Demanufacturing and Remanufacturing Systems for Circular Economy

Prof. Tullio Tolio

20-21st September 2017, Budapest, Hungary
De– and Remanufacturing and Circular Economy

Demanufacturing and Remanufacturing (De-and Remanufacturing) includes the set of technologies and systems, tools and knowledge-based methods to systematically recover, reuse, and upgrade functions and materials from industrial waste and post-consumer products, to support a sustainable implementation of manufacturer-centric Circular Economy businesses.

Circular Economy requires a multi-disciplinary and multi-level approach.

EU – Towards a circular economy, a zero waste programme for Europe, COM (2014) 398 final
A new industrial model that decouples revenues from material input, and production from resource consumption is needed for achieving a sustainable development path, both in early-industrialized and in emerging countries.
At technical levels, different business options for Circular Economy have been proposed to generate benefits by exploiting different value-creation mechanisms:

Water, material, Energy

Gathering of Core Resources
Solid Waste, Wastewater

Primary Material Processing
Solid Waste, Wastewater

Production
Solid Waste, Wastewater

Packaging & Distribution
Solid Waste, Wastewater

Use/Service

Collection
Solid Waste, Wastewater

Disposal
Solid Waste, Wastewater

Reuse

Repair

Remanufacturing for function restore / upgrade

Recycling (Closed Loop - upcycling)

Recycling (Open Loop - downcycling)

What are the operational implications for manufacturers while introducing these Circular Economy business options?

A new manufacturer-centric Circular Economy model is needed. It grounds on the products, processes and manufacturing systems Co-evolution framework.

De-and Remanufacturing Vision and Objectives

Product

System

Manufacturing

De-Reman

Logistics

Logistics

Business Model

Global Market
Vision: Manufacturer-centric Circular Economy

Manufacturer’s Value-chain and Business Model

Company Knowledge Base

Process

Product

System
  Manufacturing
  De-Reman

Logistics

Global Market

Pre-use products

Post-use products
Industrial Motivation

Producer-centric real cases have been formalized from the automotive, railway, electronics, aerospace, heavy machinery and industrial machine industries:

- **Reuse** of copy machines at **Ricoh**.
- **Remanufacturing for function upgrade** of construction and mining equipment at **Komatsu**.
- **Remanufacturing for function restore** of mechatronic breaking system components in the rail industry at **Knorr Bremse**.
- **Remanufacturing for function restore** of mechatronic components in the automotive industry at **Robert Bosch**.
- **Closed-loop recycling** of car components and materials at **Renault**.
- **Closed-loop and open-loop recycling** of aircrafts at **Airbus**.
- **Closed-loop recycling** in the electronics industry at **Mitsubishi**.
“Premium quality remanufactured products are set to play an even more important part in Knorr-Bremse’s business... And so we are bundling our remanufacturing expertise and increasing our production capacities”. Wolfgang Krinner, Member of the Executive Board.

The current remanufacturing process is carried out in a plant of 9.000 m² for 300 individual product types.

1 - Remanufacturing decisions are taken by the operator (Standard Operations Sheets – SOS)
2 - The disassembly is performed manually.
3 - Cleaning and refurbishing are semi-automated.
4 - The PCB is manually repaired.
5 - All re-assembly operations are performed in the main line (Germany)

“Detecting potential resources in end-of-life products and safeguarding their technical and economic value is a new, and virtuous, way of sharpening your competitive edge. Who is better able than the producer of the goods and corresponding services to control these resources, ensure their quality and traceability, and make optimum use of them”. The vision of Jean-Philippe Hermine, Head of the Environmental Plan of the Renault group.

Renault’s plant in Choisy-le-Roi, near Paris, remanufactures automotive engines, transmissions, injection pumps, and other components for resale.

Renault contributes to the collection and processing of the 25% of the total End-of-Life vehicles (ELVs) in France through Indra, operating a network of 400 dismantlers processing more than 95,000 vehicles in 2015.
Closed-loop Recycling for material re-use

Following the enactment of the home appliance recycling law in Japan in 1998, Mitsubishi Electric Corporation introduced in 2010 a large-scale high-purity plastic recycling system, enabling closed-loop recycling of shredded plastic mixtures.

With this system, the company secured a stable supply of high quality plastics, also reducing the cost for producing new home appliances.
The reported industrial cases support these considerations:

- Circular Economy is already a profitable business opportunity for manufacturers in different sectors.
- The application of Circular Economy businesses is not in contrast but, in fact, is highly synergic with new product manufacturing operations.
- Uncertainties in product returns and market demand are the major causes of complexity in de-and remanufacturing systems, with respect to manufacturing systems.
- Product information plays an important role in the decision making process about de-and remanufacturing operations, and this feature provides competitive advantage to the manufacturer in the implementation of circular businesses.
- The role of advanced de-and remanufacturing technologies and systems is fundamental to achieve the required quality and efficiency of the regeneration process.
- The profitability of the business is strongly influenced by manufacturers’ product design decisions.
- A value-chain and business model reconfiguration may be needed while shifting to new Circular Economy businesses.
### Challenges and requirements for De- and Remanufacturing systems

<table>
<thead>
<tr>
<th>Global trends</th>
<th>Challenges and Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short life cycle of products and high product variety.</td>
<td>Flexibility and reconfigurability.</td>
</tr>
<tr>
<td>High variability in the conditions of post-consumer parts.</td>
<td>Variability of process sequences and processing times.</td>
</tr>
<tr>
<td>Pressure on costs and efficiency.</td>
<td>Need for hybrid automation solutions.</td>
</tr>
<tr>
<td>Poor information about return products.</td>
<td>• Need for ICT solutions and big data management systems.</td>
</tr>
<tr>
<td>High fluctuation in materials’ value.</td>
<td>• Need for in-line part and materials inspections.</td>
</tr>
<tr>
<td>Increasing product complexity.</td>
<td>Emphasis on business models, inventory and production planning.</td>
</tr>
<tr>
<td>Increasing quality requirements on recovered components/materials.</td>
<td>• Need for knowledge based tools.</td>
</tr>
<tr>
<td>Increasing attention on safety and ergonomics.</td>
<td>• Involvement of the manufacturer.</td>
</tr>
<tr>
<td></td>
<td>Need for automation, repeatability of the processes and quality assurance.</td>
</tr>
<tr>
<td></td>
<td>Need for human-centric design of disassembly/or sorting workstations.</td>
</tr>
</tbody>
</table>

In line with these requirements, methodologies, tools and enabling technologies for the **smart de-and remanufacturing systems of the future** are needed.
A simple taxonomy of de-and remanufacturing processes is proposed. The goal of this taxonomy is the positioning of each process in a typical de-and remanufacturing process-chain, highlighting its function and its scope.

The most promising physical and digital emerging technologies towards smart de-and remanufacturing systems of the future are:

<table>
<thead>
<tr>
<th>Process Stage</th>
<th>Emerging Enabling Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials and functions liberation</td>
<td>Automated disassembly via cognitive robotics; Human–Robot cooperation; Active disassembly</td>
</tr>
<tr>
<td>(disassembly and size reduction)</td>
<td></td>
</tr>
<tr>
<td>Sorting and Separation</td>
<td>Automatic Sorting; Robotic Sorting</td>
</tr>
<tr>
<td>End-recovery</td>
<td>Solid-state recycling</td>
</tr>
<tr>
<td>Inspection</td>
<td>Hyper-Spectral Imaging; Multi-sensor systems; Embedded Sensors; Internet of Things (IoT)</td>
</tr>
<tr>
<td>Cleaning</td>
<td></td>
</tr>
<tr>
<td>Reconditioning</td>
<td>Additive manufacturing; Hybrid additive and subtractive technologies</td>
</tr>
<tr>
<td>Logistics</td>
<td>Flexible and reconfigurable automation; Distributed control; Cyber-physical Systems</td>
</tr>
</tbody>
</table>
Emerging technologies - Disassembly

Emerging Technology: Cognitive Robotics

Integrates a vision system, a knowledge base, and an actuation system
Self-learning capabilities
Supports human assistance

Contribution to smart de-and remanufacturing systems

Easy system reconfiguration
Process plans adaptation to parts type and condition variability
Applicable to small lots

Current TRL
TRL: 7-8

Limitations and challenges
- Time consuming during the learning process
- High installation cost
- Need skilled operators

Architecture: “Closed Perception-Action loop”

## Emerging technologies - Disassembly

<table>
<thead>
<tr>
<th>Emerging Technology: Collaborative disassembly by human-robot cooperation</th>
<th>Shared workspace between the robot and the human. The robot executes low value tasks, while the human performs knowledge-intensive tasks (e.g. extraction of valuable components)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution to smart de-and remanufacturing systems</td>
<td>High system flexibility</td>
</tr>
<tr>
<td></td>
<td>Process plans re-allocation between the human and the robot to handle variability</td>
</tr>
<tr>
<td></td>
<td>Applicable to small lots</td>
</tr>
<tr>
<td>Current TRL</td>
<td>TRL: 7-8</td>
</tr>
<tr>
<td>Limitations and challenges</td>
<td>- Operators’ safety issues</td>
</tr>
<tr>
<td></td>
<td>- Installation costs</td>
</tr>
<tr>
<td></td>
<td>- Need skilled operators</td>
</tr>
</tbody>
</table>

Emerging technologies – End-recovery

<table>
<thead>
<tr>
<th>Enabling Technology: Solid-State Recycling</th>
<th>Re-production of light metals in bulk and sheet components without material fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution to smart de-and remanufacturing systems</td>
<td>Direct forming of the recovered material into the final component</td>
</tr>
<tr>
<td>Contribution to smart de-and remanufacturing systems</td>
<td>Enables manufacturer re-use of recovered material and waste</td>
</tr>
<tr>
<td>Current TRL</td>
<td>TRL: 8-9</td>
</tr>
<tr>
<td>Limitations and challenges</td>
<td>Needs highly purified material in input (e.g. metal chips)</td>
</tr>
<tr>
<td>Limitations and challenges</td>
<td>Applicable only to a small range of metals</td>
</tr>
</tbody>
</table>

### Emerging technologies – Inspection

**Emerging Technology: HyperSpectral Imaging**

- Detection (signal)
- Recognition (objects)
- Classification
- Material Characterisation

**Contribution to smart de- and remanufacturing systems**

- On-line material characterization: full material data storage and traceability
- Enables in-line monitoring and process control by CPSs

**Current TRL**

- TRL: 9 (few sectors)

**Challenges and limitations**

- Algorithms customization
- Fine particles characterization
- Detection problems: shadows, specular reflection, edge effect

---


# Emerging technologies – Reconditioning

| Enabling Technology: Additive Manufacturing and hybrid processes. | Defect regeneration by additive processes from digital product data  
Applied to large metal parts, typically molds and dies, turbines, or to polymeric small spare parts |
|---|---|
| **Contribution to smart de- and remanufacturing systems** | Flexibility in processing free-form shapes (damaged parts)  
Ability to produce functional graded materials  
Suited for parts functionality upgrades (hybrid processes) |
| **Current TRL** | TRL: 7-8 |
| **Limitations and challenges** | Limited to high added-value parts.  
Involvement of the manufacturer  
Surface roughness limitations |

Gas turbine burner tip repair (Siemens AG 2014)

Aeronautics turbine blades

---

Navrotsky, 2014, 3D printing at Siemens Power Service, Siemens.
De-and Remanufacturing Planning and Control

- Impact of Product Design.
- Post-use product return forecasting and control.
- Post-use product characterization.
- Process-chain planning
- Process control by Cyber-Physical Systems (CPSs).
- Production planning and control.

De-and Remanufacturing System Design

- Business Models.
- System engineering.
- Reverse logistics network configuration.
Problem: how can the quantity and quality of return products be forecasted and controlled for robust de-and remanufacturing planning?

Statistical methods and tools have been developed to forecast product returns as a function of:

- **Technological factors:** innovation cycles, product reliability and durability.
- **Non-technological factors:** social factors, users’ behavior.


De-and Remanufacturing systems engineering

**Problem:** to design de-and remanufacturing systems in order to achieve target performance goals.


Most recent approaches consider a manufacturer-centric hybrid forward and reverse logistics network, operating pre-use and post-use product distribution.

Future Research Priorities

Relevant gaps have been identified which constitute future research priorities in view of the implementation of new manufacturer-centric circular economy businesses.

- Circular Economy Engineering
- Design of circular factories
- Zero-defect de-and remanufacturing
- Automation level in de-and remanufacturing systems
- Adaptable de-and remanufacturing systems
- Digital factory technologies
- Legislation aware de-and remanufacturing design and planning
- New circular business models and value-chains
Social benefits of De-and Remanufacturing

Developing new technologies, systems and strategies for De-and Remanufacturing will bring social benefits worldwide:

- **New jobs** coupled with technological and automation innovations, due to the increased competitiveness for the manufacturers;
- **New efficient and effective technologies and systems** to be exported also to emerging countries;
- **Cheaper products (frugal innovation. e.g. Philips Healthcare)**: it enables manufacturers to offer affordable high-quality products in the emerging global markets.
- **Customers Loyalty** by offering to customers a range of services covering more than just the sale and maintenance phases.
- **Environmental and Energy savings**: raw material extraction is much more demanding from an energy point of view;
- **Robustness** in terms of independency from fluctuations and turbulence in the primary material market (e.g. for rare earths).
For more information:

Tullio Tolio, Alain Bernard, Olga Battaia, Marcello Colledani, Joost Duflou, Sami Kara, Guenther Seliger, Shozo Takata

Design, Management and Control of Demanufacturing and Remanufacturing Systems

CIRP Annals 2017 vol. II
Demanufacturing and Remanufacturing Systems for Circular Economy

Prof. Tullio Tolio

20-21st September 2017, Budapest, Hungary
Design, Management and Control of Demanufacturing and Remanufacturing Systems

Tullio Tolio*1,2 (1), Alain Bernard3 (1), Olga Battaia7, Marcello Colledani1,2 (2), Joost Duflo6 (1), Sami Kara4 (1), Guenther Seliger5 (1), Shozo Takata8 (1).

1 Politecnico di Milano, Department of Mechanical Engineering, Via la Masa, 1, 20156, Milan, Italy.
2 ITIA-CNR, Institute of Industrial Technologies and Automation, Via Bassini 15, 20133, Milan, Italy
3 Ecole Centrale de Nantes, 1, rue de la Noé, 92101, Nantes, France
4 The University of New South Wales, Faculty of Engineering, 2052, Sydney, Australia.
5 TU Berlin - IWF, Pascalstr. 8-9, 10587, Berlin, Germany
6 KU Leuven, Celestijnenlaan 300, 2422 3001 Heverlee – Leuven, Belgium
7 Institute Supérieur de l'Aéronautique et de l'Espace, ISAE-Supaero, Toulouse, France.
8 School of Creative Science and Engineering, Waseda University, Tokyo, Japan.

Supporting STCs: STC O, STC Dn, STC A.
Economic Benefits of Circular Economy

Shifting toward a circular economy model would deliver better outcomes for the European economy and yield annual benefits of up to €1.8 trillion by 2030.

Annual total cost of producing and using primary resources, EU-27, euros trillion

Source: Europe’s circular-economy opportunity
McKinsey Center for Business and Environment September 2015
De-and Remanufacturing supporting Circular Economy practices have potential to bring 80%–90% savings in raw materials and energy consumption with respect to the production of the same goods in the traditional linear model.

Example: Benefits of Remanufacturing in the automotive industry (Electronic Air Control unit).

[Source Kohler: D., Mechatronic Remanufacturing at Knorr-Bremse Commercial Vehicles Systems (CVS)].

Without a rethinking of how society uses materials in the linear economy, elements such as gold, silver, indium, iridium, tungsten and many others vital for industry could be depleted within the next 5 to 50 years.
Evolution of the concept of *Circular Economy*

Theory of **“Regenerative Design”** by Lyle introduced in the late 70s the idea of linking sustainable development to the concept of resource regeneration.

**“Cradle-to-Cradle”** design: It is an economic, industrial and social framework that aims at creating systems that are not only efficient but also essentially waste free. This model was applied to industrial design and manufacturing, social systems and urban environments.

**“Industrial Ecology”**: the study of material and energy flows through industrial systems. It adopts a systemic point of view, designing production processes in accordance with local ecological constraints, while looking at their global impact from the outset.

**“Blue Economy”**: Originated by Pauli, collected practical cases where the resources are connected in cascading systems and the waste of one product becomes the input to create a new cash flow.
Circular Economy: Value Creation Mechanisms

The modern concept of “Circular Economy” can be attributed to the MacArthur Foundation. Value is created through four major mechanisms:

The power of inner circle: the closer the product gets to direct reuse, the larger the cost savings will be in terms of material, labour, energy, capital and the associated externalities.

The power of circling longer: value created by keeping products, components, and materials in use longer within the Circular Economy. This can be achieved by enabling more cycles or by spending more time within a single cycle.

The power of cascaded use: value created by using discarded materials from one value chain as by-products, replacing virgin material in another.

The power of pure circles: uncontaminated material streams increase collection and redistribution efficiency while maintaining quality.
Summary figures.

- 8 authors from 3 continents.
- 25 pages.
- 7 industrial real cases.
- 15 figures.
- 311 references.
A simple taxonomy of de- and remanufacturing processes is proposed. The goal of this taxonomy is the positioning of each process in a typical de- and remanufacturing process chain, highlighting its function and its scope.

The most promising physical and digital emerging technologies towards smart de- and remanufacturing systems of the future are revised.

<table>
<thead>
<tr>
<th>Process Stage</th>
<th>Emerging Enabling Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials and functions liberation.</td>
<td>Automated disassembly via cognitive robotics; Human–Robot cooperation; Active disassembly.</td>
</tr>
<tr>
<td>Sorting and Separation.</td>
<td>Automatic Sorting; Robotic Sorting.</td>
</tr>
<tr>
<td>End-recovery.</td>
<td>Solid-state recycling.</td>
</tr>
<tr>
<td>Inspection.</td>
<td>Hyper-Spectral Imaging; Multi-sensor systems; Embedded Sensors; Internet of Things (IoT).</td>
</tr>
<tr>
<td>Reconditioning.</td>
<td>Additive manufacturing; Hybrid additive and subtractive technologies.</td>
</tr>
<tr>
<td>Logistics.</td>
<td>Flexible and reconfigurable automation; Distributed control; Cyber-physical Systems.</td>
</tr>
</tbody>
</table>
At technical levels, different business options for Circular Economy have been proposed to generate benefits by exploiting different value-creation mechanisms:

- **Remanufacturing for function restore / upgrade**
- **Recycling (Closed Loop - upcycling)**
- **Recycling (Open Loop - downcycling)**

What are the operational implications for manufacturers while introducing these Circular Economy business options?
De-and Remanufacturing Vision and Objectives

Sector 1: Business Model

Sector 2: Product

Sector 3: Cross-sectorial value-chains

- System
- Logistics

Global Market

Manufacturing
De-ReMan

Process

Vision and Objectives

Global Market

Logistics

Cross-sectorial value-chains
# Emerging technologies - Sorting

## Emerging Technology: automated robotic sorting

- Object recognition and robotic actuation of the sorting process
- Easy and safe integration in industrial environment
- Fast sorting

## Contribution to smart de-and remanufacturing systems

- Easy reconfiguration
- Adaptable to different material properties (size, shape, materials)

## Current TRL

TRL: 9 (building waste)

## Limitations and challenges

- Complex for small particles.
- Complex programming.

### Example: Zen Robotics

Emerging technologies – Disassembly

Emerging Technology: Active Disassembly

- Reversible and detachable joints for active disassembly.
- Life-cycle cost reduction

Contribution to smart de-and remanufacturing systems

- Fast localization of fasteners
- Short and repeatable disassembly tasks.

Current TRL

TRL: 7-8

- Complex product design.
- Initial cost
- Interaction with product operating conditions.

Limitations and challenges

- Complex product design.
- Initial cost
- Interaction with product operating conditions.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working principle</td>
<td>Phase change materials</td>
<td>Compression of closed-cell foam</td>
<td>Damping by elastomer</td>
</tr>
<tr>
<td>Example</td>
<td>Component A</td>
<td>Component A</td>
<td>Component A</td>
</tr>
<tr>
<td></td>
<td>Component B</td>
<td>Component B</td>
<td>Component B</td>
</tr>
<tr>
<td></td>
<td>Microspheres</td>
<td>Closed cell foam</td>
<td>Elastomer</td>
</tr>
<tr>
<td></td>
<td>Double sided tape</td>
<td>Snap-fit</td>
<td>Screw</td>
</tr>
<tr>
<td>Required installation</td>
<td>Oven</td>
<td>Pressure room</td>
<td>Manual disassembly station</td>
</tr>
</tbody>
</table>


Social Benefits at European Level: effect on jobs

**FIGURE 17 QUALITATIVE EMPLOYMENT EFFECTS OF A CIRCULAR ECONOMY TRANSITION**

<table>
<thead>
<tr>
<th>Line Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>EU employment today&lt;br&gt;• 218 million jobs in EU-28, 2014&lt;br&gt;• Unemployment rate: 10.2%</td>
</tr>
<tr>
<td><strong>Direct effects</strong></td>
<td>Waste and recycling sectors&lt;br&gt;• Today -2.3 million jobs, -1% of EU jobs’&lt;br&gt;New jobs from increased recycling, reverse logistics, secondary markets</td>
</tr>
<tr>
<td></td>
<td>Raw material sectors&lt;br&gt;• Substitution from raw materials to secondary implies less demand for virgin raw materials&lt;br&gt;Some of the resulting employment loss outside EU</td>
</tr>
<tr>
<td></td>
<td>Manufacturing sector&lt;br&gt;• Today, 30 million manufacturing jobs, -14% of EU jobs&lt;br&gt;New jobs due to upgrade, repair, re-manufacturing activities (labour intensive)&lt;br&gt;Jobs loss in new products manufacturing&lt;br&gt;Net effect likely to differ substantially between sectors and companies</td>
</tr>
<tr>
<td><strong>Indirect effects</strong></td>
<td>Manufacturing&lt;br&gt;• Possible price increase on materials reduce demand&lt;br&gt;Some of the resulting employment loss outside EU</td>
</tr>
<tr>
<td></td>
<td>Raw material sectors&lt;br&gt;<strong>Induced effects</strong>&lt;br&gt;Increased consumption in all sectors&lt;br&gt;<strong>Increased consumption driven by lower prices</strong></td>
</tr>
<tr>
<td></td>
<td>“Eco innovation effect”&lt;br&gt;<strong>New jobs created by innovation and investments from circular economy transition</strong></td>
</tr>
<tr>
<td><strong>Circular economy vision</strong></td>
<td>Potential new EU employment base&lt;br&gt;• Overall positive circular economy effect on jobs&lt;br&gt;More important are general labour market policies about gender inclusion, retirement age, and structural barriers regarding entry salaries, etc.</td>
</tr>
</tbody>
</table>

Source: Europe’s circular-economy opportunity. McKinsey Center for Business and Environment September 2015