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De-Manufacturing Systems

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Abstract

De-Manufacturing Systems allow implementing optimized End-Of-Life strategies and are necessary to support a sustainable and competitive Manufacturing/De-Manufacturing integrated paradigm. However, available technologies, management methods and business models present several limitations that make landfill and, at a lower extent, materials recycling, the most diffused End-Of-Life practices. To overcome these limitations, this paper proposes an integrated multi-disciplinary research framework addressing single technologies improvement, system integration and business model coherency. The main challenges and research opportunities are presented that can boost the development of sustainable De-manufacturing Systems at industrial level.

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1. Introduction and challenges

Manufacturing is a fundamental pillar of modern society, significantly contributing to employment and welfare. Manufacturing is necessary to keep high value-added knowledge and competences in high-wage countries, which are key competitive factors of advanced economies. It is an indispensable element of the innovation chain: manufacturing enables technological innovations to be applied in goods and services, making new products affordable and accessible to a multitude of consumers, thus increasing societal and economic benefits. However, recently, concerns have been raised on the energy and resource efficiency of manufacturing operations. As a matter of fact, manufacturing absorbs a significant fraction of the produced energy and materials. For example, it is responsible for the consumption of more than one third of the primary energy produced [1]. For these reasons, it is of paramount importance to propose new paradigms for sustainable and competitive manufacturing. Within this scope, on the one hand, it is necessary to develop processes, technologies and methods decreasing the energy and material consumptions of manufacturing activities [2]. On

the other hand, End-Of-Life (EOL) processes must be viewed under an integrated Manufacturing/De-Manufacturing perspective, thus supporting the reduction of primary raw materials consumed during the manufacturing operations. De-Manufacturing can be defined as the “break down of a product into its individual parts with the goal of reusing and remanufacturing parts, or recycling the remainder of the components” [3]. A De-Manufacturing strategy should find the right mix between (i) product remanufacturing and re-use, (ii) sub-assemblies and components re-use within manufacturing, (iii) material recycling and recovery, (iv) incineration and (v) waste disposal in landfills [4] to maximize the residual value of end-of-life products and to minimize the environmental impact.

In order to push the establishment of structured De-Manufacturing operations, different countries are pursuing this issue through regulations. For example, in Europe the regulation fixes recycling targets for Waste Electrical and Electronic Equipment (WEEE) and End of Life Vehicles (ELVs) – EU Directives 2012/19/EU and 2000/53/EC. These regulations, however, are targeted to specific manufactured products (for example, many industrial products such as

machine tools, robots, trains, etc., are not included in this legislation). In addition, regulations set a normative framework to organize EOL tasks, but the overall performance depends on the quality and efficiency of the De-Manufacturing Systems. Nowadays, available technologies, management methods and business models constitute serious barriers to the development of successful De-Manufacturing systems. In fact, for many high-tech products, the only available end-of-life treatments are open-loop recycling of materials, to be sold in the secondary raw material market, or landfilling. These businesses are well-established but less favorable in terms of recovery of value added to manufacturing [3] [4]. They are traditionally conducted with massive use of manual operations and with poor support of advanced technology and automation.

In order to boost De-Manufacturing as a new competitive paradigm it is important to define the conditions for a profitable sustainable business. This implies the solution of technological, economic and social issues that, in turn, pose significant multi-disciplinary research challenges. This paper formulates the concept of De-Manufacturing Systems, provides example of the potential impact of these solutions in a growing sector, the mechatronic component industry, and sets the framework for future research in this area.

2. De-Manufacturing systems

A De-Manufacturing System can be defined as the set of resources (human and technological), organization, IT infrastructure and associated business model to enable product De-Manufacturing (Fig. 1).

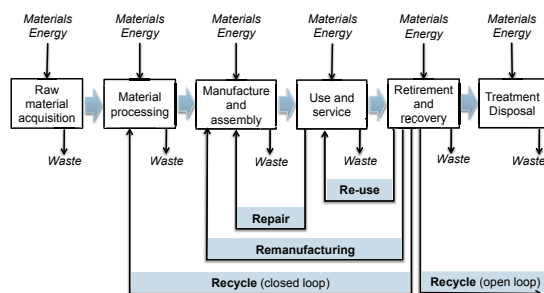


Figure 1 – Products and materials Life Cycle

De-manufacturing processes typically include disassembly, remanufacturing, recycling and recovery processes. Disassembly is generally the first step of the process. It is usually performed with the scope of isolating (i) hazardous components that cannot enter the recycling flow, (ii) re-usable parts with high residual value, (iii) parts that need to go through a dedicated recycling process chain. Manual disassembly is typically implemented at the state of the art.

Remanufacturing entails renovating used parts or components so that they can perform their function similar to new ones. Remanufacturing generally consists in dismantling the used units into their components, inspecting these components, repairing defective components or replacing them with new ones, reassembling the units, readjusting as

necessary and submitting them to the final quality test, that usually the same used for new manufactured parts. Remanufacturing is recognized to be the most beneficial end-of-life treatment. It preserves more or less 85% of the initial value, while recycling preserves almost 7.5% of initial value. Remanufacturing processes use 20-25% of the energy needed to manufacture the same product. The cost of remanufacturing can be between 45% and 65% less than the manufacturing cost. Remanufactured components are traditionally not re-used in the manufacturing process to be assembled in new products, although their quality could support this model. Remanufactured components are typically sold in the aftermarket as spare parts. For example, in the automotive industry, of the total gross profit of the car manufacturer, the new car sells contributes to the 18%, the service generates 14% while the spare parts market generates 39%.

Recycling is mainly performed by mechanical processes or by thermal processes. Mechanical recycling systems are multi-stage systems including size-reduction and separation technologies. The scope of size-reduction technologies is to (i) reduce the size of the particles in favor of downstream separation processes, (ii) liberate inhomogeneous particles thus increasing the quality of the separation process. The scope of separation stages is to split a mixed input stream into two or more output streams in which the concentration of target materials is greater than in the input stream. In recycling industry, mechanical separation is performed by a series of separation stages involving different separation technologies that classify materials on the basis of their properties. A separation process creates an environment in which particles with a high value of the property move differently from those with a low value of the property. Under ideal separation conditions, the inspection will be perfectly accurate and the material flow will be correctly classified. However, in the real world, random disturbances cause "contamination" of the output flows, where materials are wrongly classified. Thermal recycling processes are typically based on pyrolysis. This process enables to separate organic from non-organic fractions. However, although improvements have been proposed in the last years, pyrolysis generates serious environmental concerns due to the energy required for the process and the need for emissions treatment plants. For some materials, recycling processes enable to reach target grades that are comparable to market requirements (copper, aluminum). Otherwise, recovery processes need to be implemented.

Recovery processes make use of chemical reactions to separate the target materials at very high grade levels. They are typically performed in batches. One of the most advanced technology in this field is hydro-metallurgical processes [15]. These processes have recently been proved to be more sustainable than traditional metallurgical recovery processes. Nowadays, there are several limitations that prevent companies from implementing a successful De-Manufacturing System. First, the inefficiency of disassembly processes was pointed out as one of the major limitations. The low productivity and the high labor cost of manual disassembly in high-wage countries are not compatible with the residual value of many disassembled products. An extreme

disassembly process efficiency increase (65%-80%) would be required to make automatic disassembly a convenient strategy for products such as mobile phones and personal computers [3]. On the other hand, the implementation of automated disassembly is made technically complex by the high variability of input materials and their quality conditions. This would require flexible systems able to detect the type and conditions of parts to be disassembled and to adapt to their shape and wear conditions, both at macro-level, for the mechanical parts, and micro-level, for electronic components. Consequently, successful disassembly automated systems are rare in practice, are dedicated to specific products and require considerable investments (“Sony Minidisc” [2], “Fuji single-use camera” [5]). The most spread disassembly solution is currently manual disassembly supported by specific tools, such as manual automated disassembly toolkits and disassembly-oriented fasteners, while fully automated flexible solutions implying robots and adaptive systems are still an academic target and are in their early conception phase [3] [5]. A barrier to automated disassembly is surely the lack of EOL-oriented design practices [3] [6] [7].

Similar limitations are also found at mechanical shredding and separation process level. In spite of the high variability in the end-of-life products and material mixtures to be recovered, state-of-the-art mechanical recycling systems are extremely rigid. They feature a monolithic design where it is complex to modify the material flow routing depending on the specific mixture under treatment. The process parameters are traditionally set by the recycling machine designer based on a, typically small, material sample provided by the end-user, in the design and commissioning phase. These parameters are normally kept constant throughout the system life-cycle. The technologies are often derived from other industrial areas (for example mining), and are not equipped with modern automation technologies, neither conceived for flexible operations. Finally, in line data gathering systems for the characterization of the particles shape, size and chemical composition are not state-of-the-art technological solutions and only sampling inspection on small batches can be performed by X-Ray Fluorescence (XRF) or Mass Spectroscopy (MS) techniques.

Another reason hindering the establishment of successful integrated EOL strategies is the lack of proven business models supporting the implementation of such strategies. The ownership of products during and after the phase of use is a crucial factor [3]: if the remanufacturer coincides with the manufacturer or if the two actors establish a partnership, important synergies and efficiencies can be obtained with the effect of lowering the implementation barriers. The setup of efficient reverse logistics networks to guarantee a significant and stable waste collection rate is also considered as a relevant barrier, especially from the recycler side.

Finally, methods to financially assess the impact of EOL processes based on the uncertain residual value of the inputs, their potential market and the cost of different EOL strategies are missing. Such methods should support the selection of the optimal EOL strategies and the macro-design of EOL process, for example in terms of level of disassembly to be reached [6]. To gather information on the residual value of products,

RFID systems, the adoption of Prognostics and Health Management (PHM), condition monitoring, statistical pattern analysis, Vibration analysis, Weibull analysis and Life Cycle Units were proposed [3] [5].

For these reasons, De-Manufacturing research should be addressed in a comprehensive multi-level and multi-disciplinary approach [8]. The proposed approach (Figure 2) consists of three levels of research actions, from machines technology to business model, passing through the system integration level.

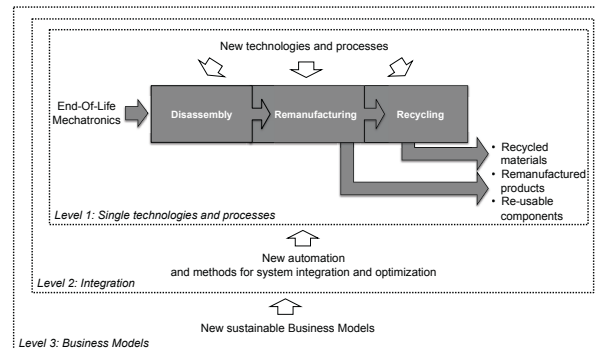


Figure 2 – Multi-level integrated De-Manufacturing research approach.

At a first level, disassembly, remanufacturing and recycling technologies and processes should be improved in order to flexibly deal with the large variability of end-of-life products and in order to exploit the potentials of technological innovations that have been developed in the last years in manufacturing processes. At a second level, the integration and inter-dependencies of the three processes should be considered. Integrated control and simulation approaches to optimize system design and operations management by regulating materials flows and process parameters according to input materials, workloads and availability of machines, represent approaches already used in manufacturing that can increase the overall efficiency of De-Manufacturing. At a third level, sustainable business models should be defined considering all the EOL strategies that can be dynamically implemented by such innovative integrated and flexible De-Manufacturing technologies, based on varying market conditions and on the uncertain input products to be treated. In the next section, an example of application of these concepts to the De-manufacturing of mechatronic components in the automotive industry is given.

3. Mechatronic Components

Among the different type of products, mechatronic parts present relevant challenges and opportunities with respect to De-Manufacturing. Mechatronic products can be defined as systems combining mechanics, electronics and information technology [9]. They allow the conversion between electrical, hydraulic, thermal or pneumatic energy for the control of all modern devices and machines adopted in industrial and private life (such as cars, airplanes, machine tools, medical

equipment, etc.) [10]. The increase of intelligent devices and advanced functionalities in current products pushes the rapid diffusion of mechatronics. For example, a modern car contains up to 60 electronic controllers [11] and it is estimated that electronics will account for the 40% of value adding in car manufacturing in 2015 [11]. The novelty of technology is also the cause of frequent problems associated with the introduction of these products (in Germany 1,4 million vehicles were called back in 2004 in the frame of 137 call back campaigns [11]). As a consequence, the volume of mechatronics components at their End-Of-Life (EOL) –most of them still having a residual value- and the volume of products that need to be repaired during their life is increasing. This is a critical issue from the environmental point of view and, at the same time, a big opportunity for the manufacturing industry.

Mechatronics parts, in fact, are a major source of high grade Printed Circuit Boards (PCBs), which are high value-added components containing key-metals, as defined by the “Critical Raw Materials for the EU - Report of the Ad-hoc Working Group on defining critical raw materials, 2010”. Due to their composition (a typical “populated” PCB is about 25% metals, including copper, iron, nickel, silver, gold, palladium, and others [12]), PCBs are also called “Urban Mineral Resources”. Through successful De-Manufacturing of mechatronics, it could be possible to reduce the dependency from the key-metals extracting countries (China, Russia, the Democratic Republic of Congo and Brazil), and to decrease the sourcing price and related turbulences. This would allow European manufacturing companies using key-metals as raw materials to be more competitive.

Despite this opportunity, the global PCBs waste disposal in 2013 evidenced that still more than 40% of the PCB waste is landfilled, creating a considerable burden on environment and human health [13]. For the remaining fraction of PCBs that are not land-filled, it can be estimated that the majority of PCBs collected in the world are nowadays processed in China by an informal sector, which adopts low measures for environment and workers health protection, and which is not able to reach high quality levels of recycled materials [14]. With respect to the most diffused EOL strategies, it can be estimated that in 2013 the 52% of globally collected PCBs were recycled to obtain secondary materials and that only the 6% were remanufactured or reconditioned [13]. The following geographic distribution of the different EOL processes is estimated:

- Remanufacturing – 49% Asia, 28% North America, 22% Europe;
- Recycling – 54% Asia, 28% Europe, 14% North America;
- Reconditioning – 48% Asia, 25% Europe, 18% North America.

In terms of global trends, it is forecasted that in the next five years, the global volume of remanufactured and reconditioned PCBs will grow respectively of the 36% and of the 25%, while the volume of recycled PCBs will moderately grow (of about the 3%).

These data confirm the strategic opportunity of De-Manufacturing of mechatronic products according to the

integrated De-Manufacturing system concept illustrated in Section 2, which allows maximizing the performance through the implementation of the most suitable EOL strategies. They also confirm the opportunity for high-wage countries, that could gain the leadership in this sector by developing a new sector of De-Manufacturing technologies and services, grounded on the worldwide recognized knowledge and competence on manufacturing technologies.

4. De-Manufacturing pilot plant

An example of De-Manufacturing plant, integrating different stages of the De-Manufacturing process chain is the pilot plant recently installed at ITIA-CNR, the Institute of Industrial Technologies and Automation of the National Council for Research, in Milan, Italy, within a research project supported by the Lombardy Region. The plant layout is represented in Figure 3. Three main “processing cells”, each one dedicated to a specific phase of the De-Manufacturing process chain, are implemented. The cells are completely integrated and the End-Of-Life mechatronic products can flow through all the cells with the aim of gathering the highest possible residual value from the De-Manufacturing treatment. The first cell is dedicated to the robotics disassembly of the mechatronic components. Two cooperating robots and a lightweight robot assist the operator in the disassembly operations. For example, for Electronic Control Units (ECUs), one of the most promising automotive mechatronic components for De-Manufacturing treatments, the task can consist in the extraction of the PCB from the metallic case. In order to provide to the process the required level of flexibility enabling to treat many different types of mechatronic components in the same system, human-robot cooperation principles are implemented. Therefore, the lightweight robot supports the operator in demanding disassembly tasks, while the cooperating robots are dedicated to flexible transportation and loading processes. After macro-disassembly, the PCB is clamped on a flexible pallet, designed ad-hoc for this application, and goes through a modular transportation system with decentralized control to the second cell. This cell is dedicated to testing, repair and remanufacturing operations. A functional test is performed on the PCB and, according to the output of the testing process, specific components can be automatically disassembled from the PCB and substituted. In alternative, this technology can be used to perform selective disassembly, i.e. disassembly of components that have high residual value and can be re-used, or have hazardous components that must follow specific downstream treatments. If the PCB is repaired, it is sent back to the re-assembly operations. If the end-of-life PCB is not suited for remanufacturing/repair, because of technical or economic reasons, it is automatically sent to the third cell, applying mechanical recycling processes. In this portion of system, the materials are liberated by a two-stage size reduction process. Firstly, a gentle shredding stage is performed by a slowly rotating single-shaft shredder. In the second stage a fine-pulverizing stage is performed, reaching a particle size range below 1mm. After this process, dimensional separation and electrostatic separation are

performed to separate the metallic fraction from the non-metallic fraction. An in-line inspection station, based on hyperspectral imaging, is also implemented in order to characterize the size, the shape and the composition of the mixture and to enable to adapt the separation process parameters on the basis of the specific mixture under treatment. Also, this stage can be used for final quality control. The recycling cell is equipped with a newly designed flexible transportation system, based on a combination of pneumatic and mechanical modules, enabling to easily reconfigure the process flow depending on the type of product under processing. The output of this process is a highly pre-concentrated metallic mixture that can be sent to metallurgical processes for final recovery, thus avoiding energy demanding thermal treatments based on pyrolysis.

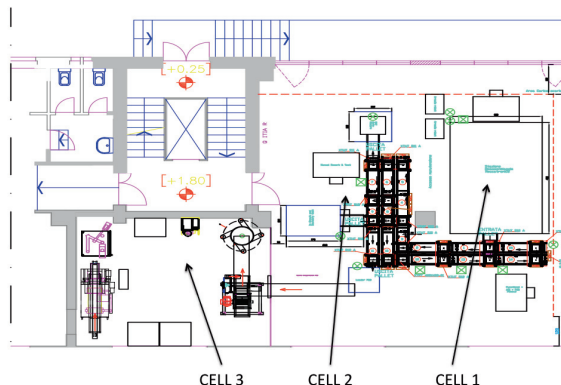


Figure 3 – Layout of the De-manufacturing Pilot Plant at ITIA CNR.

5. Research challenges

The industrial implementation of advanced De-manufacturing systems requires several research challenges to be addressed.

5.1. Human-machine interaction

As De-Manufacturing of mechatronic products entails the macro disassembly of a wide variety of components, not designed to be disassembled, by the means of standard Industrial Robots (IRs), the cooperation human-robots in the process seems an extremely fruitful approach to increase the efficiency of the task [5]. Moreover, re-assembly tasks should be easily integrated in the plant. Physical Human-Robot Interaction (pHRI) is a new paradigm in plant design since unstructured environments without physical fences allow easy access to the plant for supervision, cooperation with IRs in executing the same task or in performing different concurrent application sharing tools, spaces and objects. Safety problems related to pHRI are major challenges to be addressed from a technical and operational point of view, also paving the way to new enabling standards in this direction.

5.2. De-Manufacturing Process Models

With the objective of providing intelligence to De-Manufacturing processes and enable their adaptability to

different product and context conditions, advanced multi-physics process models are required. Such process models should be able to characterize the interaction between the De-Manufacturing equipment and the product under treatment, including both granular mixtures or product sub-components. For example, for mechanical recycling processes, multi-body, multi-material simulation models seem to be promising tools [17]. They provide the ability to jointly capture the effect of the De-Manufacturing processes physics on the material under treatment and the impacts between the particles in motion, thus is the major cause for separation process variability and inaccuracy. However, further effort needs to be devoted to the validation of these models in real settings.

5.3. De-Manufacturing System Engineering

Since De-Manufacturing systems entails the integration of different process stages and technologies to gather the desired value from end-of-life products, system engineering approaches need to be developed to support the efficient integration of these stages. These models should be hybrid in the sense that they should incorporate the simultaneous modelling of discrete parts and continuous granular flows. State of the art system engineering models do not have such capabilities. Moreover, they should consider complex material flows including multiple re-entrant loops modelling the reprocessing of un-liberated mixtures. Although this problem is found in other manufacturing processes, such as semiconductor manufacturing, these models are not well developed yet.

5.4. Reconfigurability of De-Manufacturing Systems

It was recently proved [16] that the high volatility in the material values in the secondary material market calls for the ability of easily reconfigure material flows in the De-Manufacturing plants. Indeed, as the material value changes, the recycling strategy and the target recyclable materials may also change, thus calling for process-chains designs that are targeted to the specific market situation. State-of-the-art De-Manufacturing processes are not reconfigurable, both in terms of material flow and of process parameters. This limitation undermines the economic efficiency of these systems. In addition, De-Manufacturing Systems should be reconfigurable to be able to process different types of products over time. In fact, technology evolution in many product categories will determine massive volumes of discarded products for a certain time horizon, until they completely exit the market (for example, Cathode Ray Tube (CRT) televisions).

5.5. Energy in De-Manufacturing systems

Depending on the specific technologies that are implemented, the energy consumption in De-Manufacturing systems can be extremely high, thus mining the sustainability of the overall recovery process. For example, it is well known that thermal processes, such as pyrolysis, are highly energy demanding processes in De-Manufacturing. Methodologies for monitoring the energy consumptions in De-Manufacturing

systems are currently not adopted and will be extremely important to assess the overall sustainability performance of De-Manufacturing, under a Life Cycle Assessment (LCA) perspective.

5.6. Virtual De-Manufacturing

System level engineering capabilities to achieve the appropriate integration among the De-Manufacturing stages have to be achieved, according to Figure 2. With this goal, a virtual factory framework for the interoperability seem to be a promising key enabling technology. The core idea is the possibility to realise, coupled with physical plant, its virtual representation in order to test alternative system configurations and process-chains before changes in the real plant are implemented and without interfering with its operations. Moreover, the Virtual De-Manufacturing system should be able to incorporate multi-scale and multi-physics models, such as those described above, in order to support effective design and re-design of the De-Manufacturing system. Cyber-Physical Systems (CPS) has emerged as a key technology for improving and streamlining design, planning, control and monitoring complex manufacturing processes. However, CPS tools for modelling De-Manufacturing systems are not available and require substantial research efforts to be achieved. A first attempt in this direction has been made in [17], where a multi-scale model integrating process and system layers for recycling systems has been proposed.

5.7. New De-Manufacturing business models

Research at business model level is needed to economically and environmentally validate the concept in specific application areas. Algorithms will have to be developed for the dynamic identification of the most suitable EOL strategies with respect to the type and conditions of incoming products, the market value of product, components and materials. Such algorithms will have to be integrated in the control strategies of De-Manufacturing plants. The overall sustainability of new integrated technologies and methods will have to be assessed considering the uncertainty of market conditions, due to materials price fluctuations and to the fast technology trends which will make available massive volumes of different products to be treated over time. Such an assessment will have to give indications on the scale of the plants and on their geographic location in different regions, according to the flows of materials to be treated. Proper simulation models will have to be developed for logistics purposes and trans-national waste flows analysis. Furthermore, issues of value chain reengineering will have to be faced in order to affirm the integrated De-Manufacturing paradigm. In fact, in the current situations, the fragmentation of the value chain would allow several actors to become an integrated De-manufacturer by acquiring the necessary enabling technologies and management methods. The most viable options have to be identified and supply chains which support the cooperation of all involved stakeholders (De-manufacturers, technology providers, manufacturers and customers) will have to be designed.

Finally, proper marketing strategies and practices will have to be defined for the successful and synergic co-existence of Manufacturing and De-Manufacturing systems.

6. Conclusions

De-Manufacturing Systems can constitute the driver for sustainable economy and sustainable growth in high-wage countries. However, major technological, methodological and business oriented innovations need to be developed as enabler for this new concept, which directly affects both the energy footprint and the raw material consumption in manufacturing operations. This paper has formulated the concept of De-manufacturing Systems and has outlined areas of research with strong potential benefits to the achievement of the overall goal.

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