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End-of-Life recovery as an intelligent model for the 2035 manufacturing industry

Enhancing the approach of designing for end-of-life recovery options

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END-OF-LIFE RECOVERY AS AN INTELLIGENT MODEL FOR THE 2035 MANUFACTURING INDUSTRY:

Enhancing the approach of designing for end-of-life recovery options

Abstract

As the world moves into the second fifth of the 21st century, people and even professionals of engineering constantly ponder how life could be in the next 20 years. This essay offers a brief description of what issues a design and manufacturing company should take into account in order to position itself to be a leading major high-tech global enterprise in 2035. Through insight into the future, characteristics and requirements for a successful company within the industrial marketplace are reviewed. An analysis of some of the technology advances that could be applicable is performed, as well as how the combination of these with conventional design practices would leverage end-of-life recovery processes. The principles of operation of Industry 4.0 (also known as the fourth stage of industrialization) are revised, along with the effects of artificial intelligence (AI), additive manufacturing (AM), and a revolutionary approach in the form of intelligent materials on forward and reverse supply chains. Further to AI and AM, key research areas to EOL such as design for disassembly (DfD), intelligent materials, and information cloud are briefly discussed. Finally, details of the mode of operation of the company in order to succeed in its mission, the partnerships that will need to form, and the necessary technologies to support its employees in being globally competitive are presented.

Introduction

Modern-day products are typically designed for ease of manufacturability, meaning that designs are created so that manufacturing is achieved as economically and efficiently as possible. However, at the end of the product's life cycle, disassembly for the purpose of End-Of-Life (EOL) recovery can be difficult and highly resource consuming, turning the process into a non-profitable and undesirable activity for companies. For some products, the value of the recovered material is deemed insignificant when compared to the time and effort needed to recover such materials. The majority of these non-functional products end up in landfills, since the methods currently used to recycle these products are unsystematic and ineffective, prompting the well-known harmful release of toxic chemicals into the air, soil, and water. Logically, to many corporate decision-makers, monetary value and mitigation of environmental impact are the two main motivations for EOL recovery.

Over the past few years, environmental concerns and government legislations have compelled manufacturers to undertake recycling efforts at the end-of-life stage of their products. In addition, such legislation has inspired take-back programs among companies who are now starting to see EOL recovery as a business opportunity [1], an approach that is expected to evolve steadily over the next 10+ years to become a benchmark for several sectors of the manufacturing industry. Moreover, such an approach also introduces the possibility to engage with the customer and give them the opportunity to provide constructive feedback on the product, therefore setting the foundations for a customer-oriented service, which is one of the aims of the prototypical 21st century company. By participating in recovery procedures, companies would become more committed to their products long after they are sold to consumers. This long-term commitment to their products also portrays companies in a good light in the eyes of consumers and improves brand image. More importantly, participation in EOL recovery procedures inspires companies to be more environmentally conscious.

Looking at achieving highest rates of EOL recovery, companies would need to develop the capacity to generate closed-loop processes that ensure effectiveness in accomplishing the desired end results. Materials involved in the manufacturing of a product hold the key to success, since the post-EOL destination or use of such materials would define the level and type of impact on both the environment and the financial aspect. This observation calls for the development of intelligent, self-evolving materials able to adapt to different circumstances by changing their microstructure and mechanical properties in order to fulfill different functionalities. Materials with such abilities would behave in a 'multi-modal' way and adequately conform to the requirements of a number of product's life-cycles, therefore promoting reuse and longevity. Regardless of the positive effect that would generate on the environment, these use of these materials would introduce dramatic cost savings within the entire structure of the product design and manufacturing process.

Designing and manufacturing for EOL recovery will also open up a new window for the appropriate management of energy resources, which would align with the principle of adopting energy solutions to comply with both financial and environmental responsibilities in 2035. Nonetheless, to take full advantage of this somewhat emerging scheme, companies need to rapidly research, embrace and digest all inherent aspects of it, in order to develop a clear insight into how to succeed in their quest for sustainability.

An Insight into 2035

Considering the way in which the majority of companies within the manufacturing industry currently operate, the most common thoughts that would come to mind are: resource extractive and wasteful; linear product systems; design for high-profit manufacturability with manufacturing operations overseas; decentralized operations and communication. Extrapolating this into 2035, and for systems with significant higher levels of complexity, it would simply translate into high-cost products, lengthy projects, and excessive amounts of energy required for manufacturing: an unsustainable approach. To properly address the effects of the ever-increasing levels of complexity, a company must embrace the concept of sustainability: a better business model that dispels the current practice of having to choose from economy and environment [2].

Amongst the several technology advances that could be in full application for 2035, higher levels of automation, artificial intelligence (AI), and additive manufacturing (AM) figure as the most revolutionary concepts. Higher levels of automation would decrease manufacturing times, with human input decreasing as technology gradually evolves; artificial intelligence is just an extension of machine automation, since computer systems would be ‘trained’ to learn, reason and self-correct as humans do. Additive manufacturing is a completely different approach to conventional production, since material is continuously added on a layer-by-layer basis in order get a final product instead of being manufactured by subtractive and forming techniques. Very few would have envisaged 15 years ago that additive manufacturing would be performed with metals, not to mention that it would be used at an industrial scale.

Regardless of the individual benefits that such technologies would bring along in the future, the coupling of these with an appropriate design that helps leverage some form of recovery at the end of the product’s functional or technological life would increase the possibility of achieving a higher level of sustainable manufacturing. Furthermore, it would help reduce the amount of waste generated by discarding of obsolete or non-functional products.

Industry 4.0

The path towards Industry 4.0 (also referred to as the fourth stage of industrialization) has a reciprocal relationship with the manufacturing industry; both evolve hand in hand, as if the manufacturing industry is the performing stage of Industry 4.0. And this is actually logical in a number of ways, since what is conceived and created in the latter would find in the former a platform of action. The Industrial Internet, an alternative name to Industry 4.0, is expected to substantially increase productivity in the manufacturing process and also within the supply chain [3]. Intelligent machines would take corrective actions to avoid unnecessary stops and unplanned breakdowns, thus achieving self-governed processes.

Essentially a three-dimensional process, Industry 4.0 is outlined by the following principles: (1) **horizontal integration** throughout a product life-cycle and across adjoining product life-cycles [4]. This horizontal integration is defined by the interplay of different factors such as equipment, human resources, organizational model, processes and products into a network where modules are symbolized by smart factories as the highest hierarchy element. A fully interconnected network between factors relevant to a single product life-cycle, as well as between those of adjoining product life-cycles, ensures that all smart factories are intelligently linked within the network to achieve a novel business model based on the concept of sustainability. The second principle (2), **end-to-end engineering**, cross-links stakeholders, processes, and equipment across the whole product life-cycle, from the raw material acquisition phase, through manufacturing, use and service phase, to the end-of-life phase of the product [4]. This also includes all stages of the manufacturing phase, as well as transportation between all phases.

Diving into a micro-perspective of the process, the third principle (3) is **vertical integration and networked manufacturing systems** throughout all levels of a hierarchy module or smart factory [4], including manufacturing facilities and all activities associated to the production stage, such as purchasing, marketing, sales, R&D and others. A smart factory would feature several hierarchical levels within a product life-cycle, independent of each other but perfectly communicating and exchanging data and information in order to manufacture smart products. This vertical integration is defined by the interplay of factors such as equipment, human resources, and products within the local network of a smart factory that includes all phases and activities afore mentioned. Smart factories would have an energy management system able to fulfil the dynamic requirements of both energy supply and feedback.

A company in 2035 must harmonize with the prospect that a smart factory would produce smart products using energy produced by a smart grid and clean water possibly as a byproduct of another network process, with materials procured by smart logistics, which would, at the other end of the business, also comply with smart transportation practices. Finally, the flow of all information and data within and across different product life-cycles would be interchanged via the smart cloud. A representation of the 'local' perspective for an individual smart factory is presented on Figure 1.

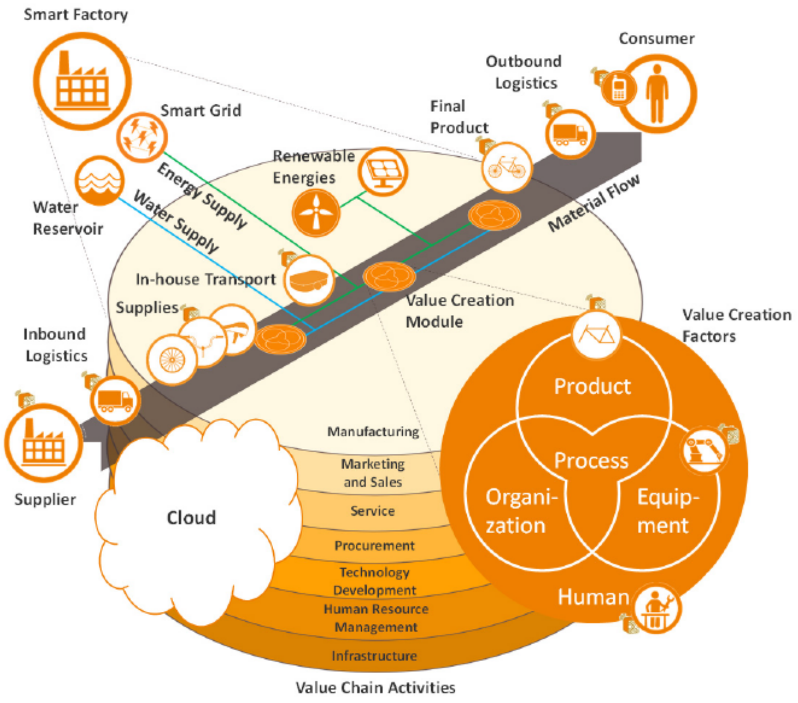

Figure 1. Industry 4.0 (Micro-perspective) [4]

From a micro-perspective point of view, the horizontal integration takes place between business modules relevant to the material and resources flow and integrated into the smart logistics. It must be noted that, either from a macro- or micro-perspective standpoint, to increase the efficiency of communications and data exchange, a company in 2035 must address all of the specific needs of their business modules while also looking at the connections within their supply chain.

Supply Chain Management

With the inclusion of the state-of-the-art technologies of 2035 into the supply chain, many challenges would be present in order to ensure adequate system interaction and performance. The level of complexity of the technologies being implemented would require a reciprocally equal effort to accomplish adaptability of the supply chain to the resulting process. For instance, to be able to use the previously described intelligent, self-evolving materials, companies of the future must have supply chains intelligently managed and controlled by means of AI-based agents, which will comprise self-governed processes using self-corrective machines and self-replenishing stocks, all based on real time data. Through the Internet-of-Things (IoT), millions of elements would interconnect to ensure that everything runs as planned across the whole product supply chain. Interconnection across the network would be so accurate and efficient that any change in any part of the chain would automatically generate adjustments on the factory floor.

As previously mentioned, one of the fundamental goals of the prototypical 21st century company is to switch from being product-oriented to a service-oriented business [2]. This would, in turn, require to implement some different considerations within the supply chain, with the customer no longer being at the end of it. A reverse supply chain (RSC), which takes into account such considerations, is regarded by many researchers and environmentalists as a pivotal element in the accomplishment of sustainable production [5]. Typically, companies would design their RSC so that the final element would either be the product's end-of-life or, for more complex scenarios, the start of a new product life-cycle. Nevertheless, the main benefit of RSCs is the possibility of end-of-life recovery outcomes, waste prevention and even resource reuse. It is worth noting that the potential profits derived from RSCs come with the drawback of a much more complex process, since the resultant return flows could well be inputs to other RSCs or even forward supply chains.

Further to the previously mentioned factors, and as an additional notion to adequate management of information within the supply chain, the ample spectrum of options in connection with prototyping through additive manufacturing would undoubtedly be something that high-tech companies in 2035 must capitalize on. When performing conceptual design duties for instance, both OEMs and suppliers could translate ideas into physical prototypes almost instantly with the use of additive manufacturing techniques. Networking of concepts and even interface designs within the supply chain would enhance the quality and accuracy of the design process, hence promoting advanced levels of innovation and robustness.

Key Research Areas

In order to achieve the high level of concurrent design that is required for a company in 2035 to position itself as a leading enterprise in design and manufacturing, a deep understanding of relevant topics is paramount. To succeed in the search of such knowledge, industry would unarguably need to partner with academia as a proven source of valid and credible findings, which would provide the former with the know-how to accomplish their goals. Furthermore, academia would also benefit from this partnership, since the renowned advantages of the industrial platform would always produce more comprehensive and influential results. Some of the key research areas that will need to be addressed are given below.

Design for Disassembly (DfD)

DfD is a complete different methodology than conventional Design for Assembly (DfA). The difficulty of DfD techniques comes from the complexity of assemblies that frequently do not lend themselves to easy reuse and recycling. DfD entails the application of three critical disciplines: (1) selection and use of materials; (2) design of components and product architecture; and (3) selection and use of joints, connectors, and fasteners. The introduction of a 'separability rating' has also been used to assess disassembly time, which is derived from the aspect of jointing. This aspect is significant as disassembly time is closely associated with undoing fasteners and connectors [6].

The approach to develop an appropriate DfD method would change from one sector of the manufacturing industry to another, which is coherent due to the different design considerations and requirements of diametrically opposed concepts being developed. Go et al. [7] provided a framework for automotive components to be designed for ease of recovery. The methodology generates optimum disassembly procedures using a genetic algorithm (GA) approach and by evaluating disassemblability of EOL products. Reimer, Sodhi and Knight [8] also used GAs to produce an integrated recycling model that would minimize cost of the collection of EOL products. Giudice and Kassem [9] introduced the concept of disassembly depth effectiveness, which depends on the number and type of components and nodes or interfaces that must be removed in order to achieve disassembly of a desired part. The efficiency of the disassembly process can be improved by modifying the main design parameters, in order to reduce effort and time during disassembly.

Considering the advantages of designing a product intended for future disassembly, introduction of a 'disassembly friendly' design prior to the development of products is beneficial. As stated by Campbell and Hasan [10], if DfD guidelines are implemented early on in the design process, the profitability of the disassembly process as well as the overall recycling operation will improve. Incentives for designing for disassembly include the reduction of raw material consumption, the reduction of the cost to make a product, and a reduced cost of disposal [11].

Artificial Intelligence (AI)

The exponential growth of AI methods and practices proposed over the past 15 years leads almost everybody to believe that it would be present in just about every aspect of the 'standard' design and manufacturing process of 2035. Currently, AI is successfully applied in practically all ambits of engineering and within several sectors such as military, financial, software development, healthcare and the public sector to name a few. This adaptability to 'each-and-every' situation has somehow led the research community to believe that even the unimaginable could be achieved, and with this rationale and drive, the quest for novel findings is always a matter of time. Nonetheless, AI could also be used to improve the results obtained from the applicability of some conventional design techniques, particularly when it is resourcefully used within optimization frameworks.

From initial efforts on ease of disassembly design, Wahab et al. [12] used Artificial Neural Networks (ANN) to develop a model able to predict reliability and durability of reused components in the automotive industry, which was subsequently optimized for reliability and life-cycle cost by means of Genetic Algorithm (GA) methods. The resulting model will provide the automotive industry with an evaluation tool for effective assessment of the reuse of components within assemblies that have reached the EOL cycle, with the aim of improving the design and manufacturing process. By using a similar approach, potential remanufacturing of a product that has reached its EOL could be evaluated with the assistance of AI techniques. AI algorithms could be applied sequentially, from the evaluation of the product EOL (analytical hierarchy process [AHP] with case-based reasoning [CBR]) and progressing onto the assessment of EOL for parts and components of the product (through the integration of both an economical and an environmental cost model) [13]. Being able to use high-technology tools for an adequate end-of-life selection strategy would certainly play to the advantage of companies competing for advanced levels of sustainability and leading enterprise status.

AI techniques could also be applied to overcome issues occurring in various dynamic segments of reverse supply chain management (RSCM) [5]. Optimization of the performance of RSC, which entails the need to design an effective and efficient infrastructure to manage the resulting channel usually formed by end-users and remanufacturers, is generally achieved by means of GA and fuzzy system (FS) methods. The development of a decision model, based on the analysis of qualitative and quantitative factors such as environmental impact, quality, legislative factors, and cost, to facilitate the selection of the best EOL recovery option can be performed through application of a multi-objective (recovery cost and quality) evolutionary algorithm (EA). CBR and GA have also been applied for solving problems related to EOL products acquisition and assessment. For the case where a number of EOL products require some form of logistic optimization, an improved differential evolution (IDE) algorithm has been used to fulfil cost savings and positive environmental effects when simultaneous pick-ups and deliveries, as well as scheduling of timeframes have been considered; tabu search (TS) and ant colony optimization (ACO) techniques have also been employed for this purpose. Additionally, FS and ANN have been successfully applied for the evaluation and selection of logistic suppliers within EOL RSCM [5].

As a closing thought on the applicability of AI in 2035, and although it may have not yet crossed the mind of some seasoned professionals in the industry, experts actually expect that this discipline will redefine management [14]. Fact is that AI will sooner than later be able to perform those time-consuming administrative tasks (estimated to use 54% of manager's time) quicker and at a lower cost, hence prompting managers to take the route of adapting to the era of smart assistants in a smart, sustainable business.

Intelligent Materials

Much of the efficiency of EOL recovery processes is directly related to the type and properties of the materials involved. As a consequence, successful companies of the future must totally embrace the use of intelligent materials, which are designed to feature properties able to change within certain defined parameters due to the effects of external factors. Materials evolve as intelligence is embodied into them through techniques based on machine learning (ML) principles, which are also called enabling technologies. Butler et al. [15] successfully applied ML to enhance and integrate synthesis, characterization and modelling of materials. Moreover, previously unknown structure-properties relationships are revealed by using models that relate system descriptors to some desirable properties, which results in the discovering of new compounds. This approach is based on the representation of crystal structures and morphology of extended solids [15].

Probability estimation, regression, clustering, and classification figure amongst the most commonly used materials algorithm in materials science. Besides providing huge improvements in both time efficiency and prediction accuracy, ML algorithms are widely applied due to the ease with which new knowledge and predictive models are extracted from existing materials data. The key to successful ML algorithms is the use of significantly faithful models, which could, however, introduce some form of computational issues due to the complexity of the molecular interactions and inherent physical properties involved [16]. Therefore, it is imperative to design and install a suitable data transfer infrastructure capable of mitigating such issues, along with efficiently handling the interpretation of data collected from sensors, actuators and simulations.

The potential social impact of discovering and seamlessly producing intelligent materials is huge, as well as paving the way for revolutionary innovation able to completely transform existing manufacturing processes to position the company as a leading high tech, global manufacturing enterprise.

Additive Manufacturing (AM)

AM has steadily become the hot topic in the manufacturing industry community. Initially conceived for rapid prototyping (RP) purposes, it has evolved rapidly to adopt a true wide range of materials (including their starting state) and surface finishes. The pace at which research is currently being conducted on this topic shows that there are no signs of any slowing down on AM technology development, but an exponential progression instead. The most common applications comprise commercial and academic use in (a) aerospace engineering, (b) automotive engineering, (c) orthopedics and dental applications, (d) tissue scaffolds, (e) biofabrication, (f) energy, (g) buildings and protective structures amongst others [17]. The list would surely grow as we move into 2035.

Similar to the case of artificial intelligence (AI), AM has not been entirely practiced for the development of new structures and advanced techniques. Hence, AM could also be used to improve the results obtained from the applicability of some conventional design methodologies, particularly when it is adequately used within repurposed design frameworks. Considering the main feature of AM, which translates in the ability to produce parts by adding material on a layer-by-layer basis, a remanufacturing strategy has been proposed to covert an EOL component into a new part without the need to return to the raw material stage [18]. The strategy uses the EOL part as the new ‘state’ of the raw material, without going through any recycling process. A combination of both AM and conventional subtractive techniques, in conjunction with pertinent heat treatments, are then employed to achieve the configuration required for the new part. These new parts, which are intended to have different functionality with respect to the initial EOL parts, are subsequently tested to ensure compliance with the specified microstructure and mechanical properties. By using an EOL part as a starting point to produce a new part, a closed-loop scheme is proposed, which is designed to reduce environmental impacts and promote process sustainability.

As previously mentioned, the full potential of AM is not totally clear yet. However, there are clear signs that the main attributes of this technique propose a novel approach where resources are maximized. Studies show that, by adopting AM into product life-cycles, savings in the production and use phases of a product are estimated at $113-370 billions and $56-219 billion respectively for 2025 [19]. It is therefore expected that, as a well-established process in 2035, savings could be significantly higher.

Information Cloud

Successful management of information would pave the way for the achievement of success for companies in 2035; business that would not invest in a proper information management system are highly likely to fall critically behind in their pursuit of achieving a high-tech leader status. For this, companies must allow for seamless sharing of information not only vertically between different internal modules of a smart factory, but also horizontally between possibly several smart factories within the closed-loop and undoubtedly between all related supply chains. The infrastructure required for interchanging of data would be of such complexity, that end-to-end solutions using information technology would necessitate the data to be embedded in a cloud. For effective development of this network, both ultimate security and a neat flow of information between all levels of business operations would have to be ensured. The cloud would also need to have the capability of allowing the real-time, continuous interchange of data between robustly linked cyber-physical systems (CPS), which would be operating in a self-organized and decentralized manner [4]. Furthermore, cloud computing promotes operations through collaborative intelligence, which is pivotal in achieving the competitive advantage required to become a leading high-tech design and manufacturing enterprise in 2035.

Operations | Partnerships | Technology

As a successful hi-tech global manufacturing enterprise, the company will have an organizational structure that ensures high levels of efficiency in their operations, while also adhering to the fulfillment of the triple bottom line: positive impact on the environment, society and economy. The company will operate based on the principles of Industry 4.0, which promotes vertical integration and networked manufacturing systems throughout all facilities (purchasing, manufacturing, sales, marketing, human resources, R&D, information technology and others) of each individual smart factory or unit. Vertical integration entails networking between all aspects that are required to manufacture end products, such as equipment (factory and office), human factor (employees, collaborators), and products (stock, raw material, factory facilities) amongst others. The Information Technology network system must ensure proper flow of information between all levels of business operations, with security protocols in place to allow collaborations between employees and suppliers but also to ensure the protection of confidential data. Likewise, a robust data transfer infrastructure must be in place to process all data related to the AI-based manufacturing processes, as well as allowing for seamless intercommunication of such data between factory floor, office floor and supply chains.

From a corporate point of view, a hierarchical horizontal integration throughout products life-cycles and between all smart factories within a corporation will be practiced. Such horizontal integration comprises networking of different factors like equipment, human resources, processes, products and even organizational models, which can vary from one smart factory to another and also with respect to all supply chains in the business. In order to include stakeholders and external collaborators across the range of products life-cycles, end-to-end engineering integration will be endorsed. The main benefit of this concept is the development of a comprehensive software tool chain that enables smart factories to assess the effects of product design at each stage of the life-cycle (planning , design, manufacturing, service, and maintenance), ensuring intelligent networking en route to sustainability.

The main forms of technology required to accomplish global consolidation of the aforementioned approaches are the Internet of Things (IoT), comprising open systems (software platforms, data and communication) and powerful embedded processors, as well as Cyber-Physical systems (CPS) that includes embedded intelligence at all levels.

Other than the fundamental partnership with academia that has been previously discussed, business in 2035 would need to partner for sustainable growth. Once again, reciprocal collaboration is key. Governmental regulations would be enforced to monitor environmental aspects in connection with all business operations, which will indicate the necessity of partnering with the government to work on a collaborative basis and overcome potential failures to achieve the desired results. Appropriate partnerships between members of the supply chain network, and the inherent requirement for durable and cooperative relations with them, would yield substantial benefits for the entire network. Finally, taking into consideration the social dimension of the triple-bottom line, companies of 2035 must form partnerships with society to work collectively towards achieving their immediate goals.

Conclusions

The challenges that would be present in 2035 call for the use of advanced, consolidated technological principles and techniques of the era in order to remain competitive and innovative. Leveraging end-of-life (EOL) recovery processes with the implementation of artificial intelligence (AI) and additive manufacturing (AM) applications would dramatically increase its effectiveness and cost savings within the product life-cycle. Furthermore, revolutionary developments such as intelligent materials, able to alter their microstructure and mechanical properties to perform multiple functionalities, would significantly enhance the applicability of EOL recovery options. Business following the structural organization of Industry 4.0, along with implementing technology such as the Internet-of-Things and cyber-physical systems (CPS), would be able to adequately manage products life-cycles to ensure profitability, sustainability and a service-oriented approach in order to become a leading global enterprise.

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