Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 91 (2020) 741–746

www.elsevier.com/locate/procedia

30th CIRP Design 2020 (CIRP Design 2020)

# Cyber-Physical Systems formalization in de- and remanufacturing and application to size reduction stage

Marco Diani[a]*, Marcello Colledani[a]

[a]Department of Mechanical Engineering, Politecnico di Milano, Via la Masa 1, 20156, Milan, Italy
* Corresponding author. Tel.: +02-2399-8208. E-mail address: marco.diani@polimi.it

## Abstract

Circular economy aims to shift from traditional linear approach of "take, make, dispose" to a closed loop scenario with the final goals of waste reduction and improvement of environmental friendly processes, creating new adaptable and resilient systems. Recycling processes, fundamental in circular economy, are facing issues related to the variability both in input and in output, showing mechanical treatments as the most promising in terms of environmental impacts and costs. First step in every recycling line is shredding. The objective is to obtain liberated particles (composed only by target materials) at a desired dimensional distribution. Cyber-Physical Systems are the most promising technology in recycling due to their capability to enable working always with optimized parameters, with a continuous exchange of information and actuations between hardware and software parts. The scope of this work is to present an architecture to optimize comminution processes, divided in two different steps, also based on Cyber-Physical Systems. First one aims to achieve the target optimal distribution, while the second one to minimize operational costs.

*Keywords:* recycling; circular economy; Cyber-Physical System; size reduction; optimization

## 1. Introduction

Circular Economy principles have been outlined for the first time by Pearce and Turner in 1989 [1]. The final goal is to transform into a closed loop the traditional economic linear approach (known as "Take, Make, Dispose"). This could be achieved through different objectives as waste reduction, reuse of End-of-Life products and reinsertion of waste as secondary raw materials. Using new adaptable and resilient manufacturing and demanufacturing processes, the opportunities to have real businesses in this field has been underlined by the Ellen Mac Arthur foundation [2]. The aim is to enable an economical sustainable business, leading to waste free systems thanks to the new circular factory concept [3][4], an innovative environment in which manufacturing and de- and remanufacturing could exist together, exploring possible synergies and exploiting mutual knowledges [5].

One of the Circular Economy pillar is waste reduction. It could be achieved through different approaches as in Figure 1 [6]. Solutions in the upper part of the triangle (which considers End-of-Life products as a resource) are preferable than that in the lower part.

Fig. 1: Waste reduction strategies [6].

In the last years, waste flows show a growth rate of 10% bringing new challenges in industrial world [7]. As an example, the amount of End-of-Life wind turbine blades is expected to overcome 30,000 tons per year between 2020 and 2030 [8].

The most relevant issue in waste treatment is related to the variability of End-of-Life (EoL) products. It is impossible to

10.1016/j.procir.2020.03.117

predict EoL conditions and lifetime is different for every product, leading to high volume of heterogenous waste. In the meanwhile, new objects are increasingly launched on the market and existing models are upgraded every year. In addition, shifting to new paradigms in different sectors is usual. As an example, electric vehicles (EVs) in automotive shows 200.000 EVs sold in 2015 doubling the sales reached in 2014 with foreseen sells equal to 1/3 of the market by 2030 [9]. Despite these factors, design for de- and remanufacturing is not widely used nowadays, with wide usage of joints and bonds that require destructive disassembly. Finally, also market prices are relevantly variables. As an example, cobalt price showed relevant fluctuations in the last years as in Figure 2 [10].

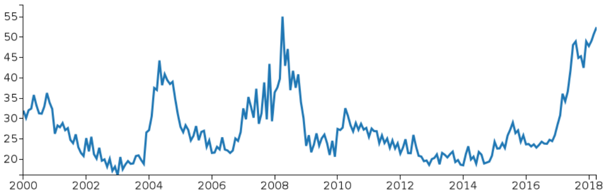

Fig. 2: Evolution of market price of cobalt in the last years [10].

Focusing on End-of-Life products, the most important solutions are re-use, repair, remanufacturing and recycling (in order of added value) [11]. Re-use consists in a new utilization without changing anything in the product. Repair aims to extend the life of the End-of-Life product, while remanufacturing restores the initial conditions of the product itself. Finally, recycling focuses on recovery of target and critical materials.

Despite this variability, nowadays recycling in Europe is done for the 85% by small and medium enterprises through several different dedicated rigid lines [7]. This lead to continuous stops to adapt the process, with high losses of time (resulting in losses of profits) and operational costs (due to non-optimized processes). In addition, high installation costs and misused recycling systems are typical issues.

To face the singular variabilities (and the sum of them), the best solution is to increase the adaptability of a recycling system using one smart line. In this work, Cyber-Physical Systems for the feed-forward control of recycling processes will be presented and applied, through a two-step procedure architecture, to size reduction.

## 2. Literature review and scope of this work

Cyber-Physical System (CPS) concept has been introduced and implemented in the last ten years [12]. The information have been collected and represented in Figure 3. Formally, CPSs are systems composed by a hardware and software part integrated together, continuously exchanging information and actions. Hardware part (which includes data gathering and actuators) collects information and send it to the software part, which is able to elaborate them through models and metamodels and optimization modules. The results are sent back to the hardware part in the form of optimized actions. The objective is to have in real-time the best process configuration, working both on system (as on workflows) and machine (as operational parameters) level [44][45].

Several examples of Cyber-Physical Systems in manufacturing could be found in literature, where usually they are called Cyber-Physical Production Systems (CPPSs). The objective is to have a fast reconfiguration of the system, both at factory and process level, considering its evolution, with the added value of working within and across all production level. The most important factors that must be taken into account are smartness, connectivity and responsivity [13].

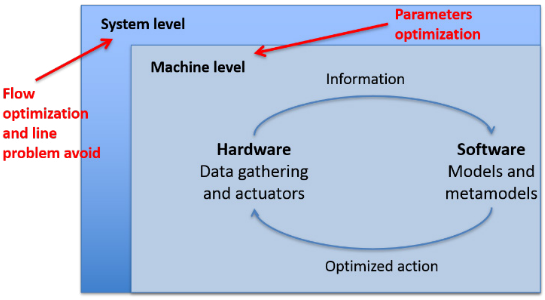

Fig. 3: CPS general scheme.

As an example, a CPPS has been developed for machining control [14]. It is able to continuously survey process parameters during milling, avoiding problems as chattering of the cutting edge, adapting process parameters in real-time and increasing tool's life. Other examples could be found for several applications as maintenance support. CPPSs have been developed also in automotive industry (e.g. Opel) to support maintenance [15] or to enable a cross-company exchange of information and a high level of transparency in the supply chain [13], leading to the creation of CPPS pilot plant for exploit and demonstrate their potentialities, located at the Institute for Computer Science and Control managed by Fraunhofer Project Center PMI at MTA SZTAKI [16][17].

It has been calculated that Cyber-Physical Production Systems are able to increase the productivity of 2,5%-5% with a cost saving of at least 900 billion dollars per year [18].

On the other hand, Cyber-Physical Systems in demanufacturing are few compared to the End-of-Life products variability. Examples could be found for remanufacturing in different fields as for high-value mechanical parts (through laser remanufacturing) [46] or turbine blades [19]. Digital Maintenance, Repair and Overhaul (MRO) has been also controlled through CPSs [20]. A structured work has been published to demonstrate the implementation of a CPS to facilitate refurbishment operations of Waste from Electric and Electronic Equipment (WEEE), based on Ultra-High Frequency Radio Frequency Identification [47].

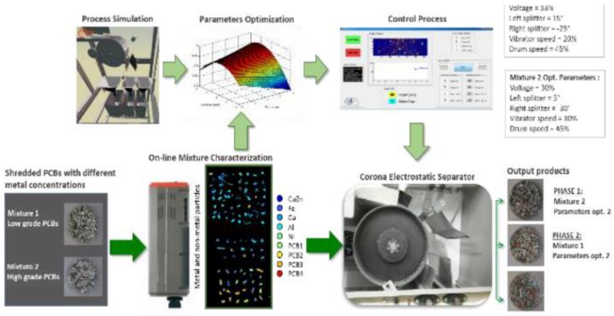

Fig. 4: Cyber-Physical System for Corona Electrostatic Separation optimization [21]

One of the most successful application in recycling is for the optimization of Corona Electrostatic Separation process and it is represented in Figure 4 [21]. Composition of the mixture of shredded Printed Circuit Boards is analysed through an HyperSpectral Imaging system. Data are gathered and sent to a multi-body simulation model which, in cooperation with an optimization module, automatically reconfigure the system with optimal parameters for the electrostatic separation machine. Preliminary experimental results obtained showed a considerable improvement in recovery of precious metals.

Focusing on recycling, processes could be divided in mechanical, thermal and chemical ones. Mechanical processes are the best ones in terms of energy consumption, by-products and environmental impact. They are typically multi-stage processes that can be grouped in four categories:

- **Size reduction** processes aim to reduce the dimensions of the particles increasing the liberation of the target material
- **Separation** processes divide the input stream into two or more flows with increased concentration of target materials
- **Splitting** steps divide the input stream into two or more flows with the same concentration of target materials as the input one
- **Mixing** steps merge and mix multiple incoming material flows into a unique output flow

Among them, size reduction processes (also called shredding, comminution or grinding) are the most important ones because they prepare the material for the next steps, or, in some cases, to obtain particles for a direct re-use [22]. The aim is to have homogeneous flows (in dimensions and materials) of high liberated particles (defined as particles composed by a small number of materials, possibly only one [23]). Also, in a mechanical recycling line, shredding is the most energy intensive process. For these reasons, a feed-forward optimization of comminution is fundamental, to achieve high quality products with competitive costs.

In the next sections, the solution developed for the feed-forward control of size reduction processes will be shown.

## 3. Architecture

A general formalization of a Cyber-Physical System in de- and remanufacturing has been developed as in Figure 5.

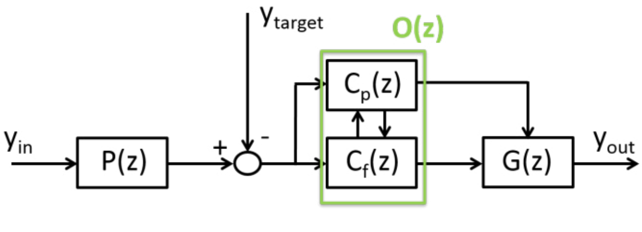

Fig. 5: Formalization of CPS for feed-forward control of demanufacturing processes

In particular, $y_{in}$ is the input signal, $y_{target}$ is the target signal, P(z) is the predictor, G(z) is the system to control, O(z) is the optimization module, $C_f(z)$ is the flow optimization and control module and $C_p(z)$ is the parameters optimization and control module.

The predictor *P* has in input information on the material and on the machine status, elaborating them and predicting the output in a feed-forward mode. This prediction is than compared with the target material characteristics (typically suggested by an operator) and the result is sent to the optimization block *O*, divided into two blocks, continuously exchanging information, both for parameters ($C_p$) and for flow ($C_f$), acting on the process system *G*.

Manufacturing processes could be optimized using Cyber-Physical Systems in feed-back configuration. The process parameters could be adapted based on the characteristics of the output due to the low variability in input. On the other hand, CPSs in demanufacturing has to monitor, optimize and control machine parameters and line flows simultaneously, facing inputs with high variability. The most suitable solution is to use a feed-forward approach as explained before.

Focus on shredding processes, they could be batch or continuous processes with different choices on tools (material, fixed or replaceable, single or multiple tools) and they have design and controllable parameters, both off-line and online. Due to the impossibility to change the grid without stopping the process, a two-step optimization procedure has been developed as summarized in Table 1.

Table 1: Two step optimization procedure for shredding processes

| Step | Objective | Input | Output | How |
|---|---|---|---|---|
| 1 | Optimize dimensional distribution of output particles | -Dimensional distribution of input particles<br>-Target output distribution | -Optimal grid size<br>-Related throghput | Offline |
| 2 | Minimize operational costs (energy consumption and tool wear) | -Throghput (from step 1) | -Rotational speed | Online (CPS) |

The first step aims to find the optimal grid to have an output dimensional distribution as similar as possible to the target one (which depends on the particles characteristics necessary for the following steps, both separation or direct re-use). This step takes as input the dimensional (and, if needed, morphological) distribution of the particles in input to the comminution machine and the target output distribution, suggesting the optimal grid size, which could be changed offline, and the related throughput. The second step has the objective to minimize the operational costs, due to energy consumption and tool wear. This step accept as input the throughput calculated in step 1 and suggests the optimal rotational speed. The optimization of this parameter could be done online through a Cyber-Physical System, able to continuously adapt it to the process status.

In Figure 6 this approach for shredding optimization and control is represented. Particles in input are characterized through a particles analyzer. The information are sent to the dimensional distribution optimization module which suggests the optimal grid to the operator, which is able to change it offline **(step 1)**. In the meanwhile, the information on the throughput is sent to the operational cost optimization module, which optimizes and continuously adapts online the rotational speed, obtaining optimal output particles both in terms of characteristics suitable for following processes and in terms of costs, competitive with virgin materials **(step 2)**.

In the next sub-sections, different models present in literature for both steps will shown and discussed as possible solutions for the proposed architecture.

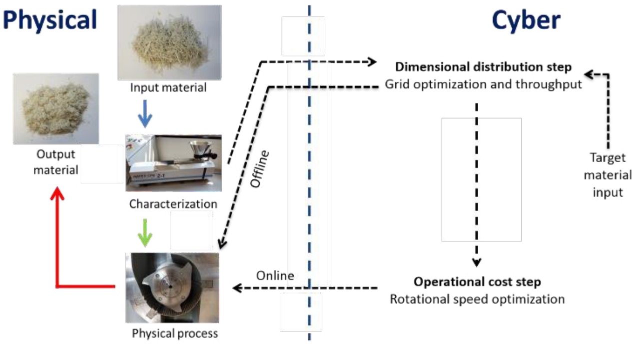

Fig. 6: Optimization procedure for shredding process

### *3.1. First step: dimensional distribution optimization*

Several models have been developed to describe size reduction processes in mineral sector. They are focused on the mineral texture of the particles [24], describing the liberation distribution as a function of particles final size [25][26]. Through Textural Modelling, the evolution of the size distribution along the shredding process could be described starting from the mineralogical information [27][28].

In most of the works, comminution has been described using Population Balance Model (PBM). The idea is to represent the evolution of the particles taking into account the proportion of each partycle type for breakage per resident time unit, the level of breakage for each selected particle and the percentage of particles which exit from the process. In particular, discrete PBMs, both in time and in size, have been used for size reduction modelling. This is due to the possibility to describe the process as the sequence of elementary breakage intervals (short in times) and to the discrete nature of methods for particles classification (as vibrating sieves or particles analyzers). Different models could be found in literature that describe size reduction through PBMs in mineralogical sector [29][30], also integrating non linear effects due to particle-particle interactions [31].

Recycling processes are deeply different from mineralogical ones as they are continuous processes that treat products composed by several materials. Neverthless, only few examples are present in literature that describes shredding in recycling sector. This differences have been outlined and the importance of product design on shredding (and liberation) has been demonstrated [32]. As an example, bonding and joints type strongly influences the results of size reduction [33].

Population Balance Models have been applied to recycling of Printed Circuit Boards [34]. Two different assumptions have been inserted and validated, leading to a portable model that can be trained with a limited set of experiments.

### *3.2. Second step: operational costs optimization*

Operational costs of size reduction processes are due mainly to energy consumption and tool wear. While shredding at higher speeds results in lower residence times, with reduced energy consumption, tool wear increases. For this reason, an optimization of total operational costs is fundamental.

Energy consumption modelling in shredding has been addressed in particular for mineralogical sector [35][36]. Considering the nature of this application, only batch processes have been considered in literature and the interest has been focused only on the relationship between energy consumption and final size of the particles, not taking into account operational parameters. The basic idea, developed and applied to different case-studies [37][38], is that the higher is the difference between input and output particles dimensions, the higher is the energy consumption. A non-empirical relationship has been also developed [39] and validated [40] based on a size-mass balance approach.

Only few works focus on energy consumption in recycling, considering all the possible factors. In a relevant work, an assumption introduced in machining [41] has been adapted [42]. The result is an equation that describes the energy demand for a shredding process dividing it into two different terms, one for the power at zero load, the other related to the power needed to perform only the shredding process. The development of this reletionship considering all the different factors impacting the energy consumption could be used for the modeling and optimization of energy cost.

Also tool wear has been modeled in literature, with a particular focus on machining. It is nowadays consolidated the Taylor’s law for tool wear, in which the life of the tool is related to the cutting speed, the material and the geometry of the tool and the material to cut. The adaptation of this formula to shredding, considering the typical rotational nature of comminution processes could lead to an analytical model that is able to predict the life of the tool as a function of the different operational parameters. Some studies have been performed on shredding, analyzing the relationships among tool wear and size reduction, material to treat and hardness of the tools [43].

## 4. Case study: composite materials

Composite worldwide market is rapidly increasing with a growth rate of 5% in the last years [48]. 95% of this market is composed by Glass Fiber Reinforced Plastics (GFRP) with a total amount of about 2.8 million tons [48]. The result is an increasing flow of End-of-Life GFRP products which are about 98% in weight of total recycled composite materials [49]. One of the most interesting sector for GFRP is wind energy, with an amount of End-of-Life GFRP wind turbine blades that will reach an amount of up to 30,000 tons per year between 2020 and 2030 [50]. Due to fiber degradation of thermal treatments and high costs of chemical recycling, the most suitable route for EoL GFRP products is a mechanical shredding to directly re-use the obtained particles in new products with high-added value. In addition, the low cost of virgin glass fibers force to use optimized processes to obtain competitive processes in terms of revenues. For these reasons, the composite sector has been chosen as case-study. Due to space reasons, the chosen models for both steps will be only presented and not detailed.

For the first step a PBM model has been chosen. Considering a discrete time interval $k$ and a continuous input flow, the equation of the model are as follow.

$$M(k) = P \cdot M^{CH}(k-1) + P \cdot M^{IN}(k-1)$$
$$M^{CH}(k) = (I - D) \cdot M(k)$$
$$M^{OUT}(k) = D \cdot M(k)$$

Where $P$ and $D$ are two matrices that describe, respectively, the probability for a particle to pass from a specific size class to a lower one and the probability for a particle to exit from the shredding chamber. $M$ is the distribution of the mass under processing, $M^{CH}$ is the distribution of the mass in chamber, $M^{OUT}$ is the distribution of the mass in output and $M^{IN}$ is the distribution of the mass in input at each time step considering the saturation of the chamber. The complete treatment of this model is in [34]. The advantage of this model is the limited set of experiments needed to train it.

This model is able to predict the distribution of the mass in output at a specific time step. This information is acquired and elaborated by an optimization module based on least square method which suggests the best grid to use for the process among the several available.

On the other hand, an analytical model as been developed to consider cost optimization which depends both on energy consumption and tool wear. The objective function is the sum of these two terms, both function of rotational speed, which minimization gives the optimal process parameters.

This approach has been applied to shredding of EoL composite products, leading to costs lower than both the virgin material and disposal costs. As an example, shredding to 4 mm of bath tubes made by polyester resin reinforced with 30% of glass fibers in weight results in a total cost of 0,092 €/kg with an optimal rotational speed of 1200 rpm.

## 5. Conclusions and future perspectives

The formalization of Cyber-Physical Systems in de- and remanufacturing has been presented. The scheme proposed has been applied to size reduction process, leading to a two-step architecture for optimization, both in dimensional distribution and operational costs, of comminution. A literature review of possible models for both steps has been presented and discussed and the application on EoL composite products has been shown. The proposed solution is able to optimize the process, enabling a real and robust Circular Economy.

The application of this architecture will be explored in the future considering different interesting waste flows as Lithium-ion batteries and plastics. The general formalization will be applied also to different groups of mechanical recycling processes (as separation stages). The final objective is to integrate the solution at system level to globally optimize the process chain performances.

## Acknowledgments

The authors acknowledge financial support from Horizon 2020 European project FiberEUse “Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites” (CIRC-01-2016-2017, Grant Agreement Number 730323).

## References

[1] Pearce DW, Turner RK. Economics of Natural Resourcing and the Environment. Johns Hopkins University Press 1989.

[2] Ellen Mac Arthur Foundation, 2017, www.ellenmacarthurfoundation.org.

[3] Jovane F, Yoshikawa H, Alting L, Boër CR, Westkamper E, Williams D, Tseng M, Seliger G, Paci AM. The Incoming Global Technological and Industrial Revolution towards Competitive Sustainable Manufacturing. Annals of the CIRP 2008; 2:641–659.

[4] Takata S. Maintenance-centered Circular Manufacturing, Procedia CIRP 2013; 11:23–31.

[5] Tolio T, Bernard A, Colledani M, Kara S, Seliger G, Duflou J, Battaia O, Takata S. Design, management and control of demanufacturing and remanufacturing systems, CIRP Annals Manufacturing technology 2017; 66, 585-609

[6] European Union Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Off J Eur Union. 2008;51:3–30.

[7] Probst L, Frideres L, Pedersen, Demetri D. Clean Technologies: closed loop waste management, EU: Business Innovation Observatory Contract No 190/PP/ENT/CIP/12/C/N03C01, 2014

[8] Faulstich M, Vodegel S, Fedianina E, Franke M, Degener P, Aigner J, Reh K. Umweltschutzgerechte Verwertung nicht etablierter Stoffströme in Abfallverbrennungsanlagen, UBA Schriftenreihe 18/2016. 2016; ISSN 1862-4804

[9] Bloomberg New Energy Finance, 2017, https://about.bnef.com/

[10] http://www.pricepedia.it/

[11] King AM, Burgess SC, Ijomah W, McMahon CA. Reducing Waste: Repair, Recondition, Remanufacture or Recycle? Sustainable Development 2006; 14, 257–267.

[12] Park KJ, Zheng R, Liu X, Cyber-physical Systems: Milestones and Research Challenges. Editorial Computer Communications 2012; (1):1–7

[13] Monostori L, Kádár B, Bauernhsansl T, Kondoh S, Kumara S, Reinhart G, Sauer O, Schuh G, Sihn W, Ueda K. Cyber-physical Systems in Manufacturing. Annals of the CIRP 2016; 65(2):621–641

[14] BaZMod consortium. Component Specific Machine Tool Configuration by the Use of Additional Cyber-physical Modules 2016, http://www.bazmod.de/

[15] Takata S, Kirnura F, van Houten FJAM, Westkamper E, Shpitalni M, Ceglarek D, Lee J, Maintenance: Changing Role in Life Cycle Management. CIRP Annals – Manufacturing Technology 2004; 53(2):643–655

[16] Kemeny Z, Beregi RJ, Erdos G, Nacsa J. The MTA SZTAKI Smart Factory: Platform for Research and Project-oriented Skill Development in Higher Education. 6th CIRP Conference on Learning Factories 2016, Gjøvik, Norway

[17] Kemeny Z, Nacsa J, Erdos G, Glawar R, Sihn W, Monostori L, Ilie-Zudor E, Complementary Research and Education Opportunities – A Comparison of Learning Factory Facilities and Methodologies at TU Wien and MTA SZTAKI. CIRP Conference on Learning Factories 2016; Gjøvik, Norway

[18] Manyika J, Chui M, Bughin J, Dobbs R, Bisson P, Marrs A. Disruptive Technologies: Advances that will Transform Life, Business, and the Global Economy. McKinsey Global Institute 2013, San Francisco

[19] Gao J, Chen X, Yilmaz O, Gindy N. An Integrated Adaptive Repair Solution for Complex Aerospace Components Through Geometry Reconstruction. International Journal of Advanced Manufacturing Technology 2008; 36:1170–1179

[20] Stark R, Grosser H, Muller P. Product Analysis Automation for Digital MRO Based on Intelligent 3D Data Acquisition. Annals of the CIRP 2013; 62(1):123–126

[21] Picone N, Colledani M, Copani G, Diani M, Tolio T. Towards Smart E-waste demanufacturing systems exploiting Cyber-physical Systems (CPSs) capabilities. Electronic Goes Green—EGG 2016, Berlin

[22] Oliveaux G, Dandy L, Leeke G. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting poperties. Progress in Materials Science 2015; 61-99.

[23] Colledani M, Tolio T. Integrated process and system modelling for the design of material recycling systems. CIRP Annals-Manufacturing Technology 2013; 62, 447-452.

[24] Gaudin AM. Principles of Mineral Dressing. 1939; vol. 351. McGraw-Hill, New York.

[25] King R. A model for the quantitative estimation of mineral liberation by grinding. Int. J. Miner. Process 1979; 6, 207e220.

[26] King R, Schneider C. Mineral liberation and the batch comminution equation. Minerals Engineering 1998; 11, 1143-1160

[27] Gay S, Wei X. Liberation modelling using a dispersion equation. Minerals Engineering 1999; 12, 219-227

[28] Gay S. A liberation model for comminution based on probability theory. Minerals Engineering 2004; 17, 525-534

[29] Broadbent S, Calcott T. A new analysis of coal breakage processes. J. Inst. Fuel 1956; 29, 524e528.

[30] Veroux A, Grotti D. Modeling and Optimization of a Multi-stage Shredding separation Systems for Recycling. Master Thesis in Industrial Engineering, Politecnico di Milano, Milan, Italy, 2010.

[31] Bilgili E, Capece M. Quantitative analysis of multi-particle interactions during particle breakage: a discrete non-linear population balance framework. Powder Technol 2011. 213, 162e173.

[32] Schaik AV, Reuter M, Heiskanen K. The influence of particle size reduction and liberation on the recycling rate of end-of-life vehicles. Minerals Engineering 2004; 17, 331-347

[33] Castro M, Remmerswaal J, Brezet J, Schaik A, Reuter M. A simulation model of the comminution-liberation of recycling stream. Relationships between product design and the liberation of materials during recycling. International Journal of Mineral Processing 2005; 75, 251-281

[34] Diani M, Pievatolo A, Colledani M, Lanzarone E. A Comminution Model with Homogeneity and Multiplication Assumptions for the Waste Electrical and Electronic Equipment Recycling Industry. Journal of Cleaner Production 2019; 211 665-678.

[35] Charles RJ. Energy–size reduction relationships in comminution. Trans. AIME 1957; 208 80–83.

[36] Bond FC. The third theory of comminution. Trans. AIME 1952; 193 484–494.

[37] Bond FC. Confirmation of the third theory. Trans. AIME 1960; 217 139–153.

[38] Austin LG. A commentary on the Kick, Bond and Rittinger laws of grinding. Journal of Powder Technology 1973; 7 315–318.

[39] Kapur PC. Self-preserving size spectra of comminuted particles. Chem. Eng. Sci. 1972; 27 425–431.

[40] Gupta VK. Validation of an energy–size relationship obtained from a similarity solution to the batch grinding equation. Powder Technology 2013; 249 396–402

[41] Gutowski T, Dahmus J, Thiriez A. Electrical energy requirements for manufacturing processes. 13th CIRP International Conference of Life Cycle Engineering 2006.

[42] Shuaib NA, Mativenga PT. Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites. Journal of Cleaner Production 2016; 120 198–206.

[43] Savage GM, Trezek GJ. Significance of Size Reduction in Solid Waste Management: Volume 2. Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency 1980.

[44] Weyer S, Schmitt M, Ohmer M, Gorecky D. Towards Industry 4.0 – Standardization as the crucial challenge for highly modular, multi-vendor production systems. IFAC-PapersOnLine 2015; 48-3 579–584

[45] Lee J, Bagheri B, Kao H. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters 2015; 3 18–23

[46] Manyika J, Chui M, Bughin J, Dobbs R, Bisson P, Marrs A. Disruptive Technologies: Advances that will Transform Life, Business, and the Global Economy. McKinsey Global Institute 2013, San Francisco

[47] Sharpe RG, Goodall PA, Neal AD, Conway PP, West AA. Cyber-Physical Systems in the re-use, refurbishment and recycling of used Electrical and Electronic Equipment. Journal of Cleaner Production 2018; 170 351-361

[48] Witten E, Sauer M, Kühnel M. Composites Market Report 2017. Industrievereinigung Verstärkte Kunststoffe September 2017; 1-54.

[49] Gutiérrez E, Bono F. Review of industrial manufacturing capacity for fibre-reinforced polymers as prospective structural components in shipping containers. Report of the Joint Research Centre of the European Commission; 2013.

[50] Faulstich M, Vodegel S, Fedianina E, Franke M, Degener P, Aigner J, Reh K. Umweltschutzgerechte Verwertung nicht etablierter Stoffströme in Abfallverbrennungsanlagen, UBA Schriftenreihe 18/2016. 2016; ISSN 1862-480