Environmental Engineering and Management Journal October 2020, Vol.19, No. 10, 1823-1829
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

PVCUPCYCLING - CIRCULAR ECONOMY AND ZERO WASTE: "UPCYCLING" WASTE FROM ELECTRICAL SYSTEMS

Consuelo Nava

ABITAlab, Department Architecture and Territory, Mediterranea University of Reggio Cal. (IT)
E-mail address: cnava@unirc.it; Phone: +039 (0)965 1697244

Abstract

A circular economy system will allow company to directly operate an effective re-cycling policy. Establishing a new "zero waste" impact scheme, in order to recover by-products from the production process, thus leading to an increased market price in comparison to their economic value, and by doing so with full respect of the blue and circular economy standards applied to the product. The main objective of the PVC upcycling project is to facilitate the transition of R.ED.EL.'s current production chain, from an economically linear model to a circular type. This is achieved through actions that aim to recycle PVC (polyvinyl chloride materials) from electrical cables ("de-manufacturing") to upcycling the same PVC into new products with a low environmental impact ("re-manufacturing"). While working from the de-manufacturing phase to the re-manufacturing phase, activating circular models with new PVC-MPS supply chains, and implementing experiments in specifically illustrated scenarios, it has also been possible to build a collaborative platform to exchange information. This process intercepts the eco-design phase thus realizing the possibility of intervention in the production of PVCupcycling prototypes.
The project won the regional competition of Calabria (EU funds-POR Calabria 14-20 axis I-action 1.2.2) and has received European funding for the "Promotion of Research and Innovation" thanks to the proposal of the following team: R.ED.EL., a media manufacturing company, in collaboration with ENEA, an Italian energy specialist research organization, UNICAL, a chemistry specialist organ-isation based at the University of Calabria, PMopenlab, an innovative eco-design and additive manufacturing start-up. C.Nava is the technical-scientific team man-ager, a sustainability and design innovation research specialist.

Key words: circular economy, eco-design, smart manufacturing, upcycling, zero waste

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

With this project R.ED.EL. aim to reach new possibilities, such as advantageous technical solutions to reuse the so-called waste material and place it into the manufacturing chain. They should also expect to gain leadership in an accelerating market, and so pursuing a real innovation strategy based on three dimensions of sustainability: environmental, economic and social. In the first experience the strategy will trigger "the transition from a linear to a circular economic model", increasing the performance level of new products and services, and enhancing skills for the operators who are involved in the process. By implementing a new design, we change the organization and function of the current model, which is centralised and therefore the project's methods are easy to apply. Thanks to this new design the company is able to control the quality of service in their "end of life cycle".

In favourable terms, the following scenarios are implemented for the company: investments in technology with a higher performance rating; significant improvements to the consequential processes of a recycling chain; integration of present machinery and the "additive" digital printing technologies necessary for prototyping a typical eco-design. New procedure and application protocols will be introduced ultimately contributing to a larger employee capacity with both scientific and consultancy partners. The proposal for the PVC upcycling project calls for an innovative circular chain inserted into an energetic and chemically dynamic environment, from which there is a feed of raw material which consequently has new resources. The company is placed directly into the innovative life cycle of technology contributing to endorsers being labelled as "innovators" (. Such early adopters are identifiable as those who embrace new technologies, and whose radical inventions are characterized by originality and design complexity.

Objectives: The project's specific innovative objectives adhere to experimental developments and industrial research, to which a circular production chain is complimentary. In detail the project addresses:

1) *Procurement of raw materials:* this is the first step of the circular model, with the specific objective of "rethinking" which raw materials are usable in the production process. In the proposed project while recording the characteristics of RAEE, PVC, and other such plastics coming from electrical cables, it will manifest itself that they have historically been single-use materials. Their history as scrap waste is based on the material consistency of the components during their time of use in the first life cycle.

2) *Design:* this second step of the circular model presents a specific objective for directing the products life cycle towards a reliable performance. The project will be realized through the eco-design model ideal "Cradle to Cradle", which will be separated into two different levels. We can define the first level as “capacity building”. Dedicated “design driven innovation” laboratories have been founded in order to create relational assets and employ the following four activities: I. Strategies, II. Development and Renewal, III. Interpretation of the Research Advancements, whereby a workshop system enables improvements of methods and equipment so that products can be developed into a prototype concept; IV. Design of the Graft Discours, this increases the company's reputation and begins attracting new competitors and stabilizing our market. The second level concerns itself with “smart manufacturing” which requires a prototyping identification phase for the product's components and its smart solutions, making use of unconventional technology and its high productivity.

3) *Production:* is the third step in the circular model and has the specific objective of reconstructing the production chain towards a zero-waste system, labelled “recovery and recycling”. This phase will perform the following strategies: - Strengthen the activities related to an "end of life" process in current systems and the relative disposal of electrical cables, leading to the increment and recovery of recyclable and reusable materials for other uses. (Fig.1) - Innovating the operation, the equipment and the platforms which are available to the company. - Modernization of sustainability models for experiments with advanced technology and increased momentum on the company's own consolidated strategy, which seeks to provide exemplary processes to reduce their impact on the environment.

4) *Distribution:* in this fourth step, of the circular model, the specific objective is to modify the core business strategy. Services will be available while supplying the products, emphasizing that the customer's sustainability objectives have been met: an efficient environmentally-energetic performance, a low environmental impact, and a circular qualification of services.

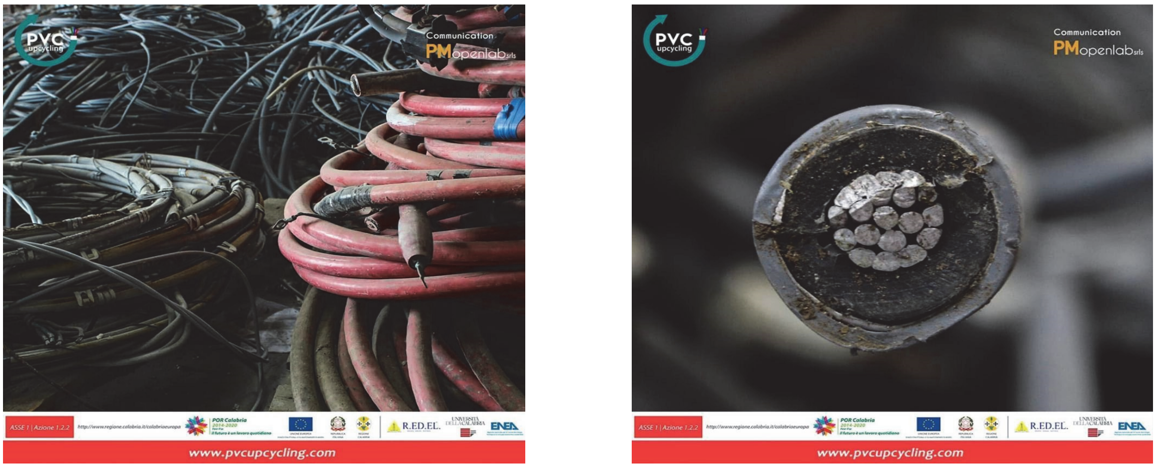
5) *Consumption:* in the fifth step of the strategic circular model the specific objective is to contribute to a new pattern, that ultimately aims to minimize the impact on the environment by reducing the amount of waste that is sent to landfill. This fits in well with R.ED.EL.'s particular production structure, which manages the end of life cycle system and can accordingly move towards expanding the supply chain to recycle all the electrical cable components, thus centralizing operations and allowing a stronger flow of resources in a renewed supply chain model.

6) *Collection-Recovery and Recycling:* the sixth and seventh steps in the circular model phase are connected by the same objective, which is to instruct the organizational and production of a model that is capable of changing the business' paradigm. There will be modifications to the company's operational internal economics, as well as research and developments becoming externally more competitive. In R.ED.EL.'s case these changes will be achieved by preserving quality, especially in the processes and products coming from its own production chain, thus intensifying innovative designing for new higher level products, namely, upcycling. Taking note of the logistical reserve return on the original prototype in comparison to the outgoing return on the new products that use electrical cables for the construction of plants during their first life cycle. These steps involve designing new levels of management for "zero waste", with a supply chain that reconfigures the existing activities with new products in order to maximize the effectiveness of knowledge systems. Thus, understanding the movements between matter and incorporated energy, while analysing each new phase of the production cycle: resources, paths, values and direction of innovation (LCA and LCC and Design Driven Innovation Model).

2. Case studies

2.1. Strategy: the innovation process and the product's transformation

The "zero waste" strategy in PVCupcycling is applied to the entire production chain; innovation feeds to the generation of new technical-scientific know-how, increases competitiveness in all the operational-technical phases of design, use, maintenance, reusing, regeneration and recycling. This addition also interfaces with those of the "circular" supply chain to business on the value chain; the company goes through the phases of procurement, manufacturing, marketing and sales, product use, product disposal, and as well as, the development of a new product. (Fig.2)



a b

Fig. 1. Waste and scrap materials from electrical cables (PMopenlab communication, 2018):
(a) The storage of disused cables from renewed electrical systems;
(b) the section of an electric cable with all component materials in plastic and aluminum and copper

R.ED.EL. is inspired by "a vision of enterprise on the possible disruptive meanings of the new product and process languages typical of technology-push" as Nava (2019) demonstrated, and thanks to this project the dream is attainable. Achieving new possibilities and advantageous technical solutions for reusing the so-called "waste" material and reworking it into its own work cycle, as well as gaining leadership in a fast-growing market, thus pursuing a real innovation strategy. Therefore, the PVCupcycling project involves both the "process" and the "product's chain" that has already been produced by R.ED.EL.

The proposed project activity is divided into actions related both to "industrial research" (IR) and to "experimental development" (ED), as defined in the six following WP's:

- WP1 (IR) is dedicated to assessing the sustainability of the activities developed on industrial waste, and whether they are in accordance with the criteria of the circular economy and whether these industrial activities lead towards a zero waste outcome.

- WP2 (IR), addresses the issue of a "Life Recycle Assessment". The production chain is defined by assimilating the instruments that are already available in the company with the newly acquired supplementary equipment in the current project. This type of integration is achieved by MIMPRENDO's actions in the start-up project. Particularly the essential knowledge that will be shared among partners, especially that which is obtained from the second raw material while improving the use of PVC.

- WP3 (IR) is mainly dedicated to identifying the possible application fields for experimentation with the reuse of PVC, which constitutes the second raw material for the project. After an exhaustive characterization both from a chemical and physical point of view of the second raw material (PVC), potential smart solutions for hybridization with other materials will be investigated in the laboratory. In-depth feasibility studies will be developed in labs which will then be the subject of further study in subsequent calls.

- WP4 (ED), has as its purpose in the development of PVC application prototypes, in which characterization tests will be carried out according to the technical standards in force.

- WP5 (ED), defines the LCC (life Cycle Cost) of the defined experimental prototype and the actions for the positioning of the company in the Circular Economy Network.

- WP6 (ED), contains the dissemination and exploitation activities of the results.

2.2. Re-manufacturing and ecodesign for additive manufacturing

The reused PVC from electric cables waste will be applied in the first commercial facing tiles pre-prototypes - categorized as experimental development - and in composites based on cement mortars, which is classified as industrial research. These groups are potentially applicable for the same company in laboratory and warehouse building works, referring to the management of electricity networks and related civil works. Other highly specialist hybrid scenarios are assembled with the use of additive technologies with a digital control process, in which the eco-design is innovated towards the production of sustainable scenarios (such as, a green parking scenario).

In addition to the above objectives we will investigate the physical, mechanical and environmental stress resistance characteristics of the composite materials obtained. As well as environmental testing we seek to define a performance profile of the products, with reference to the technical characteristics, summarized in a "sustainability toolbox".

The main phases of the re-manufacturing process can therefore be characterized by achieving the intended objectives, each of which is described in a process component, as listed below:

- traceable components: selection, characterization and definition of waste materials used as MPS (mapping and physical/chemical and morphological analysis);

- high performance components: energy-environmental profile, CO_2 expenditure, and recovery for the manufacturing of products from the recycling processes;

- "Cradle to Cradle" recycle components: industrial eco-design, operations, and prototype methods of additive manufacturing (3D printing);

- high performance components: references and collections of information and techniques for LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) components;

- trademark products: protocol and technical description for Environmental Product Declaration (EPD pre-qualification);

- commercial products: qualifications for products and possible suppliers for all operations within the production chain (possible route marking on commercial prototype components and patents).

All the prototypes are made with scenarios in the R.ED.EL. and PMopenlab srls laboratory environment, and have in-situ applications and/or different alternatives, in order to test installation and in-use responses. This activity refers to the following definition: an eco-design based on a "Innovation Driven Design" process; tests to be performed on material and system components; hybridization capacity with other aggregating materials and system compatibility for stratified or mixed components; preparation of technical data sheets relating to the scenarios; the matrix on PVC waste value in various contexts; a feasibility study in additional states for the associated design, as well as those tested in the construction site-laboratory.

Scenario no. 3 in the R.ED.EL. construction site-laboratory uses hybrid PVC components, such as MPS, in different consistencies, for example loose powder or powder printed on more than one format. The aim is to account for the quantity of recycled PVC on a functional unit and also define an environmental-energy profile for the CO_2 reduction that corresponds to the realized system.

For that reason it is a question of pursuing two other objectives for the pre-prototype phase: to assess which pre-commercial product can be found when triggering an available sector of the industrial chain, discovering which technologies are already available in the company (results based upon realized scenarios), and the effects of a circular economy at zero waste on the business model and innovative recycling-recovery chain; to evaluate which competitive markets can accommodate higher quality products and which technologies should be activated when widening the technical and economic scale of the company (scenarios to be realized soon). Employing not only a circular model with centralized logistics, but also a "product as a service" model working externally, thus triggering other supply chains and other business space opportunities. Three scenarios have been enabled concerning the field of sustainable building, featuring the PVCupcycling experiments from the site's workshop, the in-situ testing activities with R.ED.EL. and PMopenlab (Fig. 3), and environmental tests on the by-products in ENEA and UNICAL laboratories. (Fig. 4)

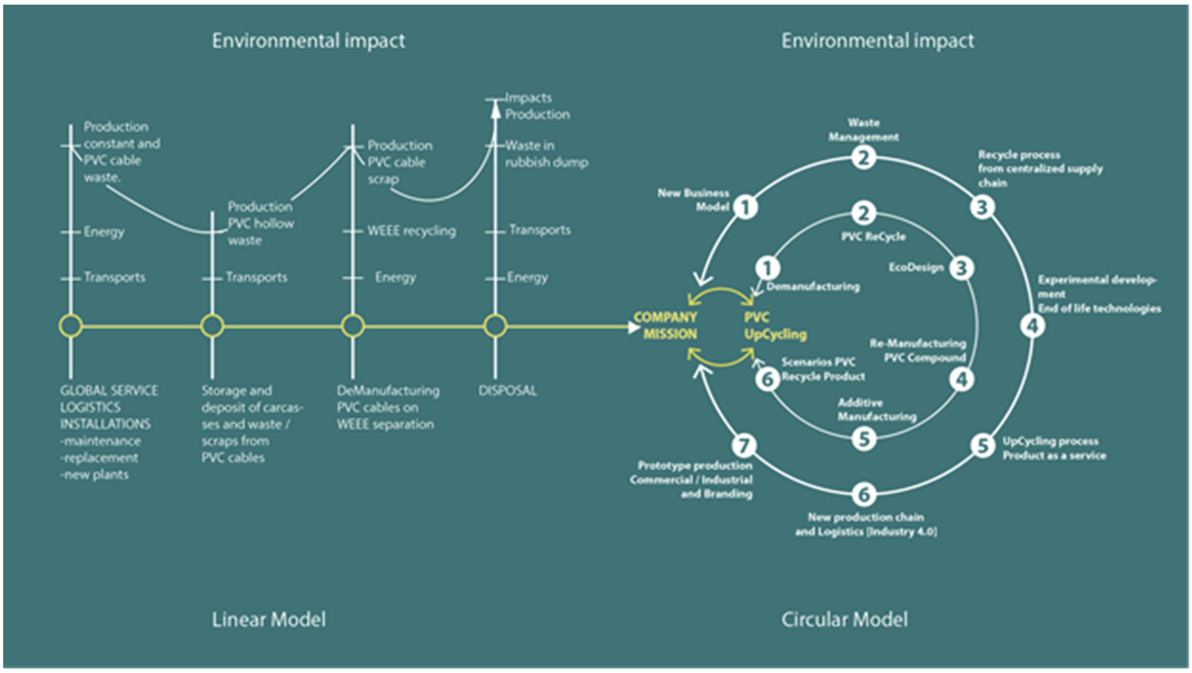
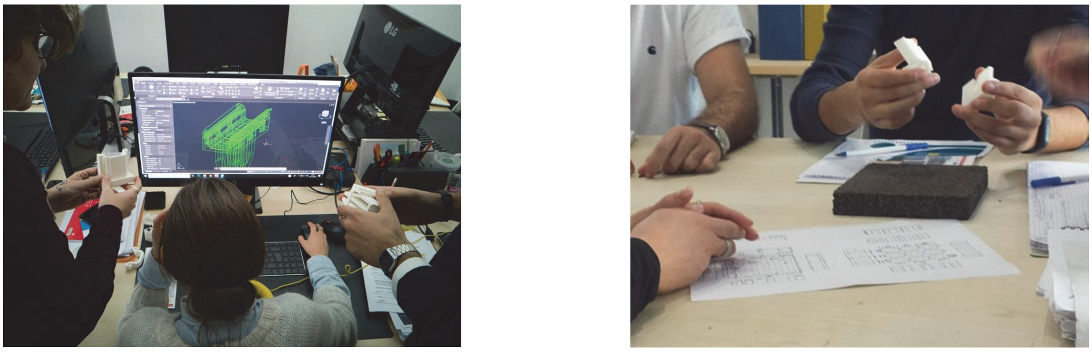


Fig. 2. From the Linear Management of PVC Cable Waste to the Circular Model of Multiple PVCupcycling Chains (Nava and Lucanto, 2020)



(a) (b)

Fig. 3. Laboratory of Eco-Design and Additive Manufacturing (PMopenlab; Reggio Cal., Italy):
(a) represent the model form manufacturing design phase
(b) represent the verification of compatibility between components to be integrated into the scenario system

(a) (b)

Fig. 4. Testing in ENEA and UNICAL Diatic Laboratory (Lucanto and Procopio, 2019)
(a) represent the samples of the virgin separated from the metallic matrices
(b) represent the first test of forming the in the mold for the press and the realization of the thickness block for the green parking

3. Results and discussion

3.1. Scenarios and area-testing

In the PVC upcycling experimentation, the manufacturing phase, which includes the supply chain and the services required for the logistical storage of cables, c/o R.ED.EL. company, is 90% covered in terms of energy consumption from the presence of photovoltaic system that has been installed in their industrial buildings. In this sense, for the integration of this energy production technology, the supply chain can be said to be more efficient and sustainable, even in the subsequent phases.

But it is clear that the de-manufacturing and re-manufacturing phase must consciously absorb what is consumed in the middle phase and move towards the afore mentioned sectors by applying sustainability principles and eco-labeling certification models that guarantee the product is coming from the recycling chain. Other production manufacturing processes do not require such an impactful method thus allowing a secondary raw material, such as the PVC compound, to be recycled as a primary, or inert, component for other hybrid systems. This may then be reintroduced into new models of use. Throughout the re-manufacturing phase it is important that the circular economy model triggers processes for ‘industrial symbiosis’ in sectors that are preferably able to take charge of other phases of the sustainable production chain. These may include but are not subject to; sustainable construction, green products, recycled products, etc. **In any case it is estimated that for every kg of recycled cable it is possible to obtain a 2kg saving of CO2 which is not emitted into the atmosphere. (VinylPlus, 2013).** Three scenarios have been enabled concerning the field of sustainable building, featuring the PVCupcycling experiments from the site’s workshop, the in-situ testing activities with R.ED.EL. and PMopenlab, and environmental tests on the by-products in ENEA and UNICAL laboratories (Nava and Lucanto, 2020).

Scenario 1: Coating for outdoor flooring - type A: recycled PVC tiles on existing reinforced screed. Experimenting on the laboratory site involves setting up the scenario on an existing resistant screed that forms the base of the external steel staircase of the R.ED.EL. offices. A tile mat is constructed almost entirely of virgin WEEE PVC and has a surface area of 120x55cm and dimensions 5x7x0.5cm. Two-component polyurethane sealants are used for fastening at the base of the existing screed and adhesive-putty hybridized with PVC powder is used for filling joints between briquettes (Fig.5).

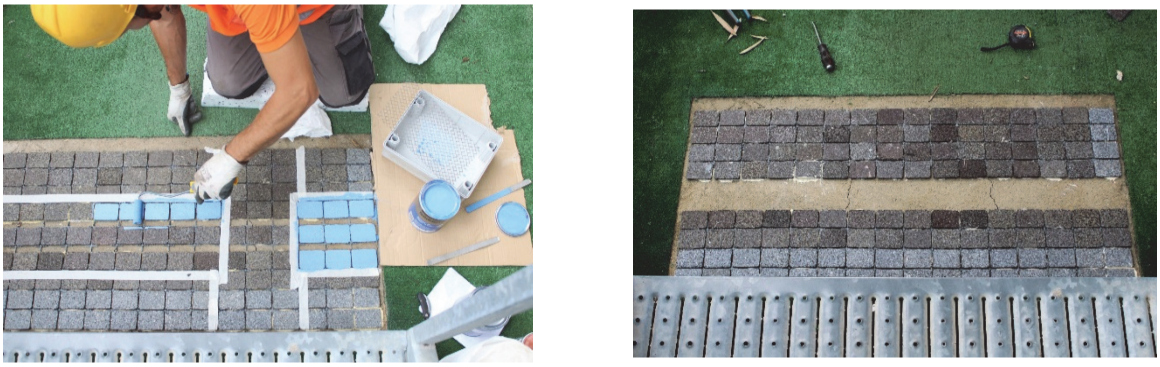
COMPONENTS: Two-component polyurethane sealants, two-component epoxy adhesive putty, recycled PVC powder, pre-painting water-based primer + fast-drying water-based enamel. IMPACTS: kg of PVC per square meter of each scenario: 3.5kg PVC; kg of CO_2 saved per square meter of each scenario: 7kg CO_2; Hours of work necessary for installation: 6h

Scenario 2_ Construction of a driveway for vehicles for handling small loads - using virgin PVC powder hybridized in cement mortar. A pedestrian area is built in front of an entrance of the company's building, with a resistant screed featuring an electro-welded mesh. Using a hybrid mixture of 75% recycled materials, with one-part concrete, one-part recycled PVC powder and one-part wielding aggregates from the company's decommissioned activities and recyclables. (Fig.6)

COMPONENTS: 25kg concrete, 24kg PVC powder, 50kg aggregates (on a functional unit of 1sqm/18cm of thickness), 10x10 welded mesh. IMPACTS: kg of PVC per square meter of scenario put in place: 24kg PVC; kg of CO_2 saved per square meter of each scenario: 50kg of CO_2; Hours required for installation: 16h for 5sqm.

Scenario 3_ Green Parking consists of a road section with draining asphalt and thick blocks made of recycled PVC - the system is hybridized with additive technologies - 3D printing of components and MPS PVC blocks. The experiment carries out what is foreseen in the project in terms of additive manufacturing and scenario realization for the hybrid components which come from eco-design processes. We seek to create a functioning, highly resilient green parking unit measuring 280x450cm. This construction will be with an integrated water absorption system in order to create a permeable and semi-permeable plant and gravel surface, with the completion screed already tested (as in scenario 1) and with a printed and modular system for the disposal of rainwater, which acts as a channel and a joint. The loading surface is reinforced by an alveolar mesh in printed PLA (polylactic acid – bioplastic), this houses the thick blocks of recycled PVC, and the permeable and semi-permeable filling, thus allowing the connection of the component-modules to the water disposal system. The latter, sized and built in the functional unit, responds in a short time to an overloaded capacity from rain washout (water bombs), with a system capacity of about 1.61 cubic meters.

The conveyed water can be recovered and reused to soak the same permeable surface, or for maintenance and waterproofing. Furthermore, 3D printing can be used to form the component prototypes; a mold for production with other performing materials, and one that is in line with industrialized processes. The use of additive technologies has triggered a process of eco-design and engineering of the components which are described in this report's annex in all its phases (WP5.2). (Fig.7)



(a) (b)_

Fig. 5. Area Testing Scenario 1 (R.ed.el Lab., 2018, Reggio Cal., Italy) (a) represent the coloring of the coating for outdoor flooring (b) represent the test of the joint thicknesses between tiles with recycled PVC powder

(a) (b)

Fig. 6. Area Testing Scenario 2 (R.ed.el Lab., 2018, Reggio Cal., Italy) (a) represent the preparation of the components for the mixture of the mortar (b) the realization of the 2nd scenario in the testing area

(a) (b)

Fig. 7. Area Testing Scenario 3 (PMopenlab, R.ed.el Lab., 2018, Reggio Cal., Italy) (a) represent the implementation of recycled and printed components, (b) the final construction already in function of the green parking unit.

COMPONENTS: 58 thick blocks in recycled PVC (16.30x17.31x5.00cm); 58 lodgings for recycled PVC blocks (16.60x15.60x3.40cm), 33 alveolar modules (18 for grass, 15 for gravel) of the size 16.60x15.50x5cm; 4 structural joints in PLA printed in 3D, 52 elements for the water storage system in PLA printed in 3D. IMPACTS: Kg of PVC per square meter of scenario put in place: 24kg PVC; kg of CO_2 saved per square meter of each scenario: 50kg of CO_2.

4. Conclusions

A "recovery and recycling" business model shifts the company's interest towards "value", not only in the quality of service and goods, but also the waste materials' phases of life in which its energy can flow efficiently through production logistics.

In this first phase of centralized logistics, the "product as service" customer is the company itself, which acts on its own waste, aiming for a low-impact "zero waste" management model, recovering and re-using its waste.

In particular, with only centralized production for its own supply chain, the company, at its maximum, produces around 960 tons per year of incoming cable scrap; half of this quantity is not sent to landfill but put back on the market and produces a gain of approx. 800,000€ for copper and for aluminium 250,000€. According to the objectives of this proposal by recycling and adding value to PVC waste, i.e. changing it from a compound to a second raw material, we will be able to attain the other 50% of scrap as a unit of cable material, saving about 140,000€ on the cost of plastic disposal, thus rendering it useful for the reinstatement of re-manufacturing into the economy. It is a question of activating an economical valuable chain with "direct" economic benefits for the company and with obvious savings for the costs of transfer to landfill and which translate into revenues for recycling activities. Other benefits are "indirect", from the management for zero waste, which reduces the environmental impact and the disposal chain for an "end of life" cycle (waste, transport, emissions, receiving systems etc. ...).

Acknowledgements

R.ED.EL s.r.l., U. Barreca (Company manager and technical manager) - Prof.ssa Arch. C. Nava (Professor Assistant UniRC/ Scientific Project Manager) | Partners: ENEA, Ing. C. Sposato (Project Contact), Ing. P. De Fazio (Manager DTE-SAEN), Ing. A. Feo (Researcher), Per. Ind. M. B. Alba (Technical Assistant), Ing. Arch. T. Cardinale (Researcher junior) - UNICAL-Dipartimento DIATIC, Prof. Ing. M. Migliori (Project Contact), Prof. G. Giordano (Full Professor of Environmental Chemistry, Dott. A. Marino (PhD student - SIACE Unical) Remanufacturing/Smart solutions - Dissemination and Branding: PMopenlab S.r.l.s whit Arch. A. Procopio, Arch. G. Mangano, Arch. A. R. Palermiti, Arch. D. Emo and Arch. D. Lucanto, Arch. G. Arena, Arch. F. Autelitano (Assistants) – Patents: Ing.Pasquale Cuzzocrea (Certifier)

References

Lucanto D., Procopio A., (2019), *Ecodesign and Manufacturing in Waste Enhancement Processes for PVCupcycling*, Proc. of Green and Circular Economy: Research, Innovation and New Opportunities, Maggioli, Rimini, 107-113.

Nava C., (2019), *Hypersustainability and Enabling Technologies. Theory, Method and Design*, Aracne, Roma, Italy.

Nava C., Lucanto D., (2020), *Eco-Innovative Scenarios for Smart Materials. The PVCupcycling Project – Circular Economy and Zero Waste*, Int. Symp.: New Metropolitan Perspectives, vol. 178, 1458-1467.

Vinylplus, (2013), *The recycling of PVC cables,* PVC Forum Italia, Dossier, On line at: https://vinylplus.eu/index.php?mact=CommunicationProjects,m81d23,default,1&m81d23published_on=2013&m81d23pager_limit=8&m81d23pager_size=5&m81d23pager_page=2&m81d23returnid=77&page=77.