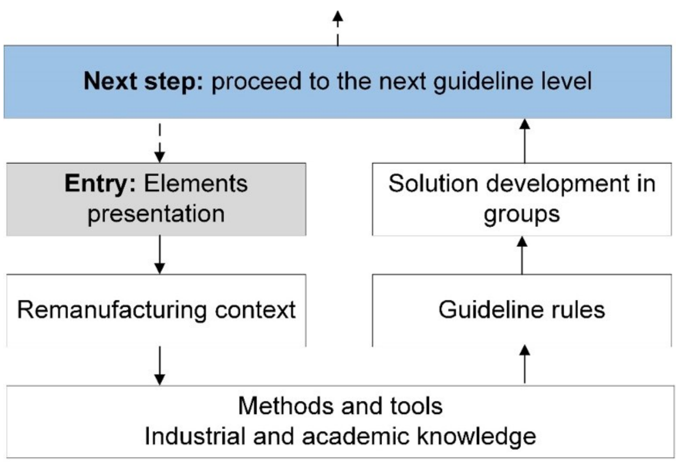


Figure 4-29: Learning cycle within remanufacturing project-oriented course

Elements of workstations design may be prototyped by using 3D printers and tested in real situation within a learning factory for Lean Management, so that the MTM analysis performed correspond to the work method established. Input data consisting of cores quantity and quality, product sales and cost structure is summarized and entered in a DES software for calculating the process output, results are expressed on a given time period for best, average and worst potential economic results. At the end of the course, each team present their remanufacturing system in front of the class and document results in a written report. The students are evaluated on the performance and the coherence of their results, as well as for the amount of value tapped from the material flow. During the first instantiation of the course, a prototypical interface was used to structure the input of guideline elements in the simulation software, which structure is presented in annex A-3. A new version of the interface is under preparation for the next edition of the course by taking into account feedback from the learners.

The scope of application is framed by the description of guideline elements which are structured in categories and entered according to a defined order to allow an adequate evaluation of the economic feasibility of the remanufacturing system. The results are scalable and can be compared to measure the success in increasing the efficiency of the system. An ergonomic use of the guidelines is provided by the defined order for information input, but the results should be entered manually in the simulation software. The interface prototype is developed for improving this feature during future administration of the course. Logic transparency between systems is clearly defined, although there is space for further refining of the influence factors. Lean and MTM methods are implemented according to the state of the art. Last, the guideline elements can be complemented with more detail or complementary modules, such as for reverse logistics or inventory management to ensure its evolutionary format. To evaluate the contribution from the interface to the ergonomics requirements set, a matrix is suggested to present contributions to the objectives previously stated in Table 4-7.

Table 4-7: Guideline evaluation for engineering education requirements

Requirements set	Contribution	Evaluation
Scope of application	Guideline elements ensure a clear determination of application scope.	●
Scalability of results	Results for the same products are scalable as they are computed with the same model elements.	●
Ergonomics	The guideline provides a defined order for information input, which should be entered manually with the current version of the interface.	◐
Logic transparency	Learners are introduced to the logic of the guideline and incrementally receive feedback for the result of each step.	●
Evolutionary format	Guideline contents can be updated for the inclusion of new elements.	●
Evaluation: ○ No contribution ◐ Partial contribution ● Dedicated		

5 Exemplary application and evaluation

Vietnam does not have an identified remanufacturing industry but has a particularly developed reuse culture, instantiated through the development of small repair workshops throughout the country, as illustrated in Figure 5-1. An analysis of the production factors shows potential advantages for the implementation of remanufacturing facilities for its low labour cost and its strategic location surrounded by major production and logistic hubs in Asia. Waste management is developing with Decree 38/2015/NĐ-CP, which addresses hazardous waste, domestic waste, industrial solid waste, the liquid waste, wastewater, industrial emissions and scrap imports [MOJ-15b]. The principle of Extended Producer Responsibility is to gain momentum in Vietnam as the national Parliament and Government enacted the Decision 16/2015/QĐ-TTg on recovery and processing of EOL products. The regulation applies to manufacturers, consumers and other organizations and individuals involved in the recovery and processing of retired products [MOJ-15a]. Several articles of the regulation mention the responsibilities of OEMs to organize used products recovery activities by established recovery points or systems for retired products which have to adapt the standard requirements about collecting, storage, transport, as of the beginning of 2018. The used products collection system might be established by the manufacturer or in cooperation in a group with other manufacturers. In addition, each OEM should highly encourage recovering the same type of products made by other manufacturers. Ministry of Natural Resources and Environment (MNRE) is responsible to establish guidelines and the technical standards for enforcing the law, controlling results and evaluating implementation progress. Waste management in Vietnam is therefore selected for the simulation of economic impacts of virtual case studies of national and international remanufacturing networks to the example of three product categories

Figure 5-1: Water pump rewinding in a Vietnamese repair workshop

5.1 Water pumps

Water pumps (WP) are major products from the water supply sector is Vietnam. The only local manufacturer market share is estimated to 5% and focuses on the supply of pumps for irrigation purposes. Competitors are mostly originating from Asia, where Japanese suppliers focus on high volume market segment and Taiwanese. South Korean and Chinese manufacturers import products most of the water pumps sold for household use [Int-07]. In this case study, the water pumps OEM is selling the pumps under an integrated PSS model including maintenance services in partnership with a leasing company. With the ambition to increase market share and margin while keeping the market premium obtained through his reliable service network, the OEM is considering to open a remanufacturing facility and to benefit from his control over returned products. The company is expecting to keep the same customer target in B2G to profit from an already existing and satisfied customer portfolio. As the growth of the market is expected at a CAGR rate of 6,7% [Fro-11], the market conditions are extremely positive and investment decision should be assessed. Table 5-1 is summarizing the strategic choices of the OEM and the resulting influence factors for implementing remanufacturing of their water pumps. The business model, investment plan, bill of material, cost units and profit and loss statements are presented in Annex A-4.

Table 5-1: Canvas business model for WP

<table>
<tr><td colspan="5">Strategy
Integrated PSS System</td></tr>
<tr>
<td rowspan="2">Key partners
Leasing company:
• pays the manufacturer
• collects payments
• owns the products
• sells back cores to OEM</td>
<td>Key activities
• Collection
• Remanu-facturing
• Distribution
• Maintenance</td>
<td rowspan="2">Value Proposition
• Product lifecycle 36 months
• Three products
• PSS with maintenance
• Only handles own products</td>
<td>Customer relationship
• Financial by leasing company
• Technical follow-up by OEM</td>
<td rowspan="2">Customer segments
• B2G
• Public waste water treatment
• Municipal facilities</td>
</tr>
<tr>
<td>Key resources
• Product specifications
• Float of vans
• Factory size: 310m²
• Inventory size: 1706m²</td>
<td>Channels
• Leasing contract
• Physical sales</td>
</tr>
<tr>
<td colspan="2">Cost factors:
• Collection success: 95%
• Identification success: 95%
• Remanufacturing success: 91,67%
• Distribution success: 96%
• Core control: 3,57% of lifetime
• Transaction efficiency: 4,33%
• Core quality: 95,31%</td>
<td colspan="3">Revenue factors
• Product value trend: -0,06% per month
• Business model premium: 104,29%
Product price; including services (time 0)
• Product A: 200€
• Product B: 230€
• Product C: 250€</td>
</tr>
</table>

The forecasted returns PF_{Cn} are predicted from the new product sales while considering only one additional lifecycle. As a PSS-type business is used model and product obsolescence is limited, the price curve is only slightly decreasing with time, as depicted in Figure 5-2.

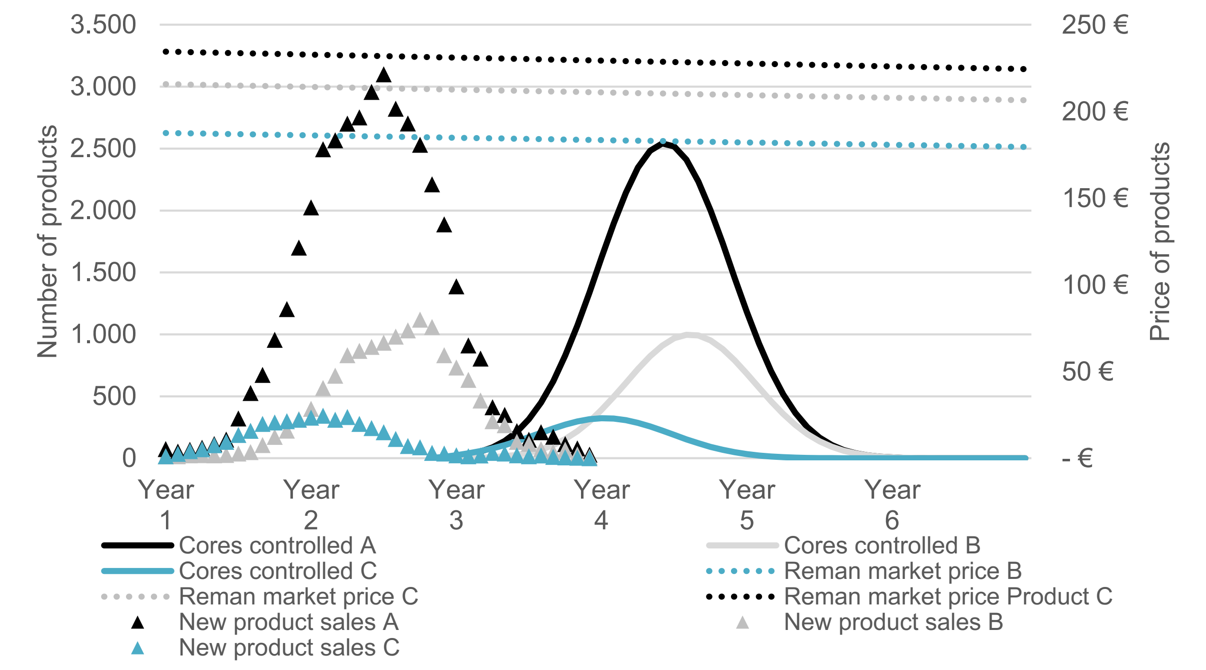


Figure 5-2: New product sales, cores returns and product prices for WP

Figure 5-3 is comparing the cumulated products controlled by the OEM and the amount of products remanufactured over time. The process is established as one-piece-flow, because the products can be shipped individually. Activity is planned to start in year 3 to ensure that enough cores are available and finishes in year 6 because all the cores have been used.

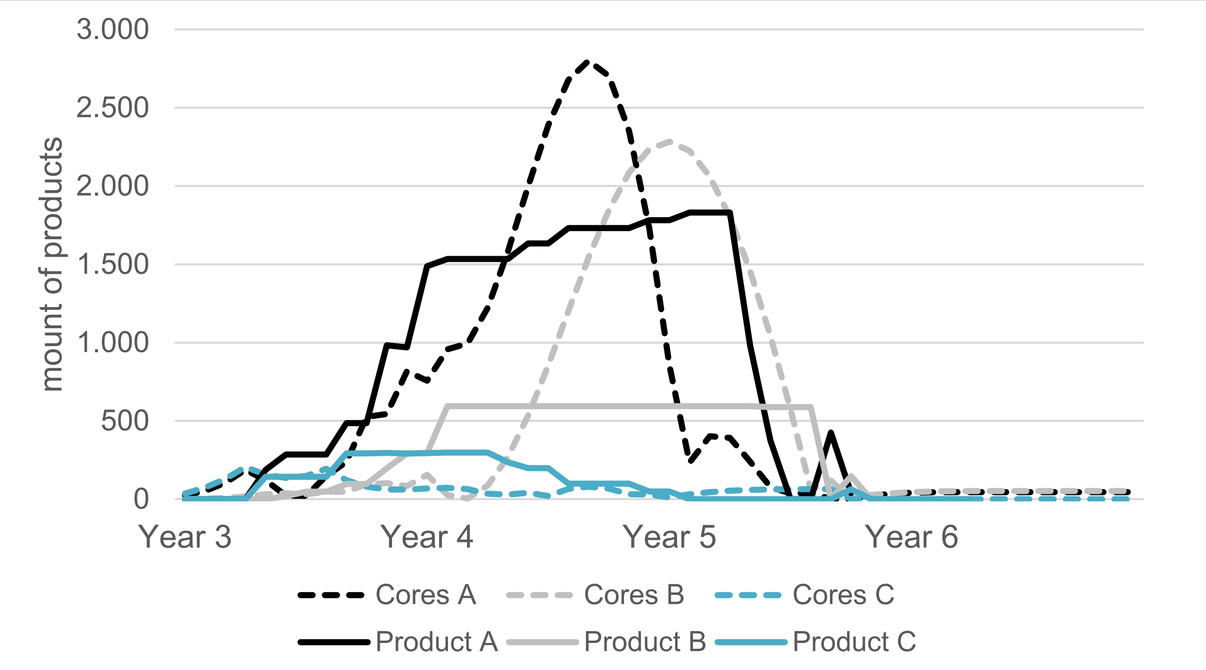


Figure 5-3: Cumulated cores controlled and remanufacturing outcome for WP

The necessary actions defining the remanufacturing process are established by a product FMEA by defining a list of detective and corrective actions as described in Table 5-2.

Table 5-2: Product FMEA for WP

Failure description			**Future situation**					
			S	**O**	**D**	**RPN**	**Detection**	**Correction**
Water pump block	**Transport water from input valve to output valve using torque**	Current leakage due to broken insulators	10	7	2	140	Visual inspection, Pressure Testing	Replacement of O-rings, plugs
		Loss or degradation of speed and torque	10	7	2	140	Visual inspection, Pressure Testing, Penetrating Dye	Welding and grinding
		Dirty water at output	10	9	2	180	Visual inspection	Replacement of O-rings, plugs
		Rust	10	7	2	140	Visual inspection	Chemical washing
		Degradation of water pumping efficiency	7	5	5	175	Ultrasonic Testing	Welding and dying
		Loud operation noise	4	5	2	40	Function check	-
Motor	**Generate, torque using electricity**	Current leakage due to broken insulators	10	9	2	180	Multi electrical measurement	Preplacement of insulators
		Loss or degradation of speed and torque	7	5	5	175	Multi electrical measurement	Re-wiring stator
		Overheat/Burnt when running	4	10	4	160	Visual inspection	Re-wiring stator, Cleaning fan, casing, cooling fins
		Loud operation noise	4	5	2	40	Function check	-
		No electrical control	2	2	2	8	Visual inspection	Replacement of controller
		Cannot be attached to base plate	5	6	2	60	Visual inspection	Replacement of connectors
		Rust	10	7	2	140	Visual inspection	Chemical washing

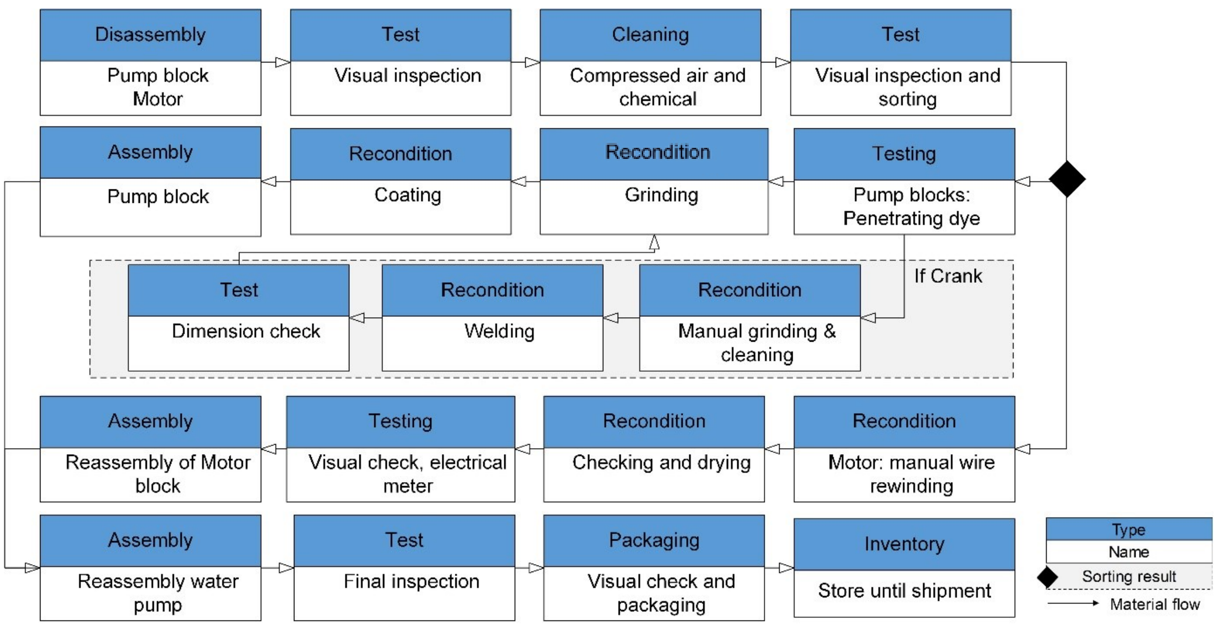


Figure 5-4: Process flow chart for WP

Table 5-3 details the process flow chart issues from the results of the Product FMEA, which orders detective and corrective actions in a logical order. After improving the process speed by the means of the simulation software, checking the economic feasibility and adapting to changeover and bottlenecks, potential failures are identified with an FMEA process presented in Table 5-3.

Table 5-3: Process FMEA for WP

Process	Failure Mode	Cause of Failure	Effect of Failure	RPN S	RPN O	RPN D	RPN total
Block disassembly	Hard to open covers and casing	Due to rust, damage of bolt/nut head	Cause damage of O-ring and plug	10	5	2	100
Block chemical cleaning	Remaining water after process	No time for drying	Effects to next processes	10	9	2	180
Block welding	Extent crack in other places	Stress due to overheat at welding spot	Potential failure during operating	7	9	3	189
Block grinding	Over-grinding	Unstable process due to the welding process	Shape of the component and fitting	8	7	2	112
Motor disassembly	Hard to disassemble roto-shaft	Rust, damage of bolt/nut head	Bearings are destroyed	10	4	2	80
Motor chemical cleaning	Remain water after process	No time for dying	Effects to next processes	10	9	2	180
Motor wire Winding	Wrong wire polar and output wire	Task specific	Machine breakdown	4	10	4	160

Figure 5-5: Exemplary factory layout for WP

The results of the PPC tactical decisions are presented with the representation of the common layout presented in Figure 5-5 and with the associated throughput expectations with a VSM in Figure 5-6.

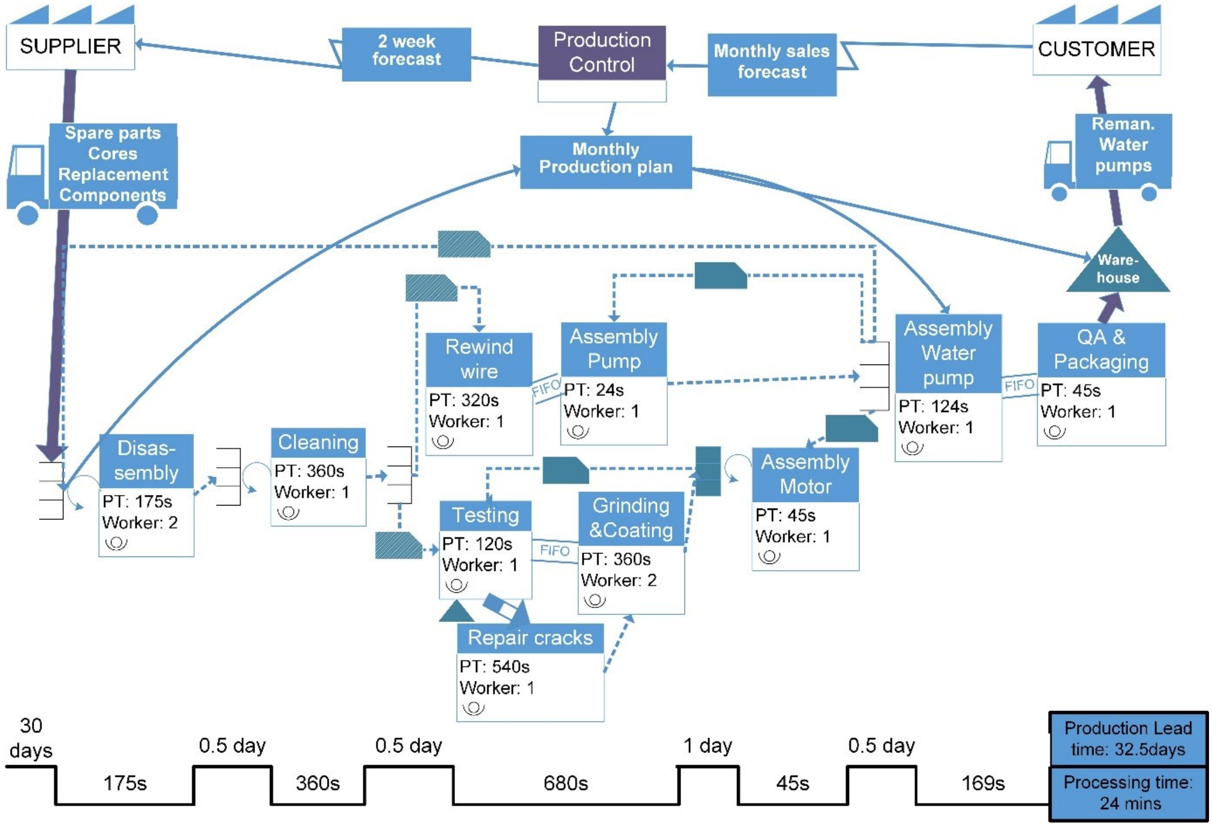


Figure 5-6: VSM chart for water pumps

Economic feasibility is expressed using return on investment under best, average and worst potential results over the 4 years of planned activity of the remanufacturing facility in Figure 5-7. The ROI expected for the total activity period varies from 356 to 451%, defining a valuable payback for potential investors in water pump remanufacturing.

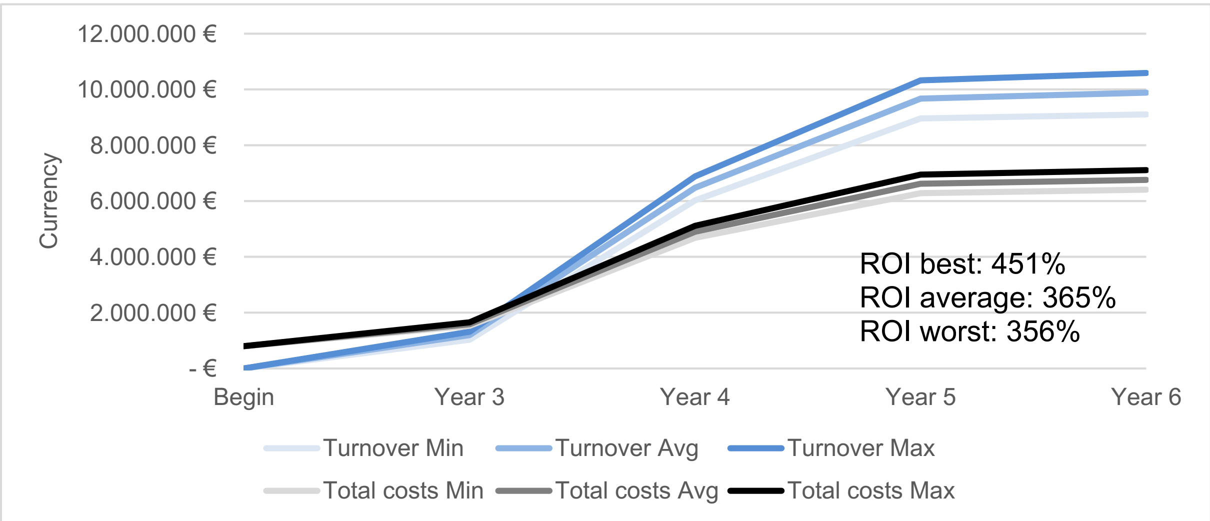


Figure 5-7: Break even and ROI with best-to worst projections for WP

5.2 Air conditioning systems

The global air conditioning market is expected to grow from 112,26 in 2016 to 169,74 billion USD by 2021 with a CAGR of almost 9% and is dominated by the Asia-Pacific demand with a market share of 61,62% of the global demand. The market is generally driven by replacement demand, as the customer are looking for efficiency and convenience of use of these systems. The trend for technological product evolution is further driven by the emergence of standards for air conditioning systems (ACS) in developed regions for improved energy efficiency [Tec-16]. The market is still fragmented between regional and local manufacturers on one hand and Japanese OEMs adopting aggressive strategies to consolidate and grow their market share. Smaller actors are struggling to compete against international conglomerates with huge infrastructure and R&D investments. This case study represents a local manufacturer from Singapore which wants to keep his position on the local market while providing a customized spare parts service while complying with product takeback legislative obligations. He is willing to find a partner in Vietnam for remanufacturing spare parts from used products. Table 5-4 is summarizing the Canvas Business Model dimensions of the remanufacturer in Vietnam, the strategic influence factors and transfer prices to the distributor. Business model, investment plan, bill of material, cost units and profit and loss statements are presented in Annex A-4.

Table 5-4: Business model for ACS

<table>
<tr><td colspan="10">Strategy
Supply of spare parts for warranty purpose</td></tr>
<tr>
<td colspan="2" rowspan="2">Key partners
Distributor
• Collects the cores in Singapore
• Send cores to Vietnam
• Transports the spare parts</td>
<td colspan="2">Key activities
• Remanu-facturing (without reassembly)</td>
<td colspan="2" rowspan="2">Value Proposition
• Product lifecycle 24 months
• Three products with different brands</td>
<td colspan="2">Customer relationship
• Only to distributor
• Forecasts sent monthly</td>
<td colspan="2" rowspan="2">Customer segments
• B2B</td>
</tr>
<tr>
<td colspan="2">Key resources
• Maintenance guidelines
• Factory 1425m²
• Inventory: 3500m², two storage levels</td>
<td colspan="2">Channels
• Direct sales
• 40’ Container capacity: 400 products, 800 assemblies</td>
</tr>
<tr>
<td colspan="5">Cost factors
• Collection success: 85,45%
• Identification success: 87,86%
• Remanufacturing success: 88,75%
• Distribution success: 86,67%
• Core control: 14,3% of lifetime
• Transaction efficiency: 4,50%
• Core quality: 86,61%</td>
<td colspan="5">Revenue factors
• Product value trend: -0,29% per month
• Business model premium: 92,50%
Assembly prices (time 0)
• External unit A: 135,98€
• Internal unit A: 72,98€
• External unit B: 142,77€
• Internal unit B: 76,63€</td>
</tr>
</table>

The core returns PF_{Cn} are predicted from the new product sales while considering two lifecycle consequent to the first use phase. As a PSS-type business is used by the distributor to sell the products under his own brand, the product obsolescence is limited, the price curve is only slightly decreasing with time, as depicted in Figure 5-8.

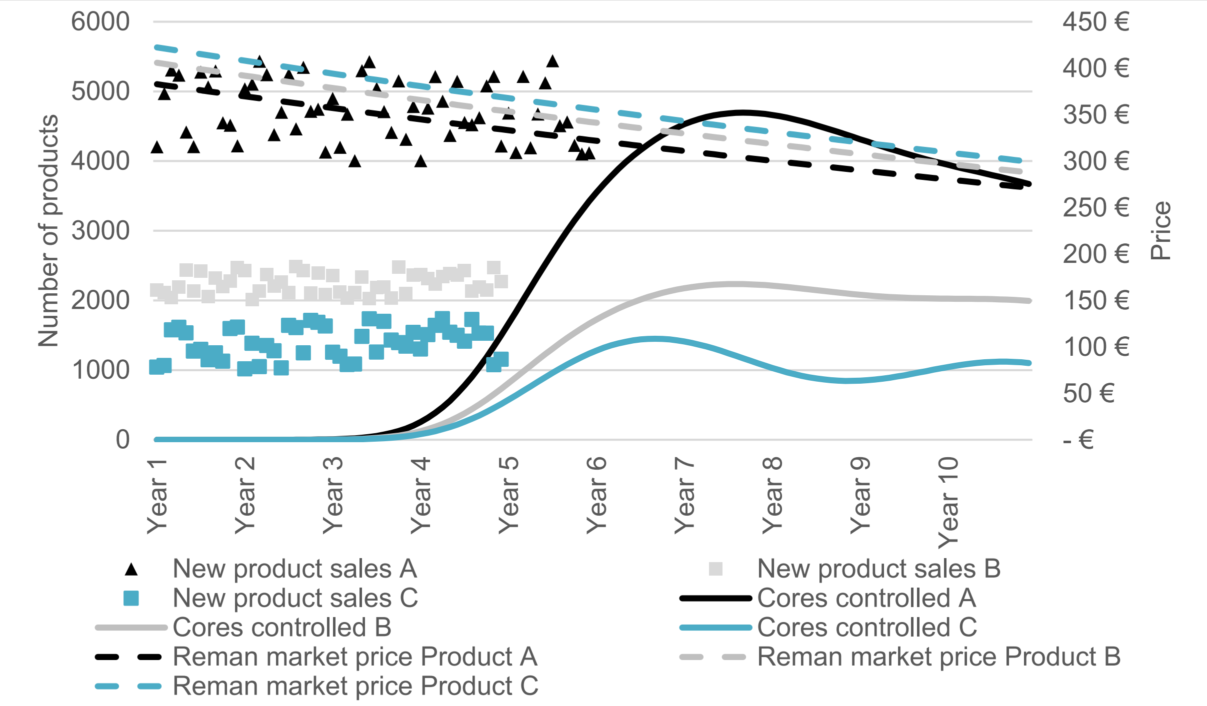


Figure 5-8: New product sales, cores returns and product prices for ACS

Figure 5-9 relates the cumulated products sent by the distributor in Singapore on request of the remanufacturer in Vietnam. The input of cores and output in remanufactured products is expressed in amount of containers sent by sea freight. Activity starts in year 5 and can continue until the year 10 as cores are available and profit ensured.

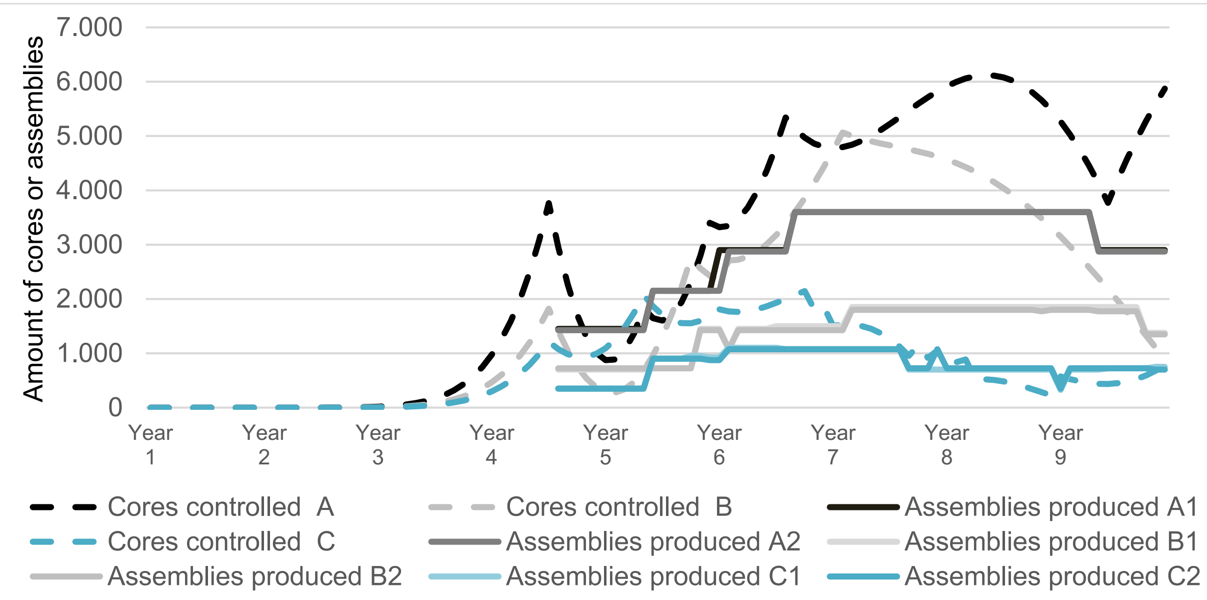


Figure 5-9: Cumulated cores controlled and remanufacturing outcome for ACS

The necessary actions defining the remanufacturing process are established by a product FMEA by defining a list of detective and corrective actions as described in Table 5-5.

Table 5-5: Product FMEA for ACS

Failure description			Future situation					
			S	O	D	RPN	Detection	Correction
Indoor unit	Push the air flow inside and through the system to exchange heat with cooling gas	Loss or degradation of heat exchange	5	8	3	120	Visual inspection, Pressure Testing	Evaporator cleaning and fixing fins
		Fail of control AC	4	7	3	84	Multi-electrical measurement	Replace receiver
		Wind speed is low	4	4	2	32	Visual inspection	Replace coil fan
		Wind direction cannot be changed	4	4	2	32	Visual inspection	Replacement motor
		Leakage of water	4	5	2	40	Visual inspection	Brazing and test piping system
		Loud noise when operating	4	5	2	40	Test vibration of motor and fan	Replace insulation
Outdoor unit	Cool the gas and converts into a liquid form	Loss or degradation of heat exchange	5	8	3	120	Multi electrical measurement	Condenser cleaning and fixing fins
		Leakage of gas	3	9	3	81	Pressure Testing	Fix compressor and piping system
		Overheat generation	5	4	4	80	Visual inspection	Cleaning of casing, motor and fan
		Loud noise when operating	4	5	2	40	Test vibration of motor and fan	Replace insulation

Figure 5-10 details the process flow chart issued from the results of the Product FMEA, which orders detective and corrective actions and consider one output per assembly remanufactured.

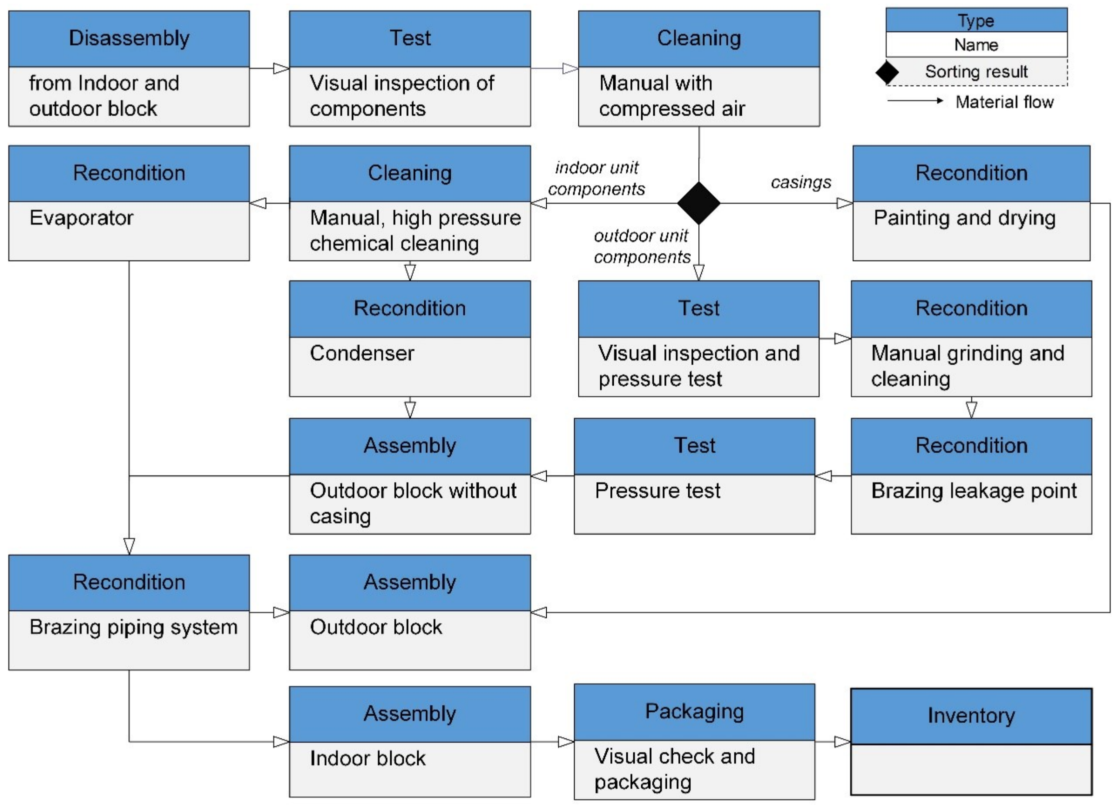


Figure 5-10: Process flow chart for ACS

After defining the process speed by DES, checking the economic feasibility and adapting to changeover and bottlenecks, the FMEA process presented in Table 5-6.

Table 5-6: Process FMEA for ACS

Assembly	Process	Failure Mode	Potential cause	Effect to system	RPN S	RPN O	RPN D	RPN	Recommend actions
Indoor and Outdoor	Disassembly	Break connector joint of piping	Task require-ment	Machine break-down	7	8	3	168	Brazing piping system
	High pressure water cleaning	Damage aluminium fins	Wrong injection nozzle direction	Low cooling capacity	4	7	3	84	Develop jig to fix relative position between injection nozzle and fins
	Chemical cleaning	Damage electrical control	Remain chemical liquid	Machine break-down	7	4	2	56	New cleaning by water
	Evaporator (Indoor) or Condenser (Outdoor)	Cutting tool damages pipe.	Impacts when removing old fins	Gas leakage	9	4	4	144	Inspection and rework leakages

The results of the PPC tactical decisions are presented with the representation of the common layout presented in Figure 5-11 and with the associated throughput expectations with a VSM in Figure 5-12.

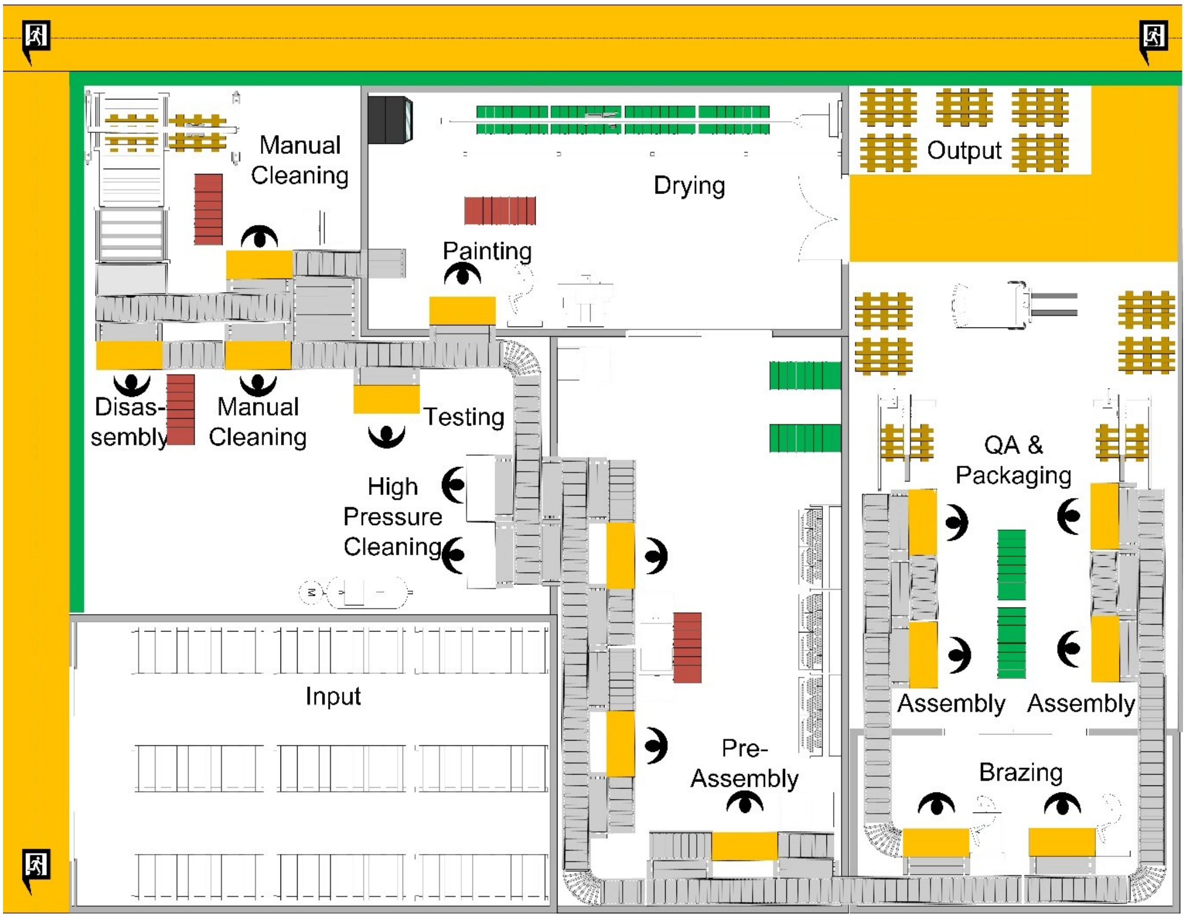


Figure 5-11: Exemplary factory layout for ACS

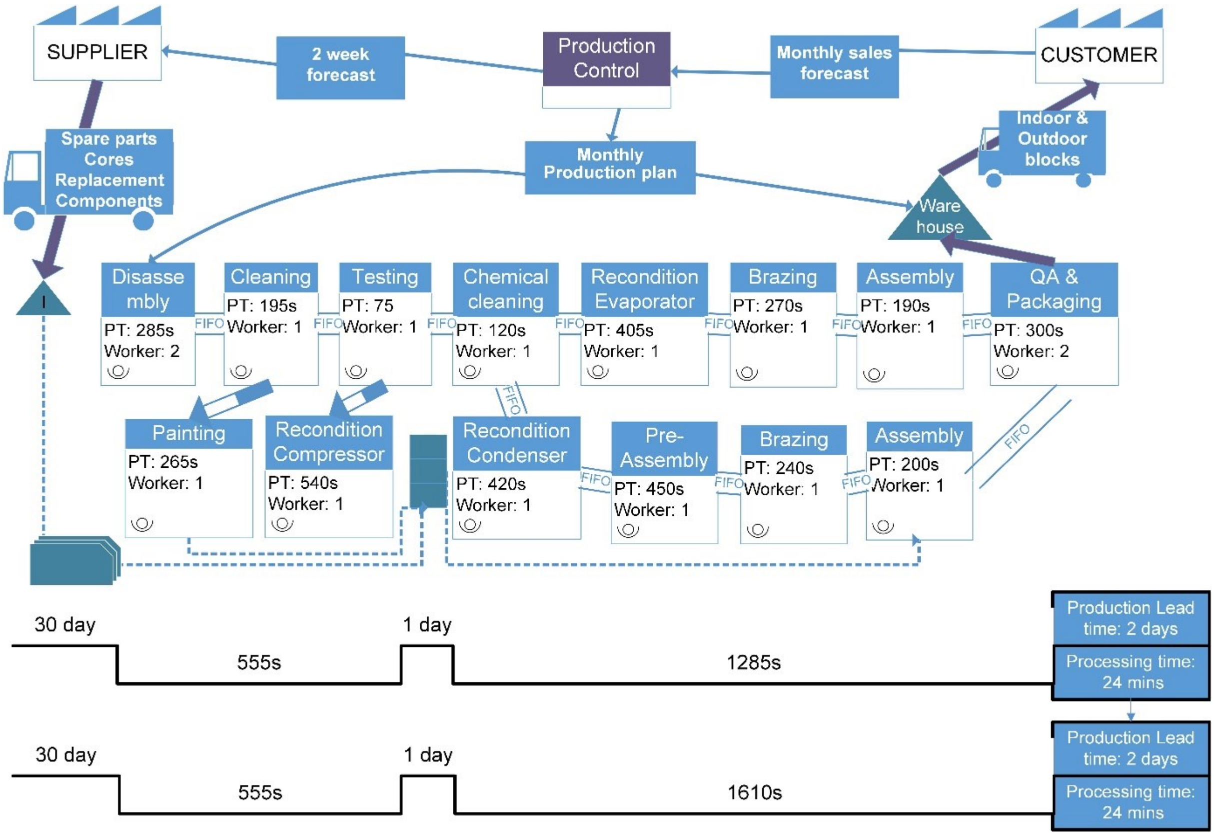


Figure 5-12: VSM chart for ACS

Economic feasibility is expressed while taking into account the best, average and worst case with regard to remanufacturing success. Investment is effected in year 4 and activity is performed until the end of year 8, as expressed in Figure 5-7. Because of a long ramp-up phase and high container size resulting in delayed sales, revenues are grieving the first years of activity and increase the risk for unprofitable activity, with a very high potential ROI variation.

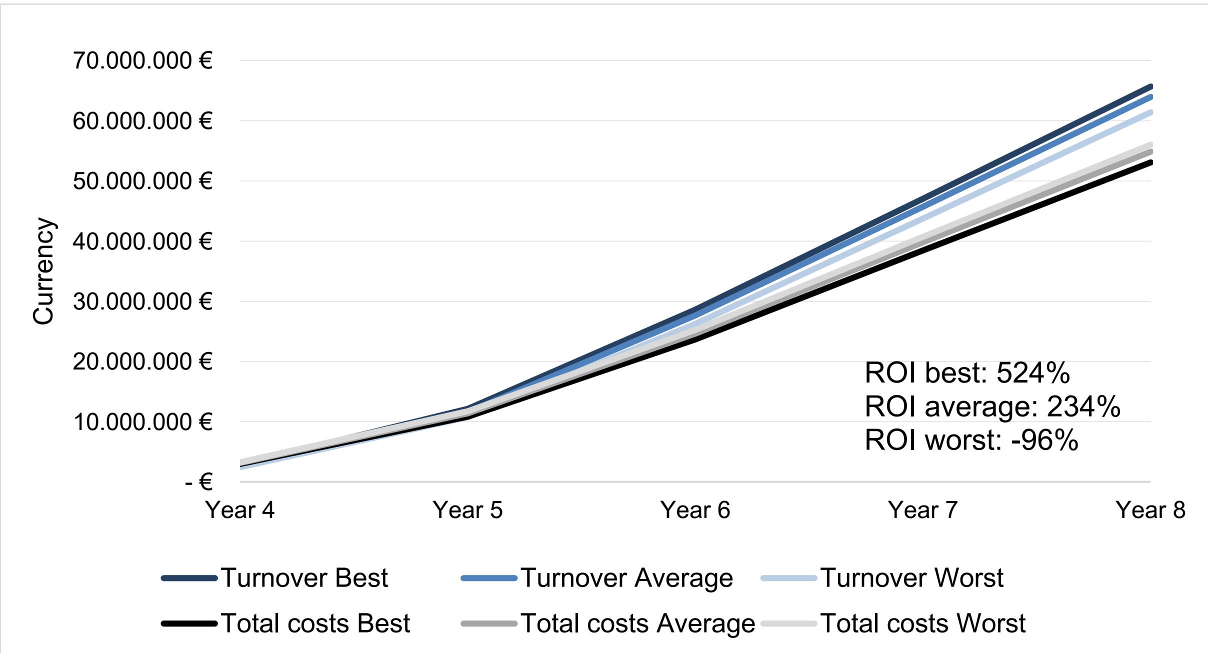


Figure 5-13: Break even and ROI with best-to worst projections for ACS

5.3 Motorbike Cylinder and Cylinder Head

Vietnam is recognized as the 4th largest motorcycle market worldwide according to the Vietnam Association of Motorcycle Manufacturers. In 2011, around 24 million motorcycles are in use and over 9.2 million motorcycles reached their EOL phase every year [Duc-15]. Most of the used vehicles are collected, disassembled and classified according to the estimated quality status of its parts, and are then distributed without being reprocessed. The old bikes are collected after being damaged, stolen or seized by the police and auctioned to specialist scrappers [ZIN-15]. The Te Lo village in the Vinh Phuc province is known as the biggest place for collecting the old motorbikes since over 10 years [Tri-16]. In a network of 600 to 700 garages, all types of vehicles are disassembled to be repaired or restored. The most common practice is the cannibalism of components, where functioning parts are reused in other bikes without being thoroughly checked [VOV-14]. Old parts are therefore a low cost but low quality alternative to buying a new part, but are however an income source for many vendors, proving that demand is existing. The most expensive part sold in this market is the cylinder head and cylinder (CCH) subassembly. Table 5-7 is summarizing the strategic choices of the OEM and the resulting influence factors for implementing remanufacturing of their water pumps. The complete business model, investment plan, bill of material, cost units and profit and loss statements are presented in Annex A-4.

Table 5-7: Canvas business model for motorbike CCH

<table>
<tr><td colspan="10">Strategy
Aftermarket sales</td></tr>
<tr>
<td colspan="2" rowspan="2">Key partners
Distributor
• Collects and send cores
• Transports and sells products</td>
<td colspan="2">Key activities
• Incoming inspection
• Remanufact-uring</td>
<td colspan="2" rowspan="2">Value Proposition
• Product lifecycle 24 months
• Three products with same brand</td>
<td colspan="2">Customer relationship
• Only to distributor
• Forecasts sent monthly</td>
<td colspan="2" rowspan="2">Customer segments
• Business (B2B) with distributor</td>
</tr>
<tr>
<td colspan="2">Key resources
• Factory 1225m²
• Inventory 3000m², 3 storage levels</td>
<td colspan="2">Channels
• Direct sales
• 20’ Container capacity: 500 products.</td>
</tr>
<tr>
<td colspan="5">Cost factors
• Collection success: 80,67%
• Identification success: 82,14%
• Remanufacturing success: 83%
• Distribution success: 87,50%
• Core control: 28,57% of lifetime
• Transaction efficiency: 4%
• Core quality: 83,67%</td>
<td colspan="5">Revenue factors
• Product value trend: -0,78% per month
• Business model premium: 57,14%
Transfer price to distributor (time 0)
• Product A: 178,78€
• Product B: 208,58€
• Product C: 218,51€</td>
</tr>
</table>

In this case, cores return PF_{Cn} are awarded only one additional lifecycle to limit quality issues due to aging of components. Furthermore, as the business model type is aftermarket sales, the price curve steep decrease with time prevents further reuse, as shown in Figure 5-14.

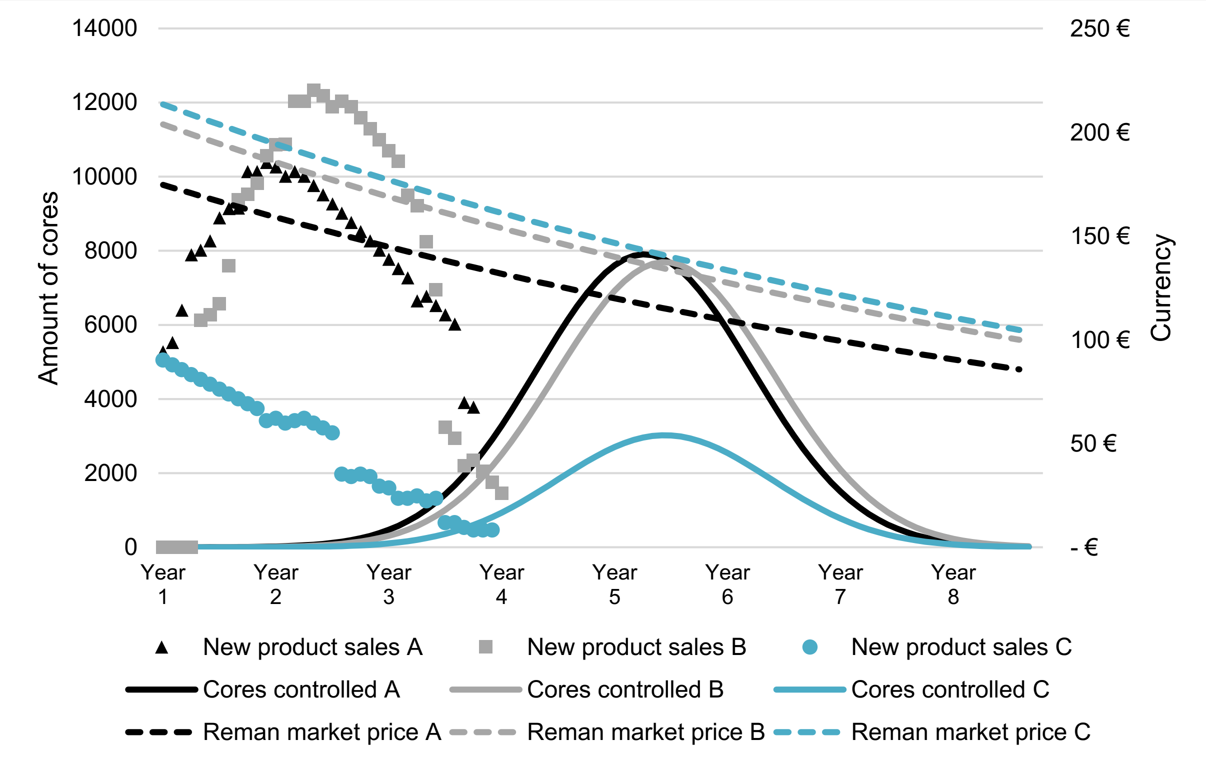


Figure 5-14: New product sales, cores returns and product prices for CHC

Figure 5-15 represents the shipment of 20' containers of CHCs by truck from the distributor to the remanufacturer facility. Activity starts in year 3 and can continue until the year 8 as the market price becomes too low to ensure the continuation of the activity.

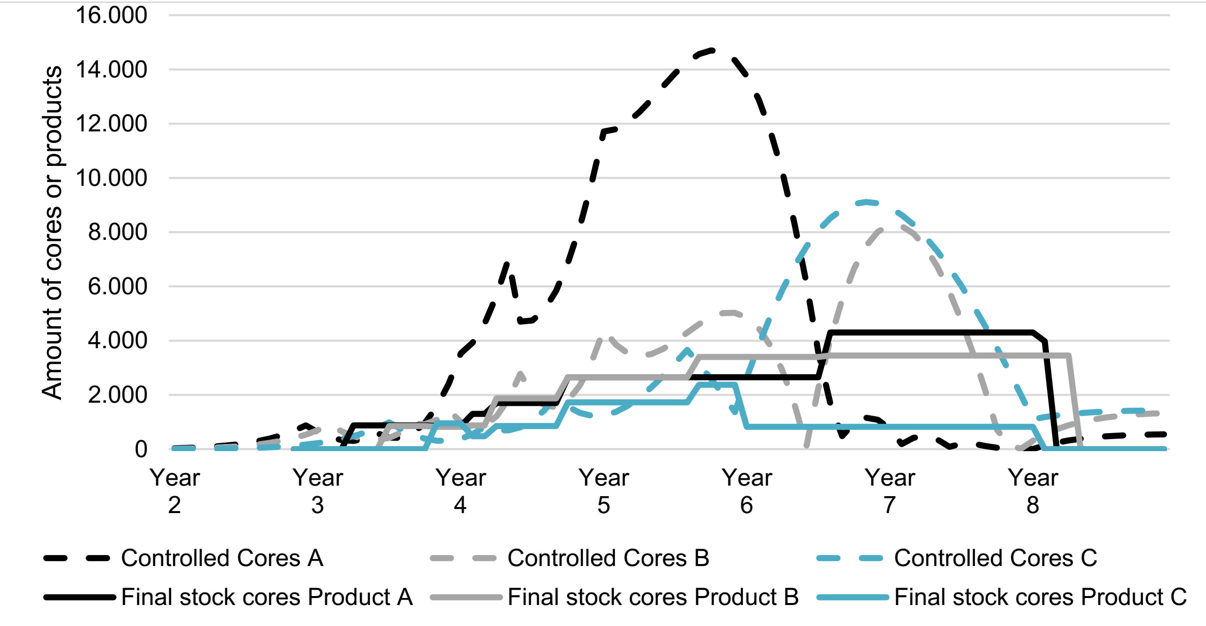


Figure 5-15: Cumulated cores controlled and remanufacturing outcome for CHC

The necessary actions defining the remanufacturing process are established by a product FMEA by defining a list of detective and corrective actions as described in Table 5-8.

Table 5-8: FMEA Product results for motorbike CCH

Failure description		RPN calculation				Detective action	Corrective action
		S	O	D	RPN		
Cylinder	Piston skirt cracking	7	8	7	392	Test	Penetrating Dye
	Piston crown burning/ erosion	7	8	6	336	Test	Visual Inspection
	Worn-out	6	7	6	252	Remanufacture	Boring
	Damaged	7	6	5	210	Test	Visual Inspection
	Damaged	7	6	5	210	Test	Penetrating Dye, TIG Welding, Grinding
	Bended	6	5	5	150	Test	Visual Inspection
	Broken/ stuck	5	7	4	140	Remanufacture	Penetrating Dye, TIG Welding, Grinding
	Piston crown gets thicker	6	7	3	126	Test	Pressure Testing
Cylinder Head	Piston Cracking	8	7	5	280	Test	Visual Inspection
	Cracking	6	6	7	252	Test	Visual Inspection
	Cracking	5	6	7	210	Test	Pressure Testing
	Cracking	6	5	5	150	Remanufacture	Penetrating Dye, TIG Welding, Grinding
	Cracking	4	5	7	140	Test	Penetrating Dye, TIG Welding, Grinding, Ultrasonic Testing

Figure 5-16 details the process flow chart issued with detective and corrective actions and a sorting operation according to the result of internal cracks, detected using penetrating dye.

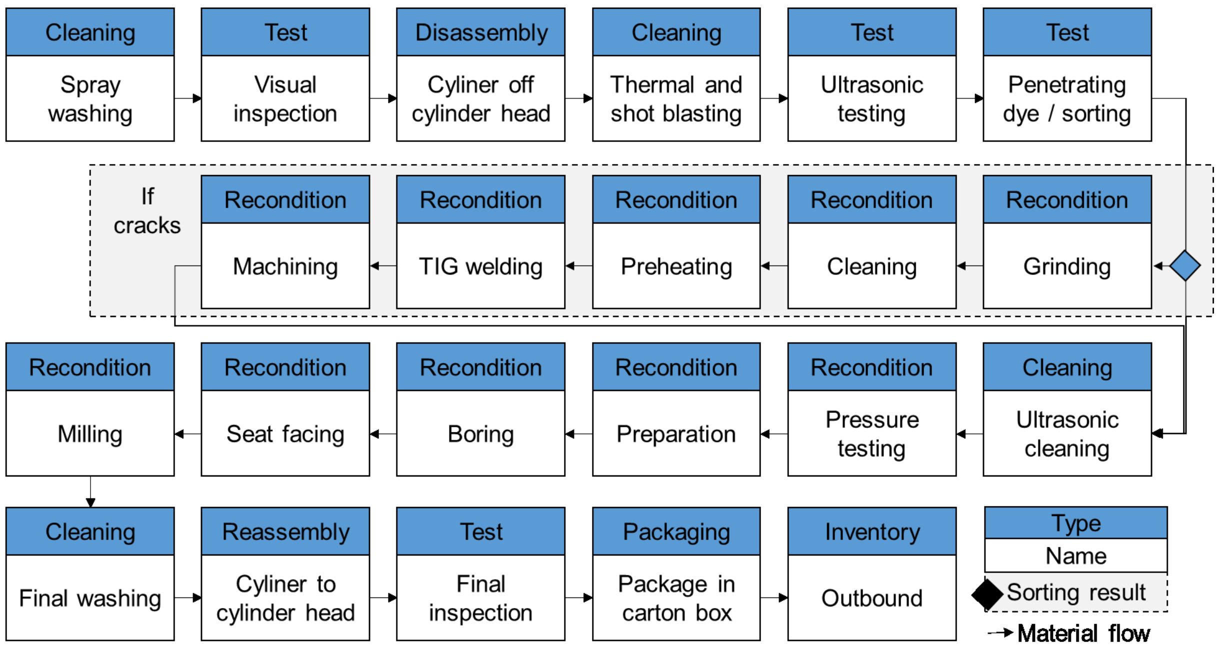


Figure 5-16: Process flow chart for CHC

After improving the process speed, checking economic feasibility and adapting to changeover, bottlenecks and checked FMEA process in Table 5-9, the layout is depicted in Figure 5-17.

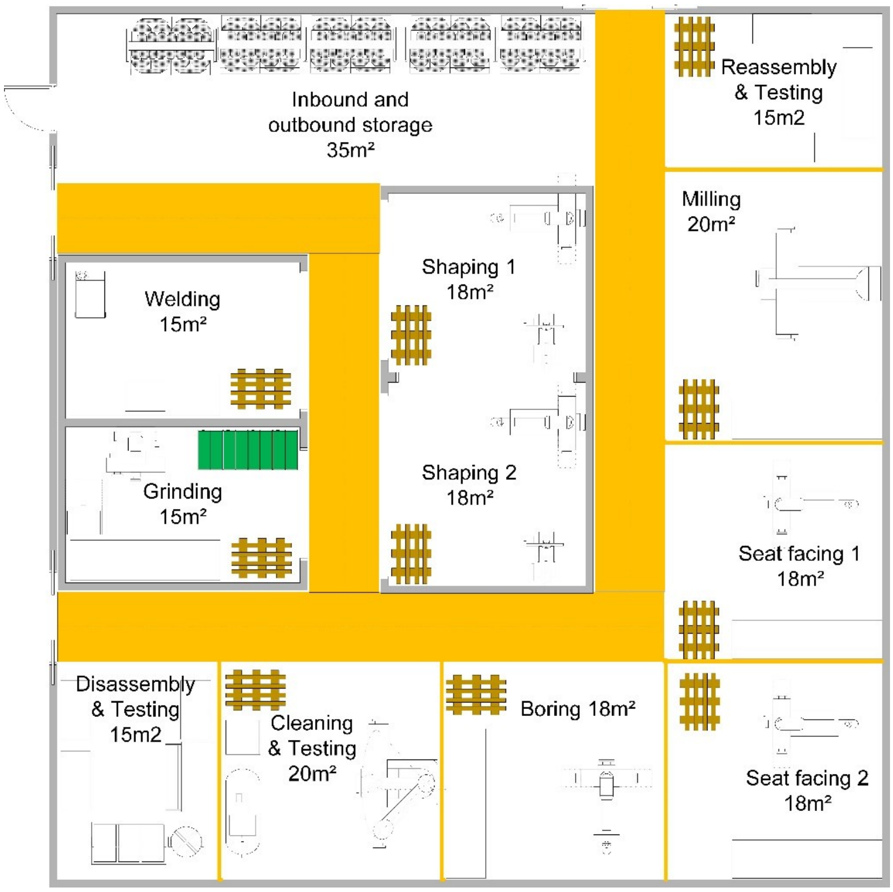


Figure 5-17: Exemplary factory layout for CHC

Table 5-9: FMEA Process analysis for CHC

Process	Failure Mode	Cause of Failure	Effect of Failure	RPN S	RPN O	RPN D	RPN total
Thermal Cleaning and Shot Blasting	Parts damaged, bent or stained	Over temperature	Part rejected, scrapped	5	5	4	100
	Poor cleaning	Masking parts	Reject and rework	7	5	4	140
	Poor cleaning	Place parts in machine	Reject and rework	7	4	4	112
	Poor cleaning	Incomplete cleaning	Fail particle count	6	6	8	288
	Component damage	Vibration	Rework or scrap	7	8	4	224
	Poor surface finish	Shots	Scrapped	7	4	7	196
	Groove damage	Wrong CT	Leak	6	5	5	150
Ultrasonic Testing	Undetected internal cracks	Machine, operator mistake	Life time of product	5	4	3	60
Penetrating Dye	Cracks are not detected	Cracks location is not easy to define	Reject and rework	6	4	8	192
TIG Welding	Excessive electrode consumption	Electrode oxidizing during cooling	Improper weld	5	9	4	180
	Electric arc	Incorrect voltage	Defected job	7	5	6	210
	Porosity in weld deposit	Entrapped impurities, hydrogen, air	Weld strength reduces	7	5	7	245
	Inadequate Shielding	Excessive turbulence in gas stream	Oxidation	6	6	8	288
Spraying washing	Poor cleaning	Spray time insufficient	Reject/New operation	7	6	5	210

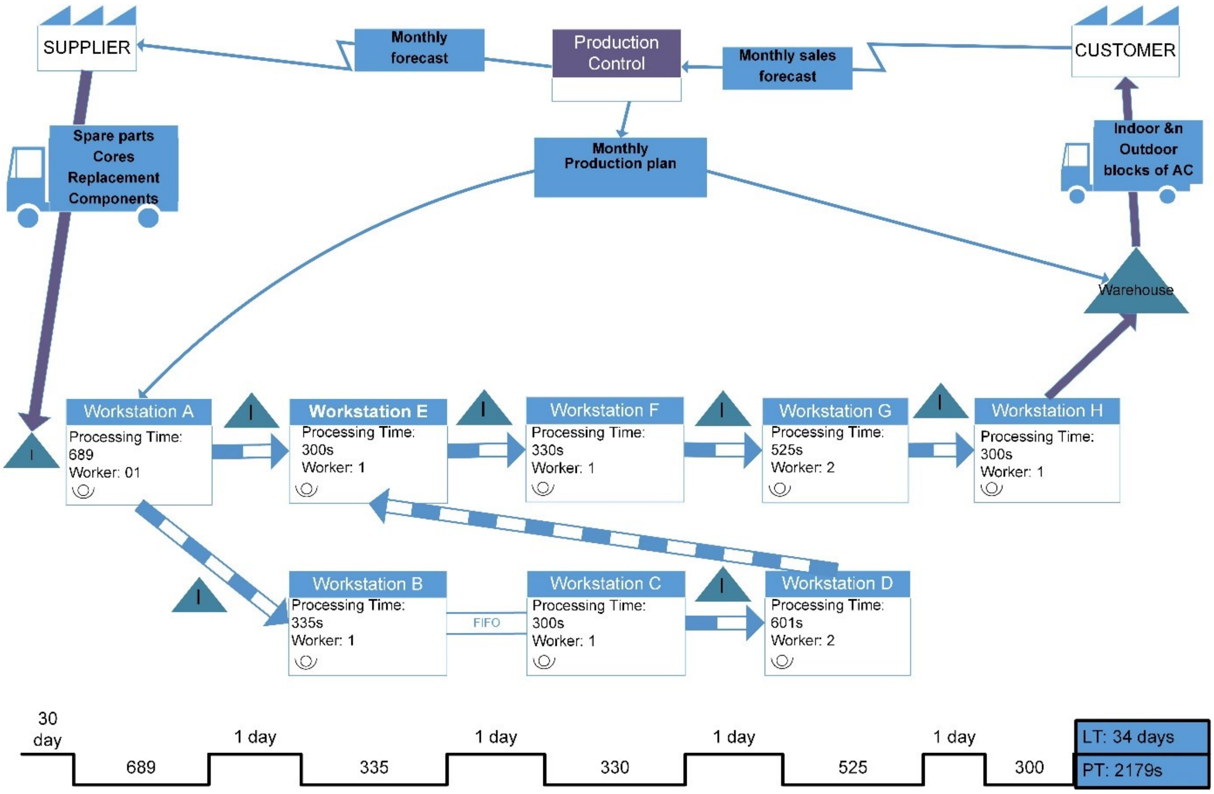


Figure 5-18: VSM chart for CHC

The throughput time is computed using VSM in Figure 5-18 and the economic results of the system presented in Figure 5-19. The activity is expected to start at the end of year 3 and finish with the end of year 8, as the product price doesn't allow remanufacturing operation any longer. Although, the profitability of the venture is ensured, an efficient quality management is critical to ensure appropriate ROI levels, ranging from 84 to 576% over 6 years of activity.

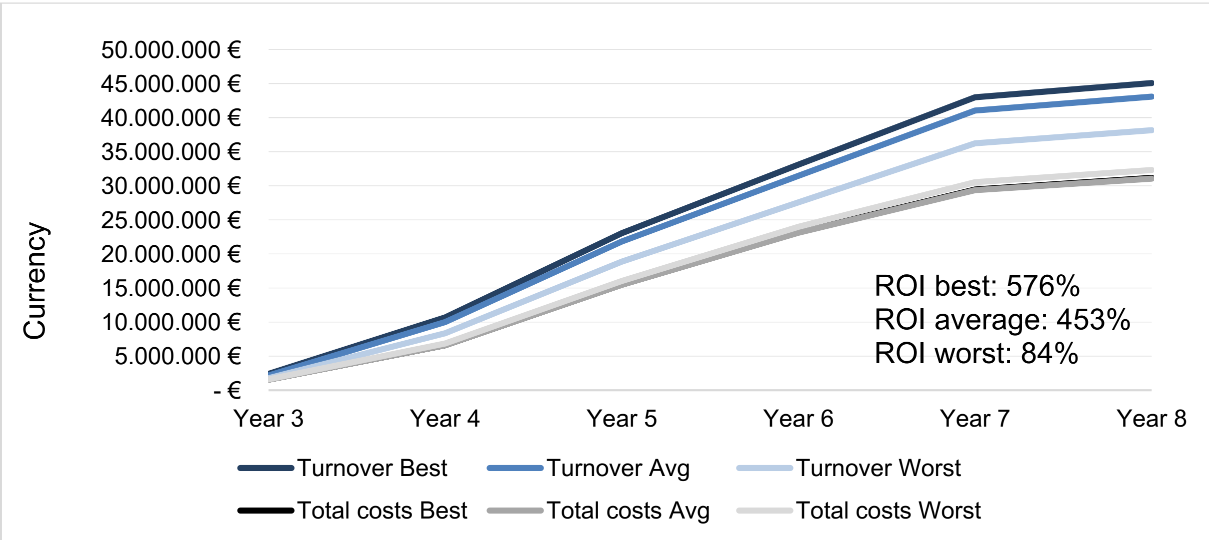


Figure 5-19: Break even and ROI with best-to worst projections for CHC

5.4 Evaluation

The results are evaluated according to five objective requirement sets focused on the four aims of Lean Production for quality, speed, economy and variability, complemented by guideline usability. The methods for quality and productivity are selected based on major criteria related to the scope definition, namely the focus on production operations management, the production planning phase and the adaptability of the method to the remanufacturing industrial environment. Both sets of methods are further assessed by their respective contribution to quality and speed requirements. The costs and revenues included in the guidelines sanction which economy requirements are achieved. The business model determination defines the strategical dimension of a virtual case, and characterises influence factors, which in turn provide information on the efficiency of the remanufacturing system. After collecting information on product price and components structure, the quality category starts with the development of a product FMEA at the component level, in order to determine a set of detective and corrective actions able to solve efficiently all failure modes. The characteristics of product and cores variance are considered by the effect of material flows on tactical choices such as the production schedule and the strategy of integration of new parts. The guideline flow for information input and output and a dedicated template serve as a basis for measuring the completion of the usability requirements compares the performance of the guideline with current methods stated in chapter 3.

The detail of each category is deduced from previous works on Lean remanufacturing and from the availability of information to perform each method. The factory is adapted to the product variety and the cores quality, while considering changeover times as well as potential failures identified with process FMEA. The Value Stream Mapping represents which future condition the factory could have at the SOP, with the indication of the process lead time. The order in which the different methods are applied in the guideline is determined by the ranking of the four aims of Lean Production for the main categories.

Quality improvements needs identified in the FMEA are handled with corrective and detective actions. Detective actions are represented by test workstations and can be manual or automatic. Corrective actions are classified in sorting, cleaning or remanufacturing operations and contents advice for technology choices based on specific research works. The choice of equipment occurs using a technology portfolio based on state-of-the-art research, allowing the related costs to be determined according to the discrete events simulation results.

Table 5-10: Evaluation of current methods

Requirement sets	Requirements	Methods			
		ReOpt	MDLR	SAPEPR	Guideline
Strategy	Business models representation	◐	○	○	●
	Stakeholders network representation	○	○	○	◐
	Country specific production factors	○	○	○	●
	Cores procurement and quality	◐	○	○	●
	Customer acceptance	◐	○	○	◐
Quality	Quality policy	○	○	◐	◐
	Quality goals	○	○	●	●
	Quality assurance	◐	○	●	●
	Quality planning and control	○	○	●	●
	Continuous quality improvement	○	○	◐	●
Speed	Separation of value and waste	○	◐	○	●
	Value stream management	○	●	○	●
	Material flows management	○	●	○	●
	Application of pull principles	○	●	○	●
	Continuous speed improvement	○	●	○	●
Economy	Product costs	◐	●	◐	●
	Process costs	◐	◐	◐	◐
	Human costs	○	◐	◐	◐
	Organization costs	◐	◐	◐	◐
	Equipment costs	◐	○	◐	●
	Sales revenues	●	●	○	●
Variability	Cores conditions variance	◐	◐	○	◐
	Product variety	○	●	○	●
	Material matching variance	○	○	○	◐
	Process variance	○	○	○	◐
Engineering Education	Scope of application	●	●	●	●
	Scalability of results	◐	○	●	●
	Ergonomics	●	○	○	●
	Logic transparency	○	●	◐	●
	Evolutionary format	○	◐	○	◐

Evaluation: ○ No contribution ◐ Partial contribution ● Dedicated

In the speed category, a selection of methods available in literature for optimizing disassembly process chain assists the creation of disassembly methods. Next, additional steps for executing the complete production process such as transport, assembly and packaging are characterized. Once all the steps of the remanufacturing process are known, the line balancing method assist in determining the workstations and operations allocation to integrate process steps according to the customer takt time. The next steps provide advice on the size of buffers and defines the process pacemaker workstation. Several products are considered to follow the same factory layout, provided that the process sequence in terms of workstation remains the same as for the principal product considered. The work method per workstation can be systematically improved by improving the work sequence described with MTM.

After defining the process-chain for each product, the assessment of the economic feasibility of the remanufacturing process verifies if remanufacturing is possible at a lower cost than the price of a new assembly. Several levers for improvements are suggested. The pitch definition helps to define targets for order lot size, which serves as a smallest denominator with the pitch per day of the actual customer order sizes. New parts integration strategy allows flexibility to increase economic results by matching production plan with customer demand in prioritizing either the fastest process delivery time, the exclusive use of remanufactured components or a balance between both strategies. The third step suggests a break-even simulation of the production output with an exemplary weekly schedule with lot sizes per product. Finally, the user uses the layout tool to define factories network to share the remanufacturing process, and simulation is used to provide or compare network results in terms of return on investment.

The final phase of the guidelines aims at defining and improving the variability influences of a remanufacturing process. The production mix is first levelled according to the pitch and it is ensured that a different product batch sequence is used, following the principles of Lean Production. Second, the quality of cores entering the remanufacturing process is classified in categories and the influence of cores quality on disassembly process time defined in an effort to balance the disassembly line. Advices for the reduction of changeover times between batches of different products is given under the consideration of SMED methodology. The modifications brought to the line for variability management are verified through a control of bottlenecks in the production process using simulation. Once the user validates the process as exemplary, a FMEA process is carried for preventing method description issues and modifications for the MTM analyses authorized. The final step of the variability category sees the generation of best-case and worst-case values as metrics of the process as a performance assessment of the process implementation.

6 Summary and outlook

This thesis consists of an analysis of the state of the art of current challenges and solutions for the improvement of remanufacturing practice. The connection of production planning and control to strategic and operational elements in remanufacturing by using specific case study information is proposed as an innovative way to represent interactions within remanufacturing systems. Specific focus is set to Lean Production and MTM as two methodologies recognized worldwide for the continuous improvement of production planning and control and standardizing description of work methods and the time value of basic human movements. Although remanufacturing is attracting the attention of the research community, limited practice demonstrates an untapped potential for improving current practice. The analysis of the ramp-up phase to higher remanufacturing intensity levels must be achieved before allowing an economically sound implementation from product design strategies. Thus, shortcomings are identified in the lack of methodologies able to evaluate, improve and verify production planning and control decisions respecting the agreed quality standards in remanufacturing to strategic decisions in line with the business model of a company. Innovation is needed in finding ways to categorize, connect and evaluate best practices in a multi-level, multi-criteria and standardized representation of a remanufacturing environment. The evaluation of the economic feasibility of remanufacturing operations within their strategical context is made possible from the production planning phase.

To overcome the identified research gap, a methodology allows the systematic planning of remanufacturing processes from the business model strategy to production planning and further to work sequences using MTM and Lean Production. By the combination of descriptive elements, business model strategies are appraised for their influence on costs, revenues and material flows through the definition of strategic influence factors. The design of international networks for collection, remanufacturing and distribution is suggested to appraise a larger extent of remanufacturing strategies, either by tapping country-specific production factors or by fining sales opportunities in unexploited markets. In an effort to distinguish remanufacturing from other EOL strategies such as repair or refurbishing, a modified FMEA approach enables a guided and systematic process-chain planning creation based on detecting and correcting failures identified in used products. Detections and corrections processes are then embedded in a comprehensive process-chain using MTM for defining methods, associated target process times and equipment, while Lean Principles are used to improve the economical effectiveness of the whole process. The remanufacturing process-chain is then checked for economic feasibility under consideration of the company strategical decisions impacting the availability and quality of cores and the targets for remanufactured products’ sales. In a last step, the process-chain is adapted to the variability effects of production mix, cores quality or market seasonality effects. Economic performance is assessed continuously by relating the financial consequences of strategic, tactical and decisions to investment, which can be analysed using Break-Even Analysis, as well as Return on Investment. This methodology is exemplarily applied by using templates for guiding input in DES software, allowing users in a virtual, modular and standardized remanufacturing factory environment, while providing rules to ensure the integrity of the system. The guideline is applied on a specific product environment is proposed with the development of a two-week project-oriented course for engineering master students, gearing potential development of remanufacturing in Vietnam. Exemplary application results are displayed by the means of three case studies, instantiated at the example of water pumps, air conditioning systems and motorbike cylinder and cylinder heads, selected for their potential to be remanufactured in the future.

In many industry sectors, such as automotive parts or printer ink cartridges, the move towards remanufacturing has been initiated by independent companies who created an incentive for OEMs to adopt the practice and tap its opportunities. The ultimate vision of this work is to define a standard platform for evaluation of economic feasibility for remanufacturing new products, with which researchers from different specialties could better identify gaps and coordinate their research efforts in improving remanufacturing practice. This comprehensive guideline allows an immersive, practice-oriented approach to remanufacturing in industry and engineering education, and develops a coordinated awareness of technical and economic issues in remanufacturing. This is especially needed as there is only a very limited amount of vocational and university specializations for remanufacturing available in the market, which impedes the recruitment of specialists by the industry. Through the development of a project-based course based on situated learning, engineering students learn ways to tap opportunities and find response for challenges though applying remanufacturing on new product families.

From the user perspective, current models for the economic evaluation of remanufacturing feasibility bring a contribution to research but do not represent a comprehensive approach, necessary for a realistic appraisal of issues faced by industry, because they only consider factors specific to their field of application. The general approach from current methods is set on a specific section of the remanufacturing process or necessitates the complete set of data which the methodology is expected to be applied, generally obtained from observing processes already applied in the industry. These limitations motivated the construction of a step-by-step guideline open to a large scope of products, with an adequate level of detail for engineering students to understand the complexity of remanufacturing. The possibility to develop an international value-adding network provides perspectives for organizational innovation in the global exercise of remanufacturing, as tapping country-specific production factors is identified by the remanufacturing industry as an essential perspective for development. The guideline serves as a template to support the input and output of information and classifies targeted methodologies addressing specific issues.

Further research is needed for the development of a more precise analysis of production planning to improve the accuracy of results provided, as for example to consider inventory management at the component level or to link modular product design to the developed remanufacturing processes. proper to remanufacturing industry. Another improvement potential concerning the scope is the inclusion of more detail in the collection, reverse logistics and ultimately the use phases of a product lifecycle, thereby allowing the creation of a comprehensive and virtual remanufacturing environment. Furthermore, an extension of the guidelines to further guide the implementation and running phase could allow to maximize continuous improvement of remanufacturing practice. Digital manufacturing solutions combining DES and CPS in a virtual environment offer the technological backbone for such a development.

Standardization is one of the pillars of the use of MTM to define the manual work processes, so it is also foreseeable to develop this tool for the automatic edition of step-by-step work instructions. The MTM analyses entered in the database with an improved definition of workplaces can be exchanged between users as potential best practices, while ensuring a common language and the replicability of methods. Such a contribution could facilitate the replication of successful businesses at a global scale and contribute the employment and public recognition. The development of a database and web service following the system architecture proposed in the work have potential to be the initiation of a standardized and collaborative definition of remanufacturing processes. Policy makers may support by an international definition of which processes need to be respected for a product to be labelled as remanufactured to recognize the efforts on quality of this industry. A collaborative platform could be developed, where skilled technicians continuously improve remanufacturing processes based on standardized data set. The research community could be associated by identifying optimization methods for specific products or processes and derive precise requirements for developing new remanufacturing technologies. Generally, the collaboration between academia and industry would be facilitated by the identification of areas where collaboration in research is urgently needed

If remanufacturing is a promising method for the maximization of the value captured from EOL products, environmental as well as social dimensions should be incorporated in future versions of the guideline to provide a thorough assessment of the sustainability of remanufacturing operations. The approach of remanufacturing operations developed in this work has potential to provide realistic appraisal before the SOP, and provides appropriate decision-making support for assessing the effective sustainability of a future remanufacturing process. By the inclusion of sector specific radical product technology shifts in real time, this multi-level approach illustrates potentials for the timely adaptation of the remanufacturing industry capacities and technologies to future material flows.

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Annexes

A-1 Glossary

Original Equipment Remanufacturer (OER)
OER means that the OEM is remanufacturing its own products and has therefore full access to information concerning product design, specifications, quality characteristic etc. The availability of spare parts and service knowledge is another advantage. The OEM can either remanufacture an entire product or use remanufactured components to supply its manufacturing processes. The result is a wider price range for the customer. Furthermore, OEMs can use strategies, such as leasing contracts, to collect cores for their own remanufacturing processes [Sun-04]

Contracted remanufacturer (CR)
The contracted remanufacturer remanufactures products or components for an OEM. Accordingly, the OEM is not directly involved in the remanufacturing process, but is still able to sell its products for a better price. The contractor can count on assistance by the OEM and will therefore receive a stable supply of cores and specific information for the remanufacturing processes [Lun-83]

Independent remanufacturer (IR)
There is almost no contact between the independent remanufacturer and the OEM. The independent remanufacturer has to buy or collect cores from certain distributors. Also, information concerning the remanufacturing processes will usually not be provided by the OEM [Jac-00]

In the market, however, it is not unusual to find mixtures of these categories. For instance, an independent remanufacturer can still be a contractor for an OEM for a specific product or even a product family [Sun-04] Moreover, in a remanufacturing process, some steps can be fully or partially outsourced to an independent company, as for example the cores collection

Product

A product can be very simply defined as the result of a process [BSI-09, APR-12]. Industry defines four categories of products: services (e.g. maintenance), software (e.g. Microsoft Windows), hardware (e.g. a generator) and processed materials (e.g. gasoline). A product is very often considered as a combination of several categories. For example, a smartphone is a combination of hardware (the smartphone itself), software (the operating system and the third party applications) and services, such as localization, music catalogues or weather previsions.

Component

Automotive Parts Remanufacturers Association Europe (APRA) Europe defines a component as “a part or small assembly of parts used as part of a larger assembly” [APR-12]. They also mention that in some industries, a component is defined as “a constituent part of a device that cannot be physically divided into smaller parts without losing its particular function”.

Spare part

Also called service parts, a spare part is a “replaceable component, sub-assembly or assembly identical to and interchangeable with the item it is intended to replace” [APR-12].

Remanufactured part

The British Standards Institution (BSI) standards emphases that “from the customer viewpoint, the remanufactured product can be considered to be the same as the new product” [BSI-09]. In Europe, the three main associations, European Association of Automotive Suppliers (CLEPA), Automotive Parts Remanufacturers Association (APRA), European Organization for the Engine Remanufacture (FIRM) share a common definition of a remanufactured part. “A remanufactured part fulfils a function which is at least equivalent compared to the original part. It is restored from an existing part (core) using standardized industrial processes in line with specific technical specifications. A remanufactured part is given the same warranty as a new part and it clearly identifies the remanufacturer. A remanufactured part is different from a reused, repaired, rebuilt, refurbished and reconditioned part” [APR-14].
In 2016, the European associations agreed with Motor & Equipment Remanufacturers Association (MERA) from U.S., Automotive Parts Remanufacturers National Association (ANRAP) from Brazil and Remanufacture Committee of China Association of Automobile Manufacturers (CPRA) on definitions of core and remanufacturing process.

Core

“A core is a previously sold, worn or non-functional product or part, intended for the remanufacturing process. During reverse logistics, a core is protected, handled and identified for remanufacturing to avoid damage and to preserve its value. A core is not waste or scrap and is not intended to be reused before remanufacturing” [APR-16]. The cores are therefore replacing the raw materials as material sources and are their availability and quality are therefore an essential element for the remanufacturing process.

Remanufacturing process

“Remanufacturing is a standardized industrial process by which cores are returned to same-as-new, or better, condition and performance. The process is in line with specific technical specifications, including engineering, quality and testing standards. The process yields fully warranted products. An industrial process is an established process, fully documented, and capable to fulfil the requirements established by the remanufacturer" [APR-16].

Pull means that operations are triggered by customer orders, for the product to flow through the production process. The aim of pull is to avoid overproduction while staying flexible to customer demand. Methods such as demand planning and forecasting are pushing products to estimated future customer needs through the production process [Wom-03].

Perfection is the continuous improvement process towards an ideal state. The application of the first four principles is a recurrent process of reducing effort, space, defects and lead times. The visualization of the future ideal state allows to develop measures in form of policy deployment to gradually reach perfection [Wom-03]. The Value Stream Mapping method, serves the application of the five principles, which can be divided into value steam analysis and value stream design. The method serves as a guidelines for the implementation of lean production and was originally developed by Toyota The production process is a combination of machines, equipment and workstations to raw materials to products [Erl-13].

The material flow depicts the linkage between machines, equipment and workstations and show when material is moved in the production process [Erl-13]

The Information flow precedes material flow as it controls the production processes and determines what products and materials are processed, and when and how to process them [Erl-13].

The customer Takt Time (TT) represents the needed rate of production to satisfy a certain customer demand in a period of time. It equals the mean sales rate for the corresponding time period. The takt time is based on mean values and is serves as an indicator. Nonetheless, it reveals the quantitative performance requirements for the production. The production processes times must be adapted to the takt time to achieve a balanced production [Erl-13].

The Operation Time (OT) computes the time parts stays in the production process, which includes the manual working time of the operator and the machine operating time. It consists further of the value-adding time (VAT) for the work tasks, which creates directly value for the customer and the ancillary times (AT) and waiting times or ancillary activities. For optimization purposes, ancillary times need to be reduced or eliminated when they do not support tasks represented by the VAT, in order to increase productivity [Erl-13].

The Processing Time (PT) indicates how long individual parts stay in a production process. The processing time equals the operation time, if only one part is processed in a production process. For processes with more than one part, the continuous processing time is when parts are sequentially processed so that several parts are in a process and the batch processing time when parts are grouped together and processed simultaneously [Erl-13].

The Cycle Time (CT) time indicates the time needed to process a single part or product. If several parts are being processes at the same time or several machine are used, CT has to be calculated to obtain the time per part. The CT equals the operation time and the processing time if only one machine is used and only one part is being processed at the same time [Erl-13].

Changeover Time (CO)

The CO time is the time for setting a machine for the next product variant. The time is measured from the process end of last good part of the last product variant to the process begin of the first good part of the new product variant [Erl-13]

Production Lead Time (PLT)

The PLT time measures the time required for one part to travel from the material receipt entrance to the product issue exit. Between these two points, the part is processed through all required process steps and may include inventory time [Erl-13]

There are many different definitions of what is waste. WOMACK AND JONES suggest that waste is any human activity which absorbs resources, but create no value for a customer [Wom-03]. NASH AND POLING see waste reduction as use, consume, spend, or expend thoughtlessly or carelessly [Nas-08]. LIKER suggest a classification of waste in a manufacturing environment according to eight categories according to the source of the waste, such as overproduction or over processing [Lik-04].

Value refers to a product offered by a company, which can either be a good, a service or a combination of both. It represents the fulfilment of customer requirements. In the customer view, a producer exists and a specific product should be bought because of its embedded value. The value of a product can only be defined by a customer. For this reason, the first step in implementation of the Lean Production is to analyse the ability for the product to meet customer requirements. Even if efficiently produced, offering the wrong product to a customer is waste [Wom-03].

The value stream represents all actions required to bring a product to the customer. WOMACK AND JONES classify these actions three critical management tasks: problem solving, information management and physical transformation. Problem solving starts with the product development stage and ends with the SOP. Information management concerns taking customer orders and the schedule deliveries. The physical transformation task relates to the production process flow from raw material to final product delivery. Three different kinds of activities can be found in the value stream: value added operations, non-value added operations which create no value but are necessary and waste operations that must be avoided. Tightening a screw brings value. The movement to bring a screw to a thread creates no value to a product however but is unavoidable. Waiting for a screw until it can be moved and tightened must be avoided [Wom-03].

Once value is specified and waste operations eliminated, the remaining activities must be sequenced logically and physically to highlight the operations flow [Wom-03]. Batch and queue system, when large amounts of parts are moved to the next process should be avoided. Aim is the elimination of transportation and waiting times, as they have the highest potential for improvement of lead times [Dic-15].

A-2 Producer-oriented business model qualitative description

KEY ACTIVITIES	VALUE PROPOSITION	CUSTOMER SEGMENTS
Access to cores - Service contract - Remanufacturing outsourcing - Swap system - Voluntary return and property transfer - Return at the end of the use phase - Purchase as raw material **Collection organization:** - Central - Decentral **Core processes:** - Product design - Production and assembly - Reverse logistics - Remanufacturing - Service / Maintenance - Recycling and disposal **Design for X strategies** - Eco-Design - Design for Recycling - Design for Remanufacturing - Design for Disassembly - Design for Assembly	**Economic drivers** - New business strategy - New service offer - Increase of sales - Approach of a new customer segment - Cost reduction strategy - Spare parts sourcing - Brand protection - Feedback from product design - Spare parts market protection **Socio-environmental drivers** - Green marketing - Legislation compliance **Type of value** - Performance - Customization - Design - Brand - Price - Newness - Status **Form of value** - Product-oriented - Use-oriented - Result-oriented **Additional services** - Planning - Consulting - Logistical - Additional functions - Functions development **Sales price** - Below market price - Market price - Market price premium **Product value** - Long life - Standardized - Able to disassemble - Changeable spare parts - Able to reassemble **Quality** - Same - Higher **Warranty** - Same - Higher	**Market classification** - Industrialized country - Emerging country - Developing country **Market segment** - Mass-market - Niche market - Market segment - Diversification **Commercial relationship** - Business-to-Consumer - Business-to-Business - Business-to-Government - Business-to-Employee **Customer reach** - Local - Regional - National - International **Customer profile** - Newness oriented - Function-oriented **Ecological awareness** - None - Limited - High **Competition** - OEMs - Low cost producer - Used products markets - Independent repair shops - Independent remanufacturers

KEY RESOURCES	KEY PARTNERS	CUSTOMER RELATIONSHIPS	CANALS
Physical resources - Buildings - Equipment - Material **Intellectual resources** - Knowledge - Patents - Markets - Technologies **Human resources** - Employees - Qualification - Experience **Financial resources** - Own capital - Debt capital	**Value creation partner** - Service company - Toll manufacturer - Distributor - Core collector - Contracted remanufacturer - New parts supplier - End customer - Competitors	**Prospection** - Cold calling - Warm calling **Customer contact** - Transaction assistance - Relationship development **Customer distance** - No exchange - Limited exchange - Regular exchange **Customer inclusion** - None - Operative - Strategic	**Sales canals** - Direct - Indirect - Online **Distribution canals** - Physical - Virtual **Information canals** - Reputation - Word of mouth - Purchase - Loyalty

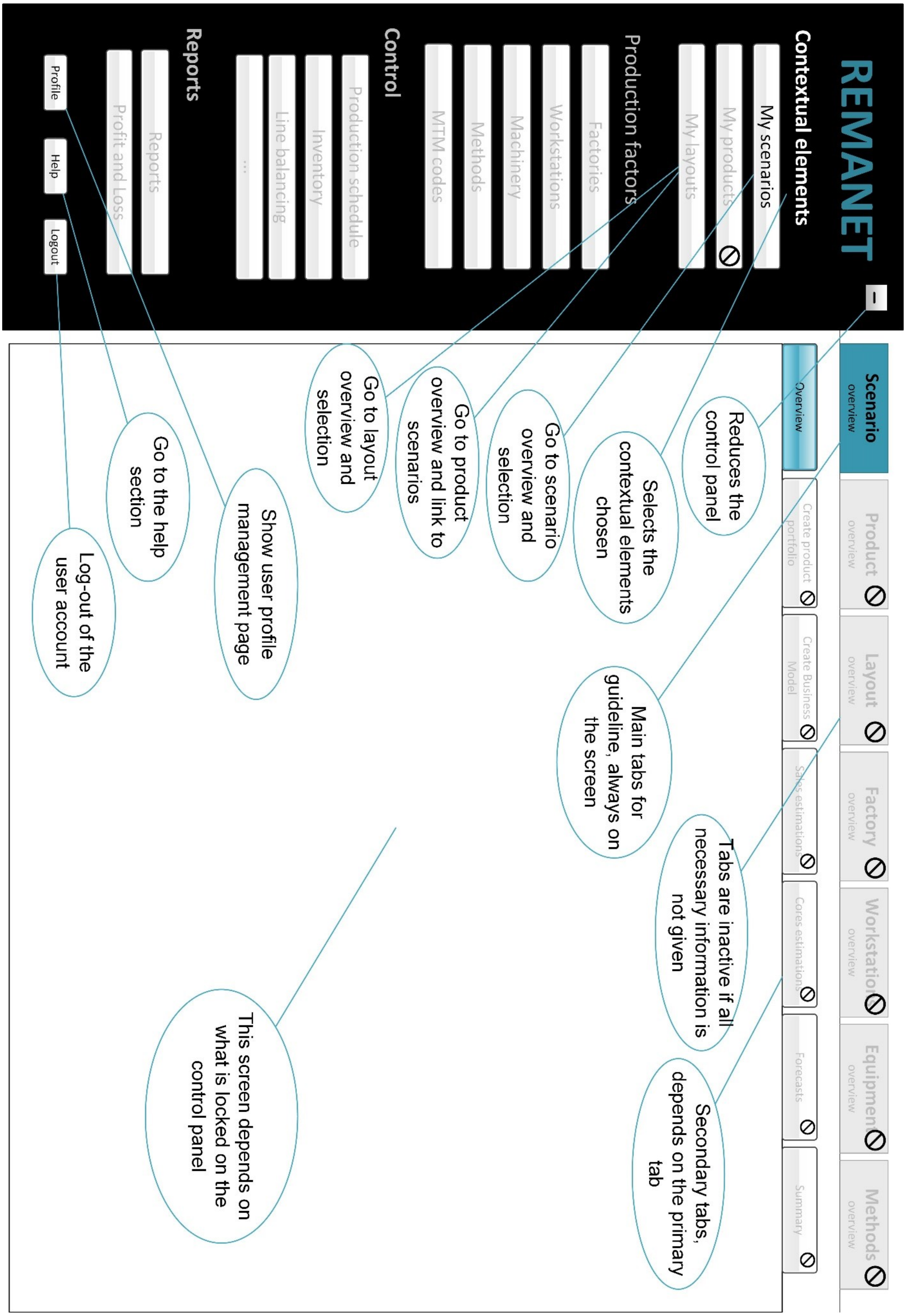
Dimension	Category	Options	Collection success	Identification success	Reman. success	Distribution success	Core control	Transaction efficiency	Core quality	Product value trend	Bus. model premium
Key activities	Access to cores	Service contract	2	2	1		2	-1	2		
		Remanufacturing outsourcing	-1		-1		1	-1		1	
		Swap system	1	1	1				1	1	
		Voluntary return and property transfer	-2	-1	-1		-1		-1		
		Return at the end of the use phase	2		1		1				
		Purchase as raw material	-1	-2			-2	-1	-2	1	
	Colle ction	Central	2	-1	1		-1		-1		
		Decentral	-1	1	-1		1	-1			
	Core processes	Product design		1							
		Production and assembly		1							
		Reverse logistics	1	2	1		1	1	1		
		Remanufacturing	1		1		1	1			
		Service / Maintenance	1	2			1	1	1	1	1
		Recycling and disposal									
	Design for X strategies	Eco-Design		1					1	1	
		Design for Recycling		-1					-1		
		Design for Remanufacturing	1	2					1		
		None		-2					-1		
Value Proposition	Economic drivers	New business strategy					-1	-1			
		New service offer				1		-1			1
		Increase of sales									
		Approach of a new customer segment				-1		-1	-1		
		Cost reduction strategy									
		Spare parts sourcing									
		Brand protection				-2	-1				
		Feedback from product design		2					2		
		Spare parts market protection	1						-1		
	SE	Green Marketing								1	
		Respect of legislation	1								
	Type of value	Performance								1	1
		Customization								-1	
		Design								-1	-1
		Brand								1	-1
		Price							-1	1	-1

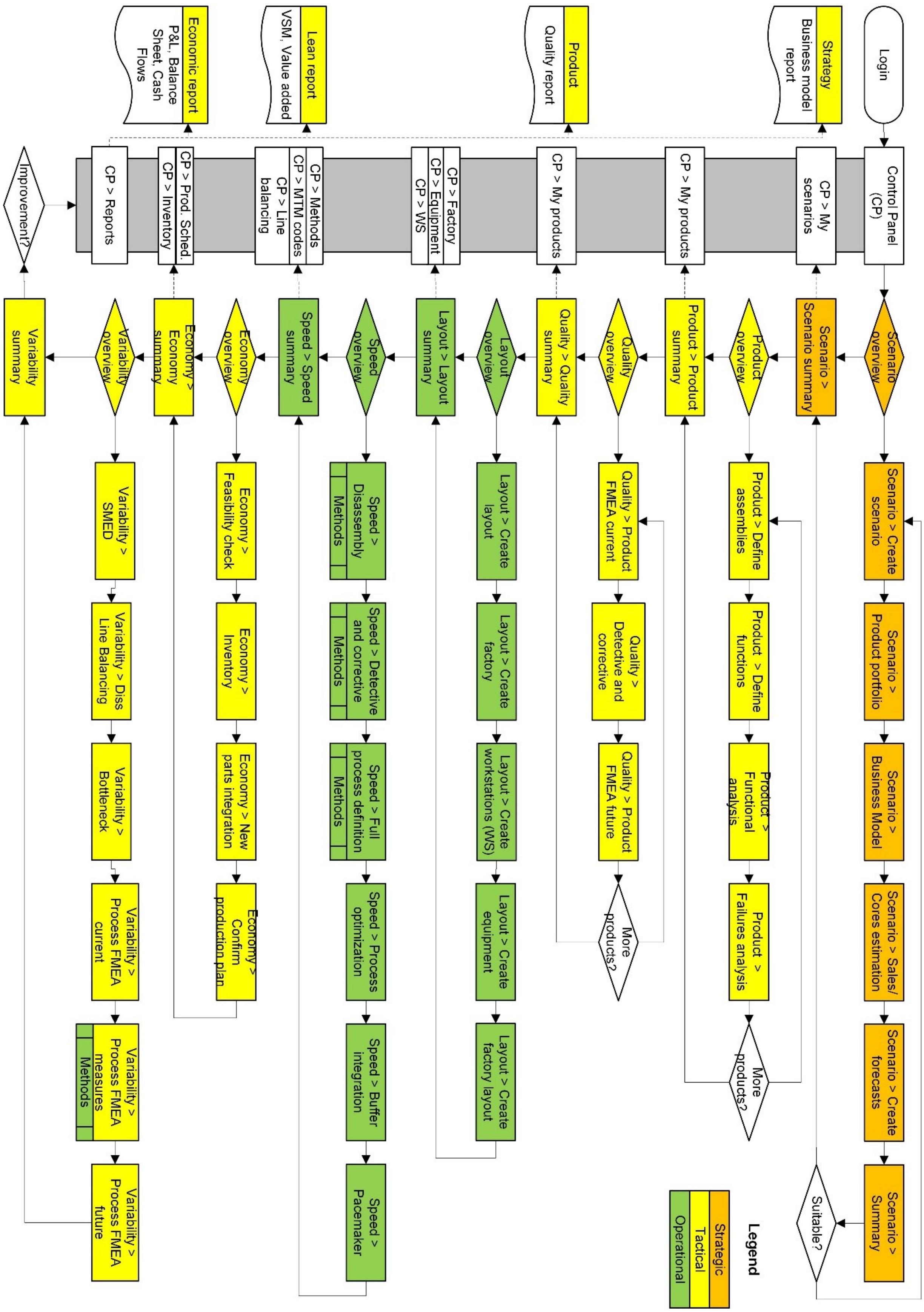
Dimension	Category	Options	Collection success	Identification success	Reman. success	Distribution success	Core control	Transaction efficiency	Core quality	Product value trend	Bus. model premium
		Newness					-1		-1	-2	-2
		Status							1	-1	-1
	Form of value	Product-oriented		-1	-1		-1		1		
		Use-oriented		1	2	1	1			1	
		Result-oriented		2	1	1	1	1	-1	2	
	Additional services	Planning				1		1	1	1	
		Consulting		1		1	1	1	1	1	
		Training				1	1	1	1	1	
		Logistical	1				1	1	1		
		Functions development				1		1	1	1	
		Functional maintenance		2		1	1		2		
	Sales price	Below market price					-1		-1	1	
		Market price								-1	
		Market price premium					1		1	-2	
	Product value	Long life			2		-1		1		1
		Standardized			1				1		
		Able to disassemble			1						
		Changeable spare parts			1						
		Able to reassemble			2						
	Quali-ty	Same							-1	1	1
		Higher			1				1	2	2
	War-ranty	Same							-1	1	1
		Higher			1				1	2	2
Customer segments	Market classifica-tion	Industrialized country	1	1			1		1	1	1
		Emerging country	-1						-1		-2
		Developing country	-2	-1			-1		-2		-1
	Market segment	Mass-market			1						
		Niche market			-1						
		Market segment									
		Diversification									
		Business-to-Consumer	-1			-1	-1			1	-1
		Business-to-Business	1			1	1			2	1
		Business-to-Government	1			1	1				1
		Business-to-Employee	2			1	1				1

Dimension	Category	Options	Collection success	Identification success	Reman. success	Distribution success	Core control	Transaction efficiency	Core quality	Product value trend	Bus. model premium
	Customer reach	Local	2			2	2	2	2		
		Regional	1			1	1	1	1		
		National	-1			-1	-1	-1	-1	-2	
		International	-2			-2	-2	-2	-2	2	
	Cust. profile	Newness oriented							1		-2
		Function-oriented							-1		2
	Price sensi tivity	Limited								-2	2
		High								-1	-2
	Ecolo. Aware.	None		-1					-1	2	-2
		Limited	1				-1			1	-1
		High	2	1					1	-1	1
	Competition	OEMs	-1				1			-1	-1
		Low cost producer									-2
		Used products markets	-1							1	-1
		Independent repair shops	-1								-1
		Independent remanufacturers	-2								-1
Key resources	Physical resources	Buildings									
		Equipment			1						
		Material									
	Intellectual resources	Knowledge		1	1					1	
		Patents		2	2						
		Brand									
		Technologies									
	Human resources	Employees									
		Qualification			1						
		Experience			2		1				
	Finan cial res.	Own capital									
		Debt capital									
	Value Creation Partner	Service company						-1			
		Toll manufacturer						-1			
		Distributor						-1			
		Core collector	1		-1		-1	-1	-1		
		Contracted remanufacturer	1				-1	-1			
		New parts supplier						-1		1	

Dimension	Category	Options	Collection success	Identification success	Reman. success	Distribution success	Core control	Transaction efficiency	Core quality	Product value trend	Bus. model premium
		End customer							-1		
		Competitors					-1	-1		-1	
		Leasing company					1	-1		1	
Customer relationship	Prospection	Cold calling								-2	
		Warm calling	1				1			2	
	Cust. contact	Transaction assistance		-1						-1	
		Relationship development	2	1						1	
	Customer distance	No exchange	-2				-1			2	
		Limited exchange	-1				1				
		Regular exchange	1				2				
	Inclusion in cust. process	None		-2	-1		-1	1	-1		
		Operative	1	1				-1		2	
		Strategic	2	1	1		1	-2	1		
Canals	Sales canals	Direct	2			2	1		1	1	
		Indirect	-1			1	-1	-1	-1		
		Online	1			2					
	Distri. canal	Physical	2							1	
		Virtual					1			1	-1
	Information canals	Reputation					1			2	
		Word of mouth		1			1			2	1
		Purchase									1
		Loyalty		2			2				2
Costs structure	Cost advantag.	None									
		Effects of scale									
		Synergy effects			2						
	Direction	Cost oriented			-1						
		Value oriented			1						
Revenues	Service	Fix									-1
		Dynamic									1
Average			0,40	0,58	0,69	0,57	0,27	-0,28	0,10	0,58	-0,03
Sum Es			18	19	22	12	14	-9	5	31	-1
Ed			7,20	10,94	15,13	6,86	3,77	-2,53	0,50	18,13	-0,03

A-3 Prototypical guideline template




Login
Control Panel (CP)
Strategy
Business model report
Product
Quality report
Lean report
VSM, Value added
Economic report
P&L, Balance Sheet, Cash Flows
CP > My scenarios
CP > My products
CP > My products
CP > Factory
CP > Equipment
CP > WS
CP > Methods
CP > MTM codes
CP > Line balancing
CP > Prod. Sched.
CP > Inventory
CP > Reports
Improvement?
Scenario overview
Scenario > Scenario summary
Product overview
Product > Product summary
Quality overview
Quality > Quality summary
Layout overview
Layout > Layout summary
Speed overview
Speed > Speed summary
Economy overview
Economy > Economy summary
Variability overview
Variability summary
Scenario > Create scenario
Scenario > Product portfolio
Scenario > Business Model
Scenario > Sales/ Cores estimation
Scenario > Create forecasts
Scenario > Summary
Suitable?
Product > Define assemblies
Product > Define functions
Product > Functional analysis
Product > Failures analysis
More products?
Quality > Product FMEA current
Quality > Detective and corrective
Quality > Product FMEA future
More products?
Layout > Create layout
Layout > Create factory
Layout > Create workstations (WS)
Layout > Create equipment
Layout > Create factory layout
Speed > Disassembly
Methods
Speed > Detective and corrective
Methods
Speed > Full process definition
Methods
Speed > Process optimization
Speed > Buffer integration
Speed > Pacemaker
Economy > Feasibility check
Economy > Inventory
Economy > New parts integration
Economy > Confirm production plan
Variability > SMED
Variability > Diss Line Balancing
Variability > Bottleneck
Variability > Process FMEA current
Variability > Process FMEA measures
Methods
Variability > Process FMEA future
Legend
Strategic
Tactical
Operational

A-4 Detailed case studies

CASE STUDY 1 – WATER PUMPS

Canvas Business Model

Dimension	Category	Options	Collection efficiency	Identificatio n efficiency	Reman. efficiency	Distribution efficiency	Core control	Transaction efficiency	Core quality	Customer demand	Bus. model premium
Canals	Distribution canals	Physical	2							1	
	Information canals	Loyalty		2			2				2
	Sales canals	Direct	2			2	1		1	1	
Costs structure	Cost advantages	Synergy effects			2						
	Direction	Value oriented			1						
Customer relationship	Customer contact	Relationship development	2	1						1	
	Customer distance	Regular exchange	1				2				
	Inclusion in customer	Operative	1	1				-1		2	
	Prospection	Warm calling	1				1			2	
Customer segments	Commercial relationship	Business-to-Government	1			1	1				1
	Competition	OEMs	-1				1			-1	-1
	Customer profile	Function-oriented							-1		2
	Customer reach	Regional	1			1	1	1	1		
	Ecological awareness	None		-1					-1	2	-2
	Market classification	Developing country	-2	-1			-1		-2		-1
	Market segment	Niche market			-1						
	Price sensitivity	Limited								-2	2
Key activities	Access to cores	Return at the end of the use	2		1		1				
	Collection organization	Central	2	-1	1		-1		-1		
	Core processes	Product design		1							
		Production and assembly		1							
		Remanufacturing	1		1		1	1			
		Reverse logistics	1	2	1		1	1	1		
		Service / Maintenance	1	2			1	1	1	1	1
Key partners	Value Creation Partner	Leasing company					1	-1		1	

Key resources	**Financial resources**	Own capital									
	Human resources	Employees									
		Experience			2		1				
		Qualification			1						
	Intellectual resources	Brand									
		Knowledge		1	1					1	
		Patents		2	2						
		Technologies									
	Physical resources	Buildings									
		Equipment			1						
		Material									
Revenues	**Service revenues**	Fix									-1
Value Proposition	**Additional services**	Functional maintenance		2		1	1		2		
		Logistical	1				1	1	1		
	Economic drivers	Cost reduction strategy									
		New business strategy					-1	-1			
	Form of value	Result-oriented		2	1	1	1	1	-1	2	
	Product value	Able to disassemble			1						
		Able to reassemble			2						
		Changeable spare parts			1						
		Long life			2		-1		1		1
		Same							-1	1	1
		Standardized			1				1		
	Quality	Same							-1	1	1
	Sales price	Market price premium					1		1	-2	
	Type of value	Brand								1	-1
		Performance								1	1
Business model specific values		Average influence E_d	1.00	1.00	1.17	1.20	0.71	0.33	0.13	0.76	0.43
		Influence weight E_s	16	14	21	6	15	3	2	13	6
		Absolute influence E_d	16.00	14.00	24.50	7.20	10.71	1.00	0.25	9.94	2.57
Standard values per business model		**0**	0.9	0.9	0.8	0.9	0.05	0.05	0.95	-0.001	-0.5%
		2	1	1	1	1	0.01	0.01	1	0	-0.9%
		Company-specific ratios	0.13	1.00	1.00	1.16	1.20	0.71	0.33	0.12	0.76
		Company -specific value	0.80	0.950	0.950	0.91	0.96	0.03	0.04	0.95	-0.6%

Profit and loss statement

Revenue	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
Sales Product A	- €	- €	722,209.45 €	3,579,386.59 €	1,668,870.30 €
Sales Product B	- €	- €	165,991.67 €	1,433,703.29 €	1,025,784.78 €
Sales Product C	- €	- €	397,936.11 €	520,125.81 €	25,887.37 €
Net Sales	- €	- €	**1,286,137.23 €**	**5,533,215.69 €**	**2,720,542.46 €**
Purchases Product A	- €	- €	236,521.02 €	1,302,976.41 €	375,657.11 €
Purchases Product B	- €	- €	62,130.72 €	489,708.35 €	369,644.68 €
Purchases Product C	- €	- €	151,903.83 €	179,733.74 €	8,991.32 €
Cost of Goods Sold	**- €**	**- €**	**450,555.57 €**	**1,972,418.50 €**	**754,293.12 €**
Gross Profit	**- €**	**- €**	**835,581.66 €**	**3,560,797.19 €**	**1,966,249.35 €**
Collection costs	10,000.00 €	10,793.61 €	93,904.21 €	335,383.70 €	74,215.85 €
Remanufacturing costs	46,056.00 €	47,877.68 €	154,513.51 €	491,651.89 €	364,985.98 €
Distribution cost	5,000.00 €	5,250.00 €	70,983.65 €	307,216.04 €	160,636.02 €
Warranty cost	2,000.00 €	2,040.00 €	70,623.02 €	316,736.04 €	162,966.43 €
Depreciation	- €	- €	103,100.00 €	103,100.00 €	103,100.00 €
Operating Expenses	**63,056.00 €**	**65,961.29 €**	**493,124.39 €**	**1,554,087.67 €**	**865,904.27 €**
Income From Operations	**- 63,056.00 €**	**- 65,961.29 €**	**342,457.27 €**	**2,006,709.52 €**	**1,100,345.08 €**
Income Tax Expense	**- €**	**- €**	**113,010.90 €**	**662,214.14 €**	**363,113.88 €**
Net Income	**- 63,056.00 €**	**- 65,961.29 €**	**229,446.37 €**	**1,344,495.38 €**	**737,231.20 €**

Value-chain determination

Activity	Element	Cost Unit	Product A	Product B	Product C
Strategy	**Market price new**	**€ / product**	200.00 €	230.00 €	250.00 €
Strategy	**Market price Reman**	**€ / product**	180.00 €	207.00 €	225.00 €
Strategy	**Price Premium Business model**	**%**	104%	104%	104%
Strategy	**Target price (w/o sales tax)**	**€ / product**	187.71 €	215.87 €	234.64 €
Collection	Core buying price	**€ / product**	2.00 €	3.00 €	4.00 €
Collection	Variable Collection price	**€ / product**	9.00 €	9.00 €	9.00 €
Collection	Collection transaction to user	**€ / product**	3.00 €	3.00 €	3.00 €
Collection	Collection recycling cost(+) or gain (-)*	**€ / product**	- 0.45 €	- 0.47 €	- 0.50 €
Collection	Core collection cost (including the collection efficiency if integrated)	**€ / product**	14.29 €	15.32 €	16.35 €
Distribution	Variable distribution price	**€ / product**	9.50 €	9.50 €	9.50 €
Distribution	Distribution transaction cost	**€ / product**	3.17 €	3.17 €	3.17 €
Distribution	Distribution cost	**€ / product**	12.67 €	12.67 €	12.67 €
Maintenance	Variable maintenance price	**€ / product**	12.50 €	12.50 €	12.50 €
Maintenance	Maintenance transaction cost	**€ / product**	4.17 €	4.17 €	4.17 €
Maintenance	Maintenance cost	**€ / product**	16.67 €	16.67 €	16.67 €

Cost units (yearly evolution for material 2%, for energy 3%, for workforce 5%)

Cost category	Type of costs	Cost Unit description	Unit	Factor	Type	Year				
						1	2	3	4	5
Collection phase	Management cost	€	-	Workforce	fixed	10000.00	10300.00	10609.00	10927.27	11255.09
Collection phase	Collection	€/units	PFCn	Workforce	variable	6.50	6.70	6.90	7.10	7.32
Collection phase	Collection logistics	€/units	PFCn	Energy	variable	2.50	2.63	2.76	2.89	3.04
Collection phase	Recycling cost (+)	€/units	RFCn	Material	variable	-9.00	-9.45	-9.92	-10.42	-10.94
Collection phase	Recycling cost (+)	€/units	RFCn	Material	variable	-9.70	-10.19	-10.69	-11.23	-11.79
Collection phase	Recycling cost (+)	€/units	RFCn	Material	variable	-11.00	-11.55	-12.13	-12.73	-13.37
Product A	Cores A	€/units	PFRn	Material	variable	2.00	2.04	2.08	2.12	2.16
Product A	Assembly A1	€/units	PFRn	Material	variable	28.90	29.48	30.07	30.67	31.28
Product A	Assembly A2	€/units	PFRn	Material	variable	60.70	61.91	63.15	64.42	65.70
Product A	Spare parts A1	€/units	PFRn	Material	variable	14.30	14.59	14.88	15.18	15.48
Product A	Spare parts A2	€/units	PFRn	Material	variable	31.55	32.18	32.82	33.48	34.15
Product A	Machine	€/units	PFRn	Energy	variable	2.70	2.78	2.86	2.95	3.04
Product A	Recycling cost (+)	€/units	PFRn	Material	variable	-3.50	-3.57	-3.64	-3.71	-3.79
Product A	Recycling cost (+)	€/units	PFRn	Material	variable	-5.50	-5.61	-5.72	-5.84	-5.95
Product B	Cores B	€/units	PFRn	Material	variable	3.00	3.06	3.12	3.18	3.25
Product B	Assembly B1	€/units	PFRn	Material	variable	30.35	30.95	31.57	32.20	32.85
Product B	Assembly B2	€/units	PFRn	Material	variable	63.74	65.01	66.31	67.64	68.99
Product B	Spare parts A2	€/units	PFRn	Material	variable	15.02	15.32	15.62	15.93	16.25
Product B	Spare parts B2	€/units	PFRn	Material	variable	33.13	33.79	34.47	35.16	35.86
Product B	Machine	€/units	PFRn	Energy	variable	3.00	3.09	3.18	3.28	3.38
Product B	Recycling cost (+)	€/units	PFRn	Material	variable	-3.80	-3.88	-3.95	-4.03	-4.11
Product B	Recycling cost (+)	€/units	PFRn	Material	variable	-5.90	-6.02	-6.14	-6.26	-6.39
Product C	Cores C	€/units	PFRn	Material	variable	4.00	4.08	4.16	4.24	4.33
Product C	Assembly C1	€/units	PFRn	Material	variable	33.24	33.90	34.58	35.27	35.97
Product C	Assembly C2	€/units	PFRn	Material	variable	69.81	71.20	72.63	74.08	75.56
Product C	Spare parts C1	€/units	PFRn	Material	variable	16.45	16.77	17.11	17.45	17.80
Product C	Spare parts C2	€/units	PFRn	Material	variable	36.28	37.01	37.75	38.50	39.27
Product C	Machine	€/units	PFRn	Energy	variable	3.30	3.40	3.50	3.61	3.71
Product C	Recycling cost (+)	€/units	PFRn	Workforce	variable	-4.50	-4.73	-4.96	-5.21	-5.47
Product C	Recycling cost (+)	€/units	PFRn	Workforce	variable	-6.50	-6.83	-7.17	-7.52	-7.90
Remanufacturing phase	Remanufacturing	€/hour	PFRn	Workforce	variable	10.00	10.50	11.03	11.58	12.16
Remanufacturing phase	Factory rental price	€	-	Energy	fixed	10000.00	10300.00	10609.00	10927.27	11255.09
Remanufacturing phase	Overhead costs	€	-	Energy	fixed	5000.00	5150.00	5304.50	5463.64	5627.54
Remanufacturing phase	Equipment	€	-	Workforce	fixed	7000.00	7350.00	7717.50	8103.38	8508.54
Remanufacturing phase	Management cost	€	-	Workforce	fixed	15000.00	15750.00	16537.50	17364.38	18232.59
Remanufacturing phase	Workstation costs	€	-	Energy	fixed	2000.00	2060.00	2121.80	2185.45	2251.02

Cost category	Type of costs	Cost Unit description	Unit	Factor	Type	Year				
						1	2	3	4	5
Remanufacturing phase	Inventory costs	€	-	Energy	fixed	3.50	3.61	3.71	3.82	3.94
Distribution phase	Logistics costs	€/units	PFDn	Energy	variable	2.50	2.58	2.65	2.73	2.81
Distribution phase	Packaging costs	€/units	PFDn	Material	variable	2.00	2.00	2.00	2.00	2.00
Distribution phase	Sales costs	€/units	PFDn	Workforce	variable	5.00	5.25	5.51	5.79	6.08
Distribution phase	Management cost	€	-	Workforce	fixed	5000.00	5250.00	5512.50	5788.13	6077.53
Use phase	Warranty workforce	€/units	PFUn	Workforce	variable	3.00	3.15	3.31	3.47	3.65
Use phase	Warranty spare	€/units	PFUn	Material	variable	4.50	4.59	4.68	4.78	4.87
Use phase	Warranty logistics	€/units	PFUn	Energy	variable	2.50	2.58	2.65	2.73	2.81
Use phase	Management cost	€	-	Workforce	fixed	2000.00	2040.00	2080.80	2122.42	2164.86

Processing time

Workstation type	MTM Analysis	Processing time (TMU) / analysis			Processing time (s) / analysis			Process time (s) / workstation			Changeover time (s)
		A	B	C	A	B	C	A	B	C	
Disassembly	Dis. 1	1210	1270.5	1331	43.56	45.74	47.92	177.12	185.98	194.84	223.18
	Dis. 2	630	661.5	693	22.68	23.81	24.95				
	Dis. 3	3080	3234	3388	110.88	116.43	121.97				
Cleaning	Cleaning	11015	11565.75	12116.5	396.55	416.38	436.21	396.55	416.38	436.21	499.65
Checking	Checking	4270	4483.5	4697	153.72	161.41	169.10	153.72	161.41	169.10	193.69
Grinding	Grinding	14469	15192.45	15915.9	520.90	546.94	572.99	520.90	546.94	572.99	656.33
Welding	Welding	915	960.75	1006.5	32.94	34.59	36.24	32.94	34.59	36.24	41.51
Wire Winding	Wire Winding	8845	9287.25	9729.5	318.43	334.35	350.27	318.43	334.35	350.27	401.22
Powder Coating	Powder Coating	9760	10248	10736	351.37	368.94	386.51	351.37	368.94	386.51	442.73
Assembly	Assembly 1	3440	3612	3784	123.84	130.04	136.23	193.33	202.99	212.66	243.59
	Assembly 2	670	703.5	737	24.12	25.33	26.53				
	Assembly 3	1260	1323	1386	45.36	47.63	49.90				
Packaging	Packaging	610	640.5	671	21.96	23.06	24.16	21.96	23.06	24.16	27.67
Total (in TMU)		60174	63182.7	66191.4	2166.32	2274.64	2382.96	2166.32	2274.64	2382.96	2729.57
Total (in minutes)					36.11	37.91	39.72	36.11	37.91	39.72	45.49

Simplified bill of materials with prices in €

Assem-bly	Function	Sub-component	Price per product			Replacement	Spare parts costs						Assembly Price			Dis-posal	Core price		
			A	B	C		A	B	C	A	B	C	A	B	C		A	B	C
Water pump block	Receive torque from motor to transport water from input to output valve	O-Ring	0.30	0.32	0.35	100%	0.30	0.32	0.35										
		Charge plug	0.40	0.42	0.46	100%	0.40	0.42	0.46										
		Discharge plug	0.40	0.42	0.46	100%	0.40	0.42	0.46										
		Gauge plug	0.40	0.42	0.46	100%	0.40	0.42	0.46										
		Switch plug	0.40	0.42	0.46	100%	0.40	0.42	0.46										
		Casting	6.00	6.30	6.90	5%	0.30	0.32	0.35	14.30	15.02	16.45	28.90	30.35	33.24	-3			
		Venturi pipe	1.00	1.05	1.15	5%	0.05	0.05	0.06										
		Diffuser	6.00	6.30	6.90	50%	3.00	3.15	3.45										
		Impeller	5.00	5.25	5.75	50%	2.50	2.63	2.88										
		Pump	1.00	1.05	1.15	5%	0.05	0.05	0.06										
		Pump	3.00	3.15	3.45	50%	1.50	1.58	1.73										
		Bearing	5.00	5.25	5.75	100%	5.00	5.25	5.75								14.29	15.32	16.35
Motor	Generate rotational movement, torque for Water pump using electricity	Key	0.10	0.11	0.12	100%	0.10	0.11	0.12										
		Rotor Shaft	12.00	12.60	13.80	50%	6.00	6.30	6.90										
		Mechanical	1.00	1.05	1.15	100%	1.00	1.05	1.15										
		Terminal	0.10	0.11	0.12	100%	0.10	0.11	0.12										
		Capacitor	10.00	10.50	11.50	100%	10.00	10.50	11.50										
		Casing and stator	25.00	26.25	28.75	50%	12.00	13.13	14.38	31.55	33.13	36.28	60.70	63.74	69.81	-6			
		Stand	0.50	0.53	0.58	100%	0.50	0.53	0.58										
		Stand pin	0.50	0.53	0.58	100%	0.50	0.53	0.58										
		Fairlead	6.00	6.30	6.90	5%	0.30	0.32	0.35										
		Driving cap	2.50	2.63	2.88	10%	0.25	0.26	0.29										
		Fan	2.00	2.10	2.30	10%	0.20	0.21	0.23										
		Fan cover	1.00	1.05	1.15	10%	0.10	0.11	0.12										

Investment and ROI (assumption: the equipment is always bought in January; straight line method is used)

INVESTMENT PLAN				DEPRECIATION VALUATION			
Current Assets		**Description**	**Investment in year 3 (€)**	**Depreciation rate**	**Depreciation (€)**		
					3	**4**	**5**
Workbench		20 Workbenches	6,000	20%	1,200	1,200	1,200
Tool boxes		14 tool boxes	1,400	20%	280	280	280
Freestanding shelf		08 shelves 900x1100x1000	1,600	20%	320	320	320
Conveyor		0.6 x16 m	2,500	10%	250	250	250
Mobile shelf		14 shelves 600	1,000	20%	250	250	250
Pushback rack		2 rack 1600x1700x1800	1,000	20%	200	200	200
Welding machine		2 Andeli welding machine	3,000	20%	600	600	600
Grinding machine		Universal cylindrical grinder	10,000	20%	2,000	2,000	2,000
Coating machine		Samyang Coating machine	70,000	20%	14,000	14,000	14,000
Rewinding machine		Magnet wire winding machine	12,000	20%	14,000	14,000	14,000
Compressor		Compress air central system	14,000	10%	14,000	14,000	14,000
Ultrasonic crack detector		2 Doppler detectors	6,000	20%	14,000	14,000	14,000
Forklift			6,000	20%	14,000	14,000	14,000
Construction			250,000	10%	14,000	14,000	14,000
Miscellaneous		Pallet, board, lighting	35,000	20%	14,000	14,000	14,000
Total			419,500		47,100	47,100	47,100
Cost of capital 8%	Average	**Cumulated Revenue after tax**	2,311,172	Average yearly ROI	229,446	1,344,495	737,231
		NPV revenues	1,950,376		229,446	1,573,941	2,311,172
		ROI with NPV	365%		-45%	275%	451%
	Worst	**Cumulated Revenue after tax**	2,267,074.90	Worst yearly ROI	224,270.30	1,334,451.69	708,352.91
		NPV revenues	1,914,048.30		224,270.30	1,558,721.98	2,267,074.90
		ROI with NPV	356%		-47%	272%	440%
	Best	**Cumulated Revenue after tax**	2,733,954	Best yearly ROI	330,903	1,515,627	887,423
		NPV revenues	2,310,263		330,903	1,846,530	2,733,954
		ROI with NPV	451%		-21%	340%	552%

CASE STUDY 2 – AIR CONDITIONERS

Canvas business model

Dimension	Category	Options	Collection efficiency	Identification efficiency	Reman. efficiency	Distribution efficiency	Core control	Network Transaction efficiency	Core quality	Customer demand	Bus. model premium
Canals	**Distribution canals**	Word of mouth		1			1				1
	Information canals	Cost oriented			-1						
	Sales canals	Business-to-Business	-1								2
Costs structure	**Cost advantages**	Business-to-Consumer	-2			-1	-1				-1
	Direction	Independent remanufacturers	-2								-1
Customer relationship	**Customer contact**	Low cost producer									-2
	Customer distance	OEMs	-1				1			1	-1
	Inclusion in customer	Function-oriented							-1	-1	2
	Prospection	Regional	1			1	1	1	1	2	
Customer segments	**Commercial relationship**	High	2	1					1		1
	Competition	Industrialized country	1	1			1		1	1	1
	Customer profile	Mass-market			1						
	Customer reach	High								1	-2
	Ecological awareness	Remanufacturing outsourcing	-1		-1		1	-1		1	
	Market classification	Central	2	-1	1		-1		-1		
	Market segment	Remanufacturing	1		1		1	1			
	Price sensitivity	None		-2					-1		
Key activities	**Access to cores**	Distributor						-1			
	Collection organization	Service company						-1			
	Core processes	Own capital									
		Employees									
		Qualification			1						
		Technologies									
		Buildings									
Key partners	**Value Creation Partner**	Equipment			1					1	

Key resources	**Financial resources**	Material									
	Human resources	Dynamic									1
		Functional maintenance		2		1	1		2		
		Approach of a new customer				-1		-1	-1		
	Intellectual resources	Cost reduction strategy									
		New service offer				1		-1			1
		Spare parts market protection	1						-1		
		Spare parts sourcing									
	Physical resources	Result-oriented		2	1	1	1	1	-1	2	
		Able to disassemble			1						
		Able to reassemble			2						
Revenues	**Service revenues**	Changeable spare parts			1						
Value Proposition	**Additional services**	Same							-1	1	1
		Standardized			1				1		
	Economic drivers	Same							-1	1	1
		Market price								-1	
	Form of value	Performance								1	1
	Product value	Price							-1	1	-1
		Word of mouth		1			1				1
		Cost oriented			-1						
		Business-to-Business	-1								2
		Business-to-Consumer	-2			-1	-1				-1
		Independent remanufacturers	-2								-1
	Quality	Low cost producer									-2
	Sales price	OEMs	-1				1			1	-1
	Type of value	Function-oriented							-1	-1	2
		Regional	1			1	1	1	1	2	
Business model specific values		Average influence E_d	0.09	0.57	0.75	0.33	0.60	-0.25	-0.21	0.85	0.25
		Influence weight E_s	1	4	9	2	6	-2	-3	11	4
		Absolute influence E_d	0.09	2.29	6.75	0.67	3.60	-0.50	-0.64	9.31	1.00
Standard values per business model		**0**	0.85	0.85	0.85	0.85	0.2	0.05	0.85	-0.005	0.9
		2	0.95	0.95	0.95	0.95	0.01	0.01	1	0	1.1
Company-specific ratios			0.0909	0.5714	0.7500	0.3333	0.6000	0.2500	0.2143	0.8462	0.2500
Company -specific value			0.8545	0.8786	0.8875	0.8667	0.1430	0.0450	0.8661	-0.003	0.9250

Profit and Loss statement

Revenue	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8	YEAR 9	YEAR 10	TOTAL
Sales Product A	1,554,072.21 €	4,891,174.05 €	8,516,579.66 €	9,808,649.89 €	10,313,094.74 €	9,157,975.08 €	10,005,989.08 €	54,247,534.71 €
Sales Product B	568,489.98 €	1,732,493.85 €	4,200,227.34 €	5,133,510.34 €	5,588,850.24 €	5,348,865.84 €	4,964,630.14 €	27,537,067.72 €
Sales Product C	583,057.02 €	2,235,766.22 €	3,379,047.34 €	3,121,315.33 €	2,339,299.79 €	2,311,801.45 €	2,445,630.22 €	16,415,917.38 €
Net Sales	2,705,619.21 €	8,859,434.12 €	16,095,854.34 €	18,063,475.55 €	18,241,244.78 €	16,818,642.37 €	17,416,249.44 €	98,200,519.81 €
Purchases Product A	1,035,811.01 €	3,268,335.49 €	5,555,890.25 €	6,585,994.61 €	6,708,521.85 €	5,962,533.39 €	6,500,396.87 €	35,617,483.46 €
Purchases Product B	544,454.69 €	1,560,629.30 €	2,679,397.48 €	3,387,216.82 €	3,562,619.39 €	3,394,757.33 €	3,147,350.68 €	18,276,425.67 €
Purchases Product C	286,677.27 €	1,345,059.48 €	2,175,134.49 €	2,041,244.29 €	1,532,016.47 €	1,481,269.68 €	1,624,576.80 €	10,485,978.47 €
Cost of Goods Sold	1,866,942.97 €	6,174,024.27 €	10,410,422.21 €	12,014,455.71 €	11,803,157.70 €	10,838,560.40 €	11,272,324.34 €	64,379,887.60 €
Gross Profit	838,676.24 €	2,685,409.86 €	5,685,432.13 €	6,049,019.84 €	6,438,087.07 €	5,980,081.97 €	6,143,925.10 €	33,820,632.21 €
Collection costs	- €	- €	- €	- €	- €	- €	- €	- €
Remanufacturing costs	1,259,164.30 €	1,919,834.09 €	2,623,106.03 €	2,967,469.98 €	3,047,145.57 €	3,040,017.88 €	3,210,835.54 €	18,067,573.40 €
Distribution cost	33,194.64 €	126,706.51 €	205,621.69 €	216,726.98 €	193,022.19 €	185,414.85 €	181,209.27 €	1,141,896.12 €
Warranty cost	- €	- €	- €	- €	- €	- €	- €	- €
Depreciation	49,230.00 €	49,230.00 €	49,230.00 €	49,230.00 €	49,230.00 €	49,230.00 €	- €	295,380.00 €
Operating Expenses	1,341,588.94 €	2,095,770.60 €	2,877,957.72 €	3,233,426.96 €	3,289,397.76 €	3,274,662.73 €	3,392,044.81 €	19,504,849.52 €
Income From	-502,912.70 €	589,639.26 €	2,807,474.41 €	2,815,592.88 €	3,148,689.31 €	2,705,419.23 €	2,751,880.29 €	14,315,782.69 €
Income Tax (40%)	- €	235,855.70 €	1,122,989.77 €	1,126,237.15 €	1,259,475.72 €	1,082,167.69 €	1,100,752.12 €	5,927,478.16 €
Net Income	-502,912.70 €	353,783.56 €	1,684,484.65 €	1,689,355.73 €	1,889,213.59 €	1,623,251.54 €	1,651,128.18 €	8,388,304.53 €

Value Chain determination

Activity	Element	Cost Unit	Product A	Product B	Product C
Strategy	**Market price new**	€ / product	420.00 €	441.00 €	462.00 €
Strategy	**Market price Reman**	€ / product	415.00 €	440.00 €	458.00 €
Strategy	**Price Premium Business model**	%	93%	93%	93%
Strategy	**Target price (w/o sales tax)**	€ / product	383.88 €	407.00 €	423.65 €
Collection	Core buying price	€ / product	40.00 €	40.00 €	40.00 €
Collection	Variable Collection price	€ / product	1.80 €	1.80 €	1.80 €
Collection	Collection transaction to user	€ / product	0.45 €	0.45 €	0.45 €
Collection	Collection recycling cost(+) or gain (-)*	€ / product	6.98 €	7.12 €	7.26 €
Collection	Core collection cost (including the collection efficiency if integrated)	€ / product	56.42 €	56.56 €	56.71 €
Distribution	Variable distribution price	€ / product	4.50 €	4.50 €	4.50 €
Distribution	Distribution transaction cost	€ / product	1.13 €	1.13 €	1.13 €
Distribution	Distribution cost	€ / product	5.63 €	5.63 €	5.63 €

Cost units (yearly evolution for material 2%, for energy 3%, for workforce 5%)

Cost category	Type of costs	Cost Unit description	Unit	Factor	Type	Year 4	5	6	7	8	9	10
Collection phase	Recycling cost A	€/units	RFC	Material	variabl	48.00	48.96	49.94	50.94	51.96	53.00	54.06
Collection phase	Recycling cost B	€/units	RFC	Material	variabl	48.00	48.96	49.94	50.94	51.96	53.00	54.06
Collection phase	Recycling cost C	€/units	RFC	Material	variabl	48.00	48.96	49.94	50.94	51.96	53.00	54.06
Product A	Cores A	€/units	PFR	Material	variabl	40.00	40.80	41.62	42.45	43.30	44.16	45.05
Product A	Assembly A1	€/units	PFR	Material	variabl	147.00	149.94	152.94	156.00	159.12	162.30	165.55
Product A	Assembly A2	€/units	PFR	Material	variabl	78.90	80.48	82.09	83.73	85.40	87.11	88.85
Product A	Spare parts A1	€/units	PFR	Material	variabl	45.00	45.90	46.82	47.75	48.71	49.68	50.68
Product A	Spare parts A2	€/units	PFR	Material	variabl	71.90	73.34	74.80	76.30	77.83	79.38	80.97
Product A	Machine	€/units	PFR	Energy	variabl	12.00	12.36	12.73	13.11	13.51	13.91	14.33
Product A	Recycling cost (+)	€/units	PFR	Material	variabl	2.00	2.04	2.08	2.12	2.16	2.21	2.25
Product A	Recycling cost (+)	€/units	PFR	Material	variabl	3.00	3.06	3.12	3.18	3.25	3.31	3.38
Product B	Cores B	€/units	PFR	Material	variabl	40.00	40.80	41.62	42.45	43.30	44.16	45.05
Product B	Assembly B1	€/units	PFR	Material	variabl	154.35	157.44	160.59	163.80	167.07	170.41	173.82
Product B	Assembly B2	€/units	PFR	Material	variabl	82.85	84.50	86.19	87.92	89.67	91.47	93.30
Product B	Spare parts A2	€/units	PFR	Material	variabl	47.25	48.20	49.16	50.14	51.14	52.17	53.21
Product B	Spare parts B2	€/units	PFR	Material	variabl	75.50	77.00	78.54	80.12	81.72	83.35	85.02
Product B	Machine	€/units	PFR	Energy	variabl	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Product B	Recycling cost (+)	€/units	PFR	Material	variabl	3.00	3.06	3.12	3.18	3.25	3.31	3.38
Product B	Recycling cost (+)	€/units	PFR	Material	variabl	4.00	4.08	4.16	4.24	4.33	4.42	4.50
Product C	Cores C	€/units	PFR	Material	variabl	40.00	40.80	41.62	42.45	43.30	44.16	45.05
Product C	Assembly C1	€/units	PFR	Material	variabl	169.05	172.43	175.88	179.40	182.99	186.64	190.38
Product C	Assembly C2	€/units	PFR	Material	variabl	90.74	92.55	94.40	96.29	98.21	100.18	102.18
Product C	Spare parts C1	€/units	PFR	Material	variabl	51.75	52.79	53.84	54.92	56.02	57.14	58.28
Product C	Spare parts C2	€/units	PFR	Material	variabl	82.69	84.34	86.03	87.75	89.50	91.29	93.12
Product C	Machine	€/units	PFR	Energy	variabl	12.00	12.36	12.73	13.11	13.51	13.91	14.33
Product C	Recycling cost (+)	€/units	PFR	Workforc	variabl	4.00	4.20	4.41	4.63	4.86	5.11	5.36
Product C	Recycling cost (+)	€/units	PFR	Workforc	variabl	5.00	5.25	5.51	5.79	6.08	6.38	6.70
Remanufacturing	Remanufacturing	€/hour	PFR	Workforc	variabl	10.00	10.50	11.03	11.58	12.16	12.76	13.40
Remanufacturing	Factory rental price	€	-	Energy	fixed	26437.50	27230.63	28047.54	28888.97	29755.64	30648.31	31567.76
Remanufacturing	Overhead costs	€	-	Energy	fixed	150000.0	154500.0	159135.0	163909.0	168826.3	173891.1	179107.8
Remanufacturing	Equipment	€	-	Workforc	fixed	90000.00	94500.00	99225.00	104186.2	109395.5	114865.3	120608.6
Remanufacturing	Management cost	€	-	Workforc	fixed	550000.0	577500.0	606375.0	636693.7	668528.4	701954.8	737052.6
Remanufacturing	Workstation costs	€	-	Energy	fixed	40000.00	41200.00	42436.00	43709.08	45020.35	46370.96	47762.09
Remanufacturing	Inventory costs	€	-	Energy	fixed	3.50	3.61	3.71	3.82	3.94	4.06	4.18
Distribution phase	Logistics costs	€/units	PFD	Energy	variabl	2.50	2.55	2.60	2.65	2.71	2.76	2.82
Distribution phase	Packaging costs	€/units	PFD	Material	variabl	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Processing time

Workstation type	MTM Analysis	Processing time (TMU) / analysis			Processing time (s) / analysis			Process time (s) / workstation			Changeover time (s)
		A	B	C	A	B	C	A	B	C	
Disassembly	Dis. 1	3425	3596.25	3767.5	123.30	129.47	135.63	492.17	516.78	541.39	620.13
	Dis. 2	10246	10758.3	11270.6	368.87	387.31	405.75				
Cleaning	Cleaning 1	12911	13556.55	14202.1	464.81	488.05	511.29	1430.61	1502.14	1573.67	1802.57
	Cleaning 2	3042	3194.1	3346.2	109.52	114.99	120.47				
	Cleaning 3	6508	6833.4	7158.8	234.29	246.01	257.72				
	Cleaning 4	17277	18140.85	19004.7	621.99	653.09	684.19				
Testing	Test 1	3734	3920.7	4107.4	134.43	141.15	147.87	199.41	209.38	219.35	251.26
	Test 2	1805	1895.25	1985.5	64.98	68.23	71.48				
Reman.	Reman. 1	4349	4566.45	4783.9	156.57	164.40	172.23	736.18	772.99	809.80	927.59
	Reman. 2	12350	12967.5	13585	444.61	466.84	489.07				
	Reman. 3	3750	3937.5	4125	135.00	141.75	148.50				
Assembly	Assembly 1	4215	4425.75	4636.5	151.74	159.33	166.92	773.01	811.66	850.32	974.00
	Assembly 2	17257	18119.85	18982.7	621.27	652.33	683.40				
Total (in TMU)		100869	105912.45	110955.9	3631.39	3812.95	3994.52	3631.39	3812.95	3994.52	4575.55
Total (in minutes)					60.52	63.55	66.58	60.52	63.55	66.58	76.26

Simplified bill of materials with prices in €

Asse-mbly	Function	Sub-component	Price per product			Replace ment	Spare parts costs						Assembly Price			Dis-posal	Core price		
			A	B	C		A	B	C	A	B	C	A	B	C		A	B	C
Indoor	Receive motor torque to transport water from input to output valve	Cover frame	10.0	10.5	11.5	10%	1.0	1.1	1.2	53.5	56.2	61.5	147.0	154.4	169.1	30.0	60.0	60.0	60.0
		Cross flow fan	6.0	6.3	6.9	20%	1.2	1.3	1.4										
		Cross Flow Fan Fixed Plate	4.0	4.2	4.6	20%	0.8	0.8	0.9										
		Evaporator block	85.0	89.3	97.8	10%	8.5	8.9	9.8										
		Copper pipe	6.5	6.8	7.5	100%	6.5	6.8	7.5										
		Louver	5.0	5.3	5.8	100%	5.0	5.3	5.8										
		Filtering Net	6.0	6.3	6.9	100%	6.0	6.3	6.9										
		Step motor for	2.5	2.6	2.9	100%	2.5	2.6	2.9										
		Remote controller	2.0	2.1	2.3	100%	2.0	2.1	2.3										
		Motor	10.0	10.5	11.5	100%	10.0	10.5	11.5										
		Electric Box	0.5	0.5	0.6	100%	0.5	0.5	0.6										
		Electric Box cover	0.5	0.5	0.6	100%	0.5	0.5	0.6										
		Electric control	9.0	9.5	10.4	100%	9.0	9.5	10.4										
Outdoor	Generate rotational movement, torque for Water pump using electricity	Fan blade	10.0	10.5	11.5	50%	5.0	5.3	5.8	78.9	82.8	90.7	78.9	82.8	90.7	20.0			
		Motor	6.0	6.3	6.9	100%	6.0	6.3	6.9										
		Compressor	50.0	52.5	57.5	10%	5.0	5.3	5.8										
		Condenser	70.0	73.5	80.5	10%	7.0	7.4	8.1										
		Copper Header for AC/Heating	10.0	10.5	11.5	100%	10.0	10.5	11.5										
		Copper pipe	5.7	6.0	6.6	100%	5.7	6.0	6.6										
		Expansion valve	10.0	10.5	11.5	100%	10.0	10.5	11.5										
		Compressor	1.2	1.3	1.4	100%	1.2	1.3	1.4										
		Low and high pressure valve	29.0	30.5	33.4	100%	29.0	30.5	33.4										

Investment and ROI (assumption: the equipment is always bought in January; straight line method is used)

INVESTMENT PLAN					DEPRECIATION VALUATION						
					Depreciation (€)						
Current Assets		Description	Investment in year 3 (€)	Depreciation rate	4	5	6	7	8	9	10
Workbench		32 Workbenches	16,000.00	20%	3,200	3,200	3,200	3,200	3,200	3,200	3,200
Tool boxes		26 tool boxes	3,200.00	20%	640	640	640	640	640	640	640
Freestanding shelf		03 shelves 900x1200x1500	1,500.00	20%	300	300	300	300	300	300	300
Conveyor		0.6 x 72 m	45,000.00	10%	4,500	4,500	4,500	4,500	4,500	4,500	4,500
Mobile shelf		8 shelves 600	800.00	20%	160	160	160	160	160	160	160
Pushback rack		1rack 1600x1700x1800	500.00	20%	100	100	100	100	100	100	100
Welding machine		1 TIG welding machine	1,000.00	20%	200	200	200	200	200	200	200
Grinding machine		Cylindrical grinder	3,000.00	20%	600	600	600	600	600	600	600
Brazing machine		2 Brazing machine 15kW	2,400.00	20%	480	480	480	480	480	480	480
Piping system		Compress air, gas system	14,000.00	20%	1,400	1,400	1,400	1,400	1,400	1,400	1,400
Painting booth		Booth 1.6 x 8 m and sprayers	4,500.00	10%	450	450	450	450	450	450	450
Forklift			6,000.00	20%	1,200	1,200	1,200	1,200	1,200	1,200	1,200
Construction			250,000.00	20%	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Miscellaneous		Pallet, board, lighting, lifts	55,000.00	10%	11,000	11,000	11,000	11,000	11,000	11,000	11,000
		Total	419,500		49,230	49,230	49,230	49,230	49,230	49,230	49,230
Cost of capital 8%	Avg.	**Cumulated Revenue after tax**	2,311,172	Theoretic yearly ROI	0	-502,913	353,784	1,684,485	1,689,356	1,889,214	1,623,252
		NPV revenues	1,950,376		0	-502,913	-149,129	1,535,356	3,224,711	5,113,925	6,737,176
		ROI with NPV	365%		-100%	-225%	-137%	281%	700%	1169%	1572%
	Worst	**Cumulated Revenue after tax**	4,791,700	Theoretic yearly ROI	0	-848,975	-253,950	1,180,272	1,183,027	1,365,307	1,089,073
		NPV revenues	16,015		0	-848,975	-1,102,926	77,346	1,260,373	2,625,680	3,714,753
		ROI with NPV	-96%		-100%	-311%	-374%	-81%	213%	552%	822%
	Best	**Cumulated Revenue after tax**	11,576,343	Theoretic yearly ROI	0	171,706	838,096	2,148,232	2,156,354	2,370,587	2,113,621
		NPV revenues	2,513,804		0	171,706	666,390	2,814,622	4,970,976	7,341,564	9,455,185
		ROI with NPV	524%		-100%	-143%	65%	599%	1134%	1722%	2247%

CASE STUDY 3 – CYLINDER & CYLINDER HEAD

Canvas business model

Dimension	Category	Options	Collection efficiency	Identification efficiency	Reman. efficiency	Distribution efficiency	Core control	Network Transaction efficiency	Core quality	Customer demand	Bus. model premium
Canals	Distribution canals	Physical	2							2	
	Information canals	Word of mouth		1			1				1
	Sales canals	Indirect	-1			1	-1	-1	-1	1	
Costs structure	Cost advantages	Synergy effects			2						
	Direction	Cost oriented			-1						
Customer relationship	Customer contact	Business-to-Employee	2			1	1				-2
	Customer distance	Business-to-Consumer	-2			-1	-1				-1
	Inclusion in customer	Independent repair shops	-1								-1
	Prospection	OEMs	-1				1			1	-1
Customer segments	Commercial relationship	Used products markets	-1								-1
	Competition	Function-oriented							-1	-1	2
	Customer profile	Regional	1			1	1	1	1	2	
	Customer reach	None		-1					-1	-1	-2
	Ecological awareness	Developing country	-2	-1			-1		-2		-1
	Market classification	Mass-market			1						
	Market segment	High								1	-2
	Price sensitivity	Remanufacturing outsourcing	-1		-1		1	-1		1	
Key activities	Access to cores	Central	2	-1	1		-1		-1		
	Collection organization	Remanufacturing	1		1		1	1			
	Core processes	Design for Recycling		-1					-1		
		Core collector	1		-1		-1	-1	-1	1	
		Distributor						-1			
		End customer							-1	1	
		Service company						-1			
Key partners	Value Creation Partner	Own capital									

Key resources	**Financial resources**	Employees									
	Human resources	Qualification			1						
		Knowledge		1	1						
		Technologies									
	Intellectual resources	Buildings									
		Equipment			1					1	
		Material									
		Dynamic									1
	Physical resources	Increase of sales									
		New business strategy					-1	-1			
		Spare parts market protection	1						-1		
Revenues	**Service revenues**	Spare parts sourcing									
Value Proposition	**Additional services**	Product-oriented		-1	-1		-1		1		
		Able to disassemble			1						
	Economic drivers	Able to reassemble			2						
		Changeable spare parts			1						
	Form of value	Same							-1	1	1
	Product value	Standardized			1				1		
		Same							-1	1	1
		Below market price					-1		-1	1	
		Green Marketing								1	
		Respect of legislation	1								
		Performance								1	1
	Quality	Price							-1	1	-1
	Sales price	Physical	2							2	
	Type of value	Word of mouth		1			1				1
		Indirect	-1			1	-1	-1	-1	1	
Business model specific values		Average influence E_d	0.13	-0.43	0.60	0.50	-0.14	-0.50	-0.69	0.88	-0.33
		Influence weight E_s	2	-3	9	2	-2	-4	-11	15	-5
		Absolute influence E_d	0.27	-1.29	5.40	1.00	-0.29	-2.00	-8.07	13.24	-1.79
Standard values per business model		**0**	0.8	0.8	0.8	0.85	0.3	0.05	0.8	-0.01	0.7
		2	0.9	0.9	0.9	0.95	0.1	0.01	0.9	-0.005	0.9
Company-specific ratios			0.1333	0.4286	0.6000	0.5000	0.1429	0.5000	0.7333	0.8824	0.3571
Company -specific value			0.8067	0.8214	0.8300	0.8750	0.2857	0.0400	0.8367	-0.008	0.7357

Profit and Loss statement

Revenue	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8	TOTAL
Sales Product A	1,080,519.58 €	2,737,861.94 €	3,741,942.98 €	3,843,550.68 €	4,403,810.76 €	668,399.46 €	16,476,085.39
Sales Product B	797,536.35 €	3,215,829.20 €	4,750,111.99 €	4,598,940.39 €	4,121,965.31 €	1,290,195.90 €	18,774,579.13
Sales Product C	294,524.62 €	1,888,940.40 €	3,326,274.37 €	1,206,442.69 €	1,032,718.13 €	81,762.44 €	7,830,662.65
Net Sales	**2,172,580.54 €**	**7,842,631.53 €**	**11,818,329.33 €**	**9,648,933.77 €**	**9,558,494.20 €**	**2,040,357.79 €**	43,081,327.17
Purchases Product A	222,526.17 €	984,931.05 €	1,805,705.66 €	1,501,884.61 €	279,906.49 €	5,498.35 €	4,800,452.34
Purchases Product B	201,815.73 €	1,137,451.32 €	2,264,362.41 €	1,596,055.07 €	739,168.13 €	5,622.82 €	5,944,475.47
Purchases Product C	70,553.73 €	392,050.94 €	831,842.88 €	364,172.05 €	371,615.31 €	31,621.22 €	2,061,856.14
Cost of Goods Sold	**494,895.63 €**	**2,514,433.31 €**	**4,901,910.95 €**	**3,462,111.74 €**	**1,390,689.94 €**	**42,742.39 €**	12,806,783.95
Gross Profit	**1,677,684.91 €**	**5,328,198.22 €**	**6,916,418.38 €**	**6,186,822.03 €**	**8,167,804.27 €**	**1,997,615.40 €**	30,274,543.21
Remanufacturing costs	1,001,864.36 €	2,324,006.19 €	3,630,116.18 €	3,866,550.59 €	4,503,627.34 €	1,567,933.80 €	18,314,186.40
Distribution cost	52,599.70 €	204,955.15 €	342,091.54 €	319,670.68 €	358,853.05 €	81,652.61 €	1,359,822.73
Depreciation	275,500.00 €	275,500.00 €	275,500.00 €	275,500.00 €	275,500.00 €	275,500.00 €	1,653,000 €
Operating Expenses	1,329,964.07 €	2,804,461.34 €	4,247,707.72 €	4,461,721.26 €	5,137,980.39 €	1,925,086.41 €	19,906,921.19 €
Income From Operations	347,720.84 €	2,523,736.88 €	2,668,710.66 €	1,725,100.77 €	3,029,823.88 €	72,529.00 €	10,367,622.02 €
Income Tax (33%)	114,747.88 €	832,833.17 €	880,674.52 €	569,283.25 €	999,841.88 €	23,934.57 €	3,421,315.27 €
Net Income	232,972.96 €	1,690,903.71 €	1,788,036.14 €	1,155,817.52 €	2,029,982.00 €	48,594.43 €	6,946,306.76 €

Value Chain determination

Activity	Element	Cost Unit	Product A	Product B	Product C
Strategy	Market price new	€ / product	420.00 €	441.00 €	462.00 €
Strategy	Market price Reman	€ / product	415.00 €	440.00 €	458.00 €
Strategy	Price Premium Business model	%	93%	93%	93%
Strategy	Price ratio value chain	%	74%	74%	74%
Strategy	Target price (w/o sales tax)	€ / product	383.88 €	407.00 €	423.65 €
Collection	Core buying price	€ / product	5.50 €	8.00 €	9.00 €
Collection	Variable Collection price	€ / product	3.50 €	3.50 €	3.50 €
Collection	Collection transaction to user	€ / product	1.75 €	1.75 €	1.75 €
Collection	Collection recycling cost(+) or gain (-)*	€ / product	- 1.06 €	-1.12 €	-1.17 €
Collection	Core collection cost (including the collection efficiency if integrated)	€ / product	12.26 €	15.31 €	16.49 €
Distribution	Variable distribution price	€ / product	4.50 €	4.50 €	4.50 €
Distribution	Distribution transaction cost	€ / product	2.25 €	2.25 €	2.25 €
Distribution	Distribution cost	€ / product	6.75 €	6.75 €	6.75 €

Cost units (yearly evolution for material 2%, for energy 3%, for workforce 5%)

Cost category	Type of costs	Cost Unit description	Unit	Factor	Type	Year					
						3	4	5	6	7	8
Collection phase	Recycling cost A	€/units	RFCn	Material	variable	-5.50	-5.78	-6.06	-6.37	-6.69	-7.02
Collection phase	Recycling cost B	€/units	RFCn	Material	variable	-5.78	-6.06	-6.37	-6.69	-7.02	-7.37
Collection phase	Recycling cost C	€/units	RFCn	Material	variable	-6.33	-6.64	-6.97	-7.32	-7.69	-8.07
Product A	Cores A	€/units	PFRn	Material	variable	5.50	5.61	5.72	5.84	5.95	6.07
Product A	Assembly A1	€/units	PFRn	Material	variable	18.00	18.36	18.73	19.10	19.48	19.87
Product A	Assembly A2	€/units	PFRn	Material	variable	51.00	52.02	53.06	54.12	55.20	56.31
Product A	Spare parts A1	€/units	PFRn	Material	variable	3.75	3.83	3.90	3.98	4.06	4.14
Product A	Spare parts A2	€/units	PFRn	Material	variable	16.65	16.98	17.32	17.67	18.02	18.38
Product A	Machine	€/units	PFRn	Energy	variable	3.30	3.40	3.50	3.61	3.71	3.83
Product A	Recycling cost (+)	€/units	PFRn	Material	variable	-1.00	-1.02	-1.04	-1.06	-1.08	-1.10
Product A	Recycling cost (+)	€/units	PFRn	Material	variable	-4.50	-4.59	-4.68	-4.78	-4.87	-4.97
Product B	Cores B	€/units	PFRn	Material	variable	8.00	8.16	8.32	8.49	8.66	8.83
Product B	Assembly B1	€/units	PFRn	Material	variable	18.90	19.28	19.66	20.06	20.46	20.87
Product B	Assembly B2	€/units	PFRn	Material	variable	53.55	54.62	55.71	56.83	57.96	59.12
Product B	Spare parts A2	€/units	PFRn	Material	variable	3.94	4.02	4.10	4.18	4.26	4.35
Product B	Spare parts B2	€/units	PFRn	Material	variable	17.48	17.83	18.19	18.55	18.92	19.30
Product B	Machine	€/units	PFRn	Energy	variable	8.00	8.24	8.49	8.74	9.00	9.27
Product B	Recycling cost (+)	€/units	PFRn	Material	variable	-1.05	-1.07	-1.09	-1.11	-1.14	-1.16
Product B	Recycling cost (+)	€/units	PFRn	Material	variable	-4.73	-4.82	-4.92	-5.01	-5.11	-5.22
Product C	Cores C	€/units	PFRn	Material	variable	9.00	9.18	9.36	9.55	9.74	9.94
Product C	Assembly C1	€/units	PFRn	Material	variable	19.85	20.24	20.65	21.06	21.48	21.91
Product C	Assembly C2	€/units	PFRn	Material	variable	56.23	57.35	58.50	59.67	60.86	62.08
Product C	Spare parts C1	€/units	PFRn	Material	variable	4.13	4.22	4.30	4.39	4.48	4.56
Product C	Spare parts C2	€/units	PFRn	Material	variable	18.36	18.72	19.10	19.48	19.87	20.27
Product C	Machine	€/units	PFRn	Energy	variable	4.50	4.64	4.77	4.92	5.06	5.22
Product C	Recycling cost (+)	€/units	PFRn	Workforce	variable	-1.15	-1.21	-1.27	-1.33	-1.40	-1.47
Product C	Recycling cost (+)	€/units	PFRn	Workforce	variable	-5.18	-5.43	-5.71	-5.99	-6.29	-6.60
Remanufacturing phase	Remanufacturing	€/hour	PFRn	Workforce	variable	10.00	10.50	11.03	11.58	12.16	12.76
Remanufacturing phase	Factory rental	€	-	Energy	fixed	107626.50	110855.30	114180.95	117606.38	121134.57	124768.61
Remanufacturing phase	Overhead costs	€	-	Energy	fixed	50000.00	51500.00	53045.00	54636.35	56275.44	57963.70
Remanufacturing phase	Equipment	€	-	Workforce	fixed	80000.00	84000.00	88200.00	92610.00	97240.50	102102.53
Remanufacturing phase	Management cost	€	-	Workforce	fixed	150000.00	157500.00	165375.00	173643.75	182325.94	191442.23
Remanufacturing phase	Workstation costs	€	-	Energy	fixed	40000.00	41200.00	42436.00	43709.08	45020.35	46370.96
Remanufacturing phase	Inventory costs	€	-	Energy	fixed	3.50	3.61	3.71	3.82	3.94	4.06
Distribution phase	Logistics costs	€/units	PFDn	Energy	variable	2.50	2.58	2.65	2.73	2.81	2.90
Distribution phase	Packaging costs	€/units	PFDn	Material	variable	1.00	1.00	1.00	1.00	1.00	1.00

Processing time

Workstation type	MTM Analysis	Processing time (TMU) / analysis			Processing time (s) / analysis			Process time (s) / workstation			Changeover time (s)
		A	B	C	A	B	C	A	B	C	
Disassembly	Dis. 1	2905	3050.25	3195.5	104.58	109.81	115.04	149.04	156.50	163.95	187.80
	Dis. 2	1235	1296.75	1358.5	44.46	46.68	48.91				
Cleaning	Cleaning	11015	11565.75	12116.5	396.55	416.38	436.21	396.55	416.38	436.21	499.65
Testing	Test 1	800	840	880	28.80	30.24	31.68	28.80	30.24	31.68	36.29
Reman.	Reman. 1	945	992.25	1039.5	34.02	35.72	37.42	34.02	35.72	37.42	42.87
Assembly	Assembly 1	2630	2761.5	2893	94.68	99.42	104.15	207.01	217.36	227.71	260.83
	Assembly 2	3120	3276	3432	112.32	117.94	123.56				
Total (in TMU)		23130	24286.5	25443	832.70	874.34	915.97	832.70	874.34	915.97	1049.21
Total (in minutes)					13.88	14.57	15.27	13.88	14.57	15.27	17.49

Simplified bill of materials with prices in €

Asse-mbly	Sub-component	Price per product			Replacement frequency	Spare parts costs						Assembly Price			Dis-posal	Core price		
		A	B	C		A	B	C	A	B	C	A	B	C		A	B	C
Cylinder	C Body	15.00	15.75	16.54	0.05	0.75	0.79	0.83	3.75	3.94	4.13	18.00	18.90	19.85	1.00	12.26	15.31	16.49
	Bolt flange 100 * 6	2.00	2.10	2.21	1.00	2.00	2.10	2.21										
	Dowel pin	1.00	1.05	1.10	1.00	1.00	1.05	1.10										
Cylinder head	CCH Body	5.00	5.25	5.51	0.05	0.25	0.26	0.28	16.65	17.48	18.36	51.00	53.55	56.23	4.50			
	Nut cap	3.00	3.15	3.31	0.20	0.60	0.63	0.66										
	Gasket head cover	1.00	1.05	1.10	0.30	0.30	0.32	0.33										
	Body CH	10.00	10.50	11.03	0.05	0.50	0.53	0.55										
	O-Ring	1.00	1.05	1.10	1.00	1.00	1.05	1.10										
	Cap tappet	2.00	2.10	2.21	1.00	2.00	2.10	2.21										
	Plug Spark	5.00	5.25	5.51	1.00	5.00	5.25	5.51										
	Bolt flange 110 * 6	1.00	1.05	1.10	1.00	1.00	1.05	1.10										
	Bolt	1.00	1.05	1.10	1.00	1.00	1.05	1.10										
	Sprocket cam	2.00	2.10	2.21	0.50	1.00	1.05	1.10										
	Bolt knock	5.00	5.25	5.51	0.50	2.50	2.63	2.76										
	Cover head side	5.00	5.25	5.51	0.10	0.50	0.53	0.55										
	Gasket head cover side	5.00	5.25	5.51	0.10	0.50	0.53	0.55										
	Gasket cylinder head	5.00	5.25	5.51	0.10	0.50	0.53	0.55										

Investment and ROI (assumption: the equipment is always bought in January; straight line method is used)

INVESTMENT PLAN				DEPRECIATION VALUATION						
					Depreciation (€)					
Current Assets		Description	Start in year 3 (€)	Depreciation rate	3	4	5	6	7	8
Workbench		100 Workbenches	65000	20%	13,000	13,000	13,000	13,000	13,000	13,000
Tool boxes		80 tool boxes	28000	20%	5,600	5,600	5,600	5,600	5,600	5,600
Freestanding shelf		03 shelves 900x1200x1500	1500	20%	300	300	300	300	300	300
Material kit		60 kits 600 x 1200	27000	20%	5,400	5,400	5,400	5,400	5,400	5,400
Washer machine		10 STW-50 1.5HP	35000	20%	7,000	7,000	7,000	7,000	7,000	7,000
Shot blasting machine		10 machines 24kw	65000	20%	13,000	13,000	13,000	13,000	13,000	13,000
Thermal cleaning machine		10 machines 6kw	10000	20%	2,000	2,000	2,000	2,000	2,000	2,000
Ultrasonic cleaner		10 Cleaner 480W	8500	20%	1,700	1,700	1,700	1,700	1,700	1,700
Ultrasonic scanner		10 Doppler scanner	38000	20%	7,600	7,600	7,600	7,600	7,600	7,600
Pressure test machine		Delta 6000	43000	20%	8,600	8,600	8,600	8,600	8,600	8,600
Welding machine		10 TIG welding machine	21000	20%	4,200	4,200	4,200	4,200	4,200	4,200
Grinding machine		10 Cylindrical grinder	75000	20%	15,000	15,000	15,000	15,000	15,000	15,000
Seat facing machine		20 HT-50-829 (5.35kW)	44000	20%	8,800	8,800	8,800	8,800	8,800	8,800
Boring machine		Cylinder Boring 42-180 (3.7kW)	110000	20%	22,000	22,000	22,000	22,000	22,000	22,000
Shaping machine		20 machines B5032 (4kW)	140000	20%	28,000	28,000	28,000	28,000	28,000	28,000
Construction			750000	10%	75,000	75,000	75,000	75,000	75,000	75,000
Miscellaneous		Pallet, board, lighting, lifts	583000	10%	58,300	58,300	58,300	58,300	58,300	58,300
		Total	711,000		275,500	275,500	275,500	275,500	275,500	275,500
Cost of capital 8%	Avg.	**Cumulated Revenue after tax**	5,526,219	Theoretic yearly ROI	-232,973	1,690,904	1,788,036	1,155,818	2,029,982	-48,594
		NPV revenues	3,934,354		-232,973	1,923,877	3,711,913	4,867,730	6,897,712	6,946,307
		ROI with NPV	453%		-67%	171%	422%	585%	870%	877%
	Worst	**Cumulated Revenue after tax**	2,727,147	Theoretic yearly ROI	-107,246	705,431	708,704	326,641	1,233,194	-139,577
		NPV revenues	1,308,174		-107,246	598,185	1,306,889	1,633,531	2,866,725	2,727,147
		ROI with NPV	84%		-115%	-16%	84%	130%	303%	284%
	Best	**Cumulated Revenue after tax**	8,225,424	Theoretic yearly ROI	391,481	1,973,411	2,142,475	1,425,512	2,216,956	75,590
		NPV revenues	4,802,923		391,481	2,364,892	4,507,367	5,932,878	8,149,834	8,225,424
		ROI with NPV	576%		-45%	233%	534%	734%	1046%	1057%