Environmental Research and Technology
https://ert.yildiz.edu.tr - https://dergipark.org.tr/tr/pub/ert
DOI: https://doi.org/10.35208/ert.1150743

Research Article

A process "algorithm" for C&D materials reuse through file-to-factory processes

Marina RIGILLO[1], Sergio Russo ERMOLLI[1], Giuliano GALLUCCIO[*1], Sara PICCIRILLO[1], Sergio TORDO[1], Flavio GALDI[2], Michela MUSTO[3]

[1]*Department of Architecture, Federico II University of Naples, Naples, Italy*
[2]*ETESIAS, Corso Nicolangelo Protopisani, Naples, Italy*
[3]*The Spark Creative Hub, Naples, Italy*

ARTICLE INFO

Article history
Received: 29 July 2022
Revised: 31 October 2022
Accepted: 19 November 2022

Key words:
Circular economy; C&D waste; Urban regeneration project; 3D print technology

ABSTRACT

The paper illustrates some of the ongoing results of the interdepartmental research Prosit "PROgettare in SostenibilITà: qualification and digitalization in construction", analyzing the key steps aimed at testing, within the actual regulatory and technological framework, new possible applications of recycled materials from construction and demolition (C&D) in sustainable and innovative supply chains. In Italy, in particular, about 98% of the non-hazardous waste from C&D activities is recycled already in 2018, as documented by the Eurostat's "Recovery rate of construction and demolition waste" report. Nevertheless, C&D waste is mainly reused for the construction of embankments and road foundations. The research, therefore, identifies in the use of file-to-factory technologies a possible way to extend the scope of the reuse of these resources to realize diversified and non-standard manufactures and components, in the perspective of a greater spread of virtuous practices of circular economy in the construction sector. In this sense, a process "algorithm" is described, designed to be scaled and replicated in different contexts for similar purposes.

Cite this article as: Rigillo M, Ermolli SR, Galluccio G, Piccirillo S, Tordo S, Galdi F, Musto M. A process "algorithm" for C&D materials reuse through file-to-factory processes. Environ Res Tec 2022;5:4:340–348.

INTRODUCTION

The need to promote circular economy to reduce the consumption of renewable resources has long been identified in European policy as one of the key issues of the environmental challenge. Notably, the EC Report for the implementation of the Second Action Plan for the Circular Economy addresses the circular initiatives as «a backbone of the EU industrial strategy, enabling circularity in new areas and sectors, [so that] life-cycle assessments of products should become a norm and the eco-design framework should be broadened as much as possible» [1]. Similarly, the EU investments for the circular economy (2016–2020) reached almost 10 million euros, intercepting both the research programs (Horizon 2020 funds and other programs), and the economic and industrial pol-

***Corresponding author.**
*E-mail address: giuliano.galluccio@unina.it

This paper has been presented at Sixth Symposium on Circular Economy and Urban Mining (SUM 2022)/Capri, Italy / 18–20 May 2022.

Published by Yıldız Technical University Press, İstanbul, Türkiye

icies (Cohesion Policy 2016–2020, European Fund for Strategic Investments and Innovfin). Despite these efforts, operational practices are struggling to reconvert the typical "take-make-dispose" process into widespread circular practices. The latter fails due to roughly three groups of reasons: economic interests, environmental concerns, and regulatory requirements [2]. In particular, limits to a more effective approach to waste management concern the difficulty in a exact quantification of waste due to illegal abandonment and the lack of an on-site monitoring system for non-dangerous waste. Also, circular processes are hindered in some UE country because of low prices for landfilling and for raw materials [3].

Especially for Construction and Demolition (C&D) waste, these factors affect the development of new production processes aimed at reducing the withdrawal of natural resources (especially land-take), and at extending the material life-span. The introduction of circular processes in the construction sector finds, in fact, its main barriers both in the technical background of experts and firms, both in the operational practices, and in the specific C&D waste regulation [4].

In the wake of the depicted scenario, the study aims at outlining a methodological process for shortening the C&D supply chains. The paper presents here the advances of the POR CAMPANIA FESR 2014/2020 research, titled "Prosit - Design in Sustainability: qualification and digitization in construction". The study concerns the application of the selective demolition process in the urban regeneration yard with the aim of testing the opportunities for recycling "in situ" the waste produced through BIM-based file-to-factory processes.

Circular Building Process in Italy: State of the Art

In Italy, the reuse, recovery and recycling of the outcomes of the complete or partial buildings demolition fails to enhance the development of supply chains consistent with the operational potential offered by the sector, nor is able to create a reference for a Secondary Raw Materials (SRM) market to be re-introduced in the construction sector [5]. The 2021 ISPRA Report on special waste highlights that of approximately 78% of inert material recovered, only a few parts are reintroduced into the construction sector, while the greater volumes are addressed to backfilling [6]. The Italian scenario is also characterized by great variability between Regions, due both to the differences in the degree of industrial development in the Country, and to the local regulations [7]. Further distinctions are recognizable in the technological and material specificity of the regional building heritage, which shows significant differences in terms of construction techniques, ages of construction, and the industrial capacity of the building sector.

In general terms, however, the difficulty in getting systemic procedures capable of integrating the various actors and contexts off the ground can be traced back to some factors characterizing the Italian system, as well as the lack of procedural tools for providing a guideline and protocols for the construction sector. In this regard, there is a certain delay in the introduction of innovative and circular processes within consolidated construction practices, as well as a weakness in the political direction. The latter, especially, seems to be unable to take fully advantages of the opportunities offered by the digital technologies, notably those aimed at Information Management, that allow to model the production of C&D flows and their traceability. Public policies seem unable to find the conceptual and legislative framework to reduce C&D production. This objective involves a combination of strategies aimed both at reducing C&D waste volumes and at enhancing SRM's performances so that the latter can be re-introduced into the construction cycle.

C&D Waste Criticalities in the Light of Enhancing the Concrete Supply Chain

The C&D waste recovery is a key issue for reducing the land-take, and the environmental impacts of the full construction chain. In particular, it should be emphasized that the concrete industry is one of the most polluting on the planet with 5% CO_2 emissions and 33% of the waste produced annually in Europe, as for a world production of about 4 billion tons for year.

The entire concrete life cycle (from extraction to production, to transport, and from use to disposal) strongly contributes to the global warming, acidification, photochemical smog, eutrophication. Several experiments carried out by research centers and private companies enhanced strategies and interventions to limit the impact of constructions by outlining new scenarios relating to the entire construction sector are inscribed within this framework.

File-to-Factory Computational Processes for Reusing the C&D Cementitious Waste

In this scenario, the PROSIT research investigated the opportunities coming from the implementation of construction processes based on digital manufacturing technologies. Specially, the focus is on the 3D printing techniques, and for the production of CDW cement mortars within the 3D printers constraints (Fig. 1).

The additive manufacturing sector has a specific research field active on producing printing materials, precisely with the aim of maximizing the content of recycled elements within cementitious mortars, and of improving the quality and performance of the final products. The implementation of additive manufacturing processes (3D printing) with cementitious materials is a key challenge featured by a strong industrial potential, as well as environmental benefits. The latter are mainly focused on the material performances with respect to the entire building process (optimization of material use, cost and construction time reduction, etc.; Fig. 2).

Figure 1. Automated work site with an on-site 3d printer. 3D Autonomous Robotic Construction System (ARCS).

Figure 2. Concrete walls 3d printing process, Winsun.

A further challenge is about the capacity of outlining a virtuous process that links the building dismantling, the recovery of materials and their reuse through digital manufacturing. Therefore, the research interest is to apply this methodology to the existing building stock, so that it bears a relevant significance in the Italian building panorama [8].

Starting from these assumptions, a procedural two-steps "algorithm" has been developed for taking together thematic areas and the issues involved in the recycle workflow.

MATERIALS AND METHODS

"Starting from the End": Site Management and on-Site Recycling

The first step in the "algorithm" concerns the aspects related to the construction site, its management and the demolition process of the building components. Looking this way, the first step is placed in the "end-of-life" phase of a building to start a new construction cycle. The first step in method is strongly influenced by the bunding context, and by the administrative and regulatory framework in which the latter is inserted. The selective demolition operations are a key secondary step in order to maximize the content of recycled materials as aggregates for the composition of cement mortars. This approach provides benefits in terms of saving time and costs, and for the C&D waste management in the design and demolition phases. According to the selective demolition protocols and guidelines [9–12], three scenarios might be addressed: up-cycling, off-site manufacturing, on-site recycle. The latter represents the preferential scenario for the development of the proposed workflow because it allows for a cost reduction in terms of material transport, and because it provides the possibility of direct recycling and reuse.

The regulatory framework governing the use of recycled aggregates for the production of building components is scattered in various documents relating to methods and quantities of C&D waste recovery.

Specifically, the UNI 8520-2 [13] identifies the different material categories that can be used as recycled aggregates according to the demolition methods. For each of these categories, the mass content is defined, and split into percentage ranges. This classification is taken from UNI 11104:2016 which defines the maximum percentages of replacement of the coarse aggregate with recycled coarse aggregate in relation to its type, exposure class and strength class of the concrete.

The exposure classes are defined within the same standard, and depend on the features related to the environment and the ways in which the product made from recycled concrete will be used. In this sense, informative examples of situations to which the exposure classes may correspond are given. The resistance classes of the concrete can be identified through the Ministerial Decree January 14, 2008.

The use of these three tools makes it possible to calculate the amount of recycled aggregates that can be used and is linked to the quality of the product and its final destination.

"Process Algorithm" Development: File-to-Factory Possibilities for on-Site Operations

The second step of the "algorithm" is aimed at identifying the most suitable process to involve in the transformation of demolition waste into construction materials. Specifically, the steps involved in using recycled aggregates for cement mortars suitable for 3D printing technology are analyzed.

Several parameters come into play within the process algorithm that frame a range of possible workflows assuming different scenarios. Great importance is attributed to information and context-related aspects (environmental characteristics, site accessibility, etc.) that contribute to the definition of the processes of demolition, recycling, and accessibility possibilities related to the activation of on-site operations. These processes are regulated by a framework of standards that provide the information related to the quantities and methods of use. Of paramount importance are the material aspects. On the one hand, parameters that derive from demolitions come into play (type of aggregates, grain size, etc.) on the other, issues that are related to the moldability of the cement mortar produced, which must possess certain physical and mechanical characteristics (rheology, hydration, etc.). These aspects directly inform the characteristics and technological choices that influence the digital manufacturing process. In this regard, two macrocategories are identified that are defined by the numerical control tool used: robotic arm and gantry system. A number of constraints related to the final products depend on these categories. The latter constitute the output of the process and consist of categories of products that can be realized in concrete through 3D printing.

The objective is to frame this type of construction process by breaking it down into steps that affect the different actors in the construction sector, with the aim of shaping itself as a decision-making tool that can be used by contracting stations to evaluate possible recovery scenarios through digital fabrication. The goal is to decline with respect to different contexts the succession of design and strategic choices leading to the workflow to be followed during the construction phase.

Expected Impact of the Proposed Methodology

The tool proposed in this research appears to be potentially useful; its implementation, however, requires the activation of a series of synergies related to the actors of the entire supply chain involved in the construction process from demolition to the creation of the printing material and 3D printing. Its operation, in fact, depends on the amount of input information in its possession that pertains to different domains. The point of the "algorithm", therefore, is precisely to seek a synthesis between different disciplines

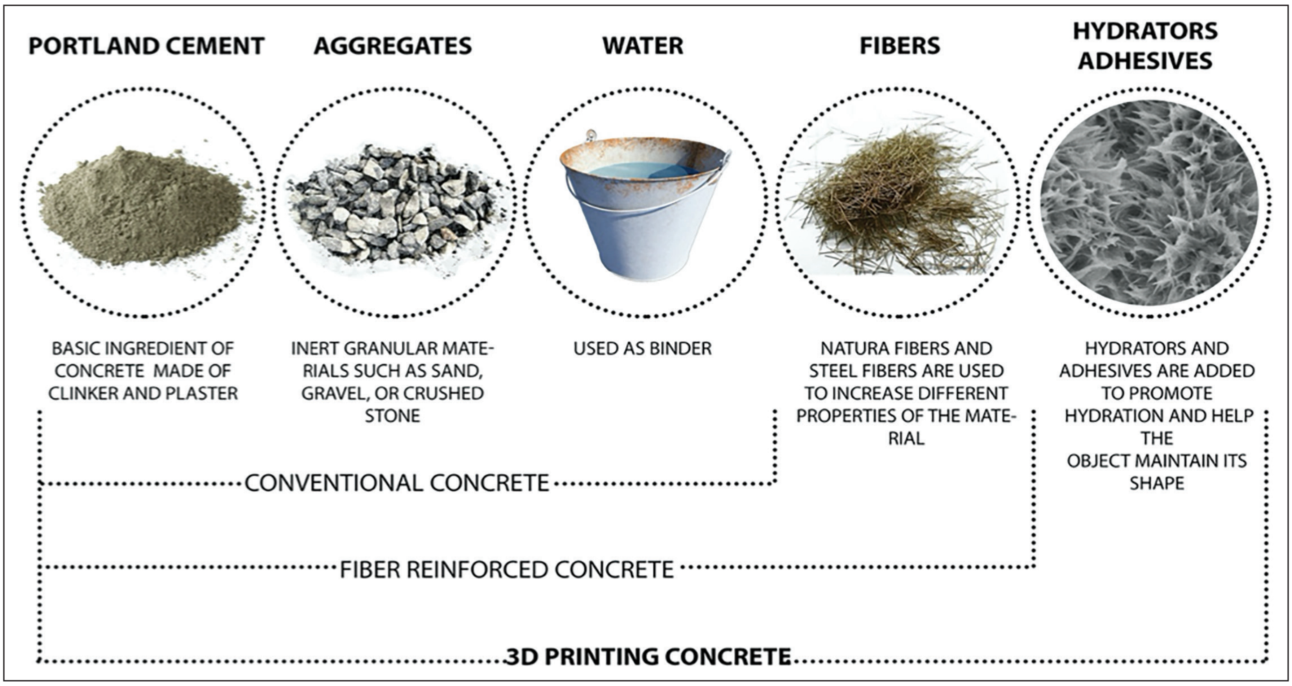

Figure 3. 3D printing concrete composition.

that are aimed at the same purpose and need mutual feedback as they inform each other. Another implication is the connection of the process algorithm to a BIM based system with the aim of recording and updating in real time aspects related to material (quantity of demolished materials) and site management (accessibility). The use of digital fabrication technologies within the construction site, moreover, implies significant changes from a socio-economic point of view within the construction site with the need, for example, to have specialized workers capable of planning and evaluating choices regarding the materials and machinery to be used. From a cultural perspective, the workflow from demolition to digital manufacturing represents a virtuous example of how technologies can change the entire construction industry by reducing economic and resource expenditures and limiting environmental impact. The case study examined considers, specifically, concrete, whose industrial supply chain is among the most polluting but is, theoretically, applicable and repeatable by referring to all materials derived from demolition and different production technologies related to digital manufacturing (subtractive manufacturing, 3D FDM printing).

RESULTS AND DISCUSSION

Quality Assessment of the Aggregates as 3D Printing Material

This part of the study analyzes the relationship between the product coming from the recycling chain, and its use as an inert for the compound used as a raw material in 3D printing. The most evident feature of the aggregate is its granularity, which is relative to the form in which it is presented. Aggregates with a diameter of less than 5 mm are defined as "sand", aggregates with a larger diameter are defined as crushed stone or generally "large aggregates", and they are those actually affected by recycling. The C&D waste treatment and recovery process can be divided into the following phases:

- Crushing phase, that is aimed at reducing cement waste in the size to make it suitable for final use;
- Separation phase, that is aimed at eliminating undesirable materials in the final product;
- Classification phase by screening, that is aimed at separating the grains according to their size to obtain homogeneous particle size fractions.

With respect to this classification, it should be emphasized that the demolition method is crucial for improving the aggregate's quality, since it directly affects the capacity in differentiate C&D waste ab-origine. In the ordinary industrial practice, in order to contain the disposal costs, construction companies care for separating C&D waste in homogeneous flows as much as possible because the recovery plants generally require greater costs in the case of poorly selected materials and/ or great volumes of undesirable fractions.

In the procedural algorithm, three ranges of aggregate diameters have been identified to be reused:

- 4–8 mm,
- 8–16 mm,
- 15–25 mm.

Figure 4. 3D printing cycle industry Expo Park, Shangai.

The size of the aggregates directly influences the diameter of the extruder to be used for 3D printing. This is because to avoid obstructions, the cement compound must flow continuously. The parameter relating to the diameter of the extruder is divided into four scales of size: less than 8 mm, between 8 mm and 5 cm, between 5 cm and 30 cm and greater than 30 cm.

This choice does not involve the definition of a specific technology (for example, gantry system - multi-axis operating system with airlift - or robotic arm). It is because the use of extruders with a smaller diameter is often combined with robotic arms, larger extruders, which need greater stability, are generally mounted on machines that use gantry system technology.

As coming from literature [14–16], the optimal composition for a cement mortar suitable for 3D printing requires the use of large aggregates with a proportion of 0.63 with respect to the total mass of the compound. These quantities were calculated through various experiments in which the printability and characteristics of the extruded material were tested. Specifically, the control of the semi-fluid's ability to exit from the extremity of the extruder is fundamental, in order to maintain a continuous flow and retaining the shape once it is deposited (Fig. 3, 4).

Site Accessibility in off/on-Site Production Scenarios

A further aspect of the proposed process is related to dual operating options offered by 3D printing, that can be on-site or off-site mode. This option involves a number of differences in terms of operating costs, of the need of skilled operators, and of the quality of the final products. Generally speaking, the on-site mode provides benefits in containing economic and energy costs relating to the waste transport and with respect to construction times. On the contrary, a number of criticalities are in the need to manage of unexpected events arising from the context during the construction phase, such as greater risks for the workforce, resolution of problems deriving from printing errors, control of the quality of the material during the extrusion phase in relation to the atmospheric conditions.

On the other hand, the off-site mode allows a greater quality control during the production phase, and it offers the possibility of printing elements featured by a greater degree of complexity also reducing risks and errors during the construction phase. These advantages are balanced by the increasing of transport and assembly costs, and by the dimensional constraints coming from the site in which the elements are manufactured. Therefore, the choice between these two methods is done according to

Figure 5. Case study area: The former industrial area Corradini, Naples.

the conditions of the operational site and, in particular, to the following conditions: the accessibility of the construction site, the availability of economic resources, specialized work forces and technologies.

CONCLUSIONS

The "algorithm" presented in this study is configured as an operational tool through which to develop building process scenarios declined with respect to the context. Its use as a decision-making tool is linked to the quantity and quality of information in its possession that constitute its inputs. Specifically, different parameters come into play, belonging to separate domains, which have been grouped into five sets:

- Material;
- Information;
- Technology;
- Performance constraints;
- Regulatory constraints.

The result is the definition of a complex system whose reading and use are not deterministic but interpretable with respect to needs that may vary according to the project (maximizing the amount of recycled materials, obtaining a certain type of product, working in a specific context).

For this reason, links between the various process steps were differentiated by dividing them into deterministic type links and indicative links to be interpreted as preferential association. What emerges is the potential of the algorithm to be used to address choices regarding the technologies to be used based on the quality and quantity of materials from demolition. One of the strengths is the possibility of parametrically declining the same process to different situations depending on the repeatability of the process from demolition to recycling and 3D printing.

The "algorithm" presented in this study was developed assuming two different scenarios. These are both theoretically appropriate and feasible according to the presence of specific constraints (for example the accessibility of the construction site for as regards the possibility of operating with on-site technologies).

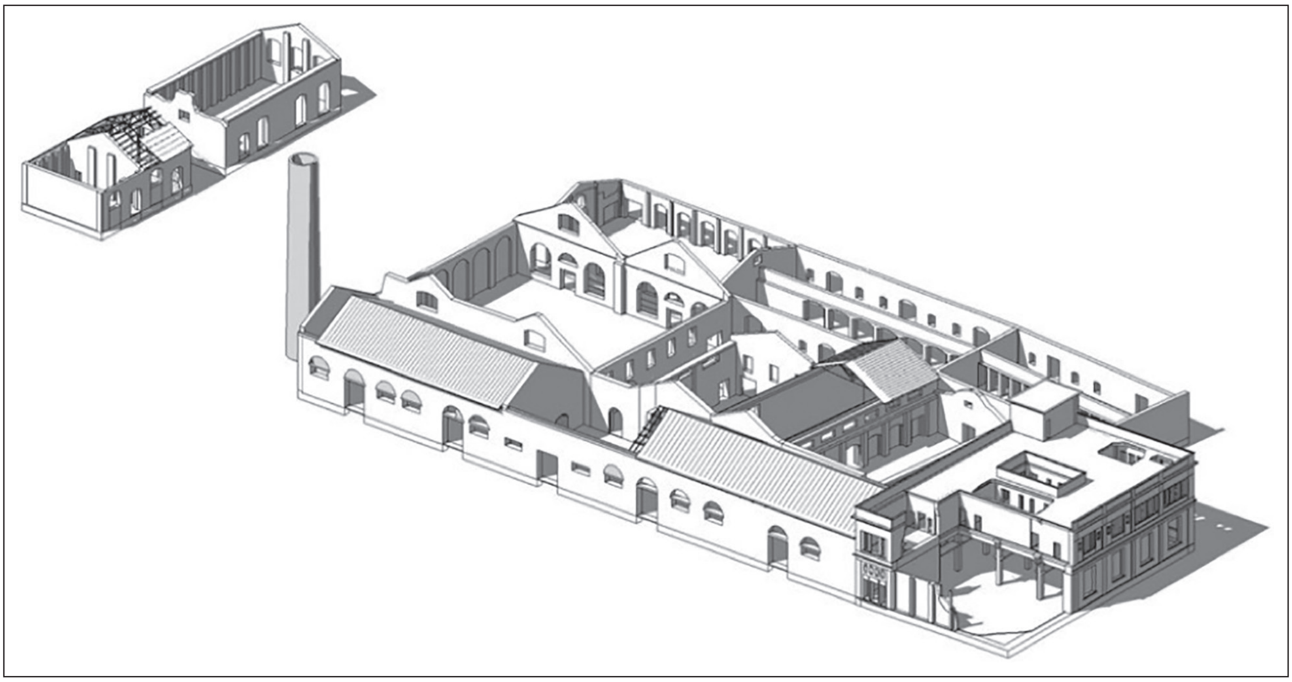

Figure 6. Former industrial area Corradini, Naples – As-is BIM Model.

Notably, the research focused on the possibility of applying the methodology to the follow, different cases:

- Urban furniture. This category has been tested with respect to 3D printing for which components are generally conceived and designed as closed elements, obtainable through a continuous printing path, realised off-site in a controlled environment;
- Façade elements. These are elements with a great level of detail aimed at maximizing the performance of the building façades;
- Interior elements. This group of elements is made up of highly customizable and site-specific components;
- Structural elements. This group consists of structural components in which issues relating to the optimization of the use of material and the quality of the recycled material are pivotal (also defined from a regulatory point of view).

The methodology is currently in the process of being tested with design case studies within the construction site of the ex-Corradini area of Naples [17], a heavily degraded site of great urban interest, which has long been off-limits to the public due to asbestos pollution (Fig. 5, 6).

ACKNOWLEDGMENTS

This research was funded by the CAMPANIA REGION, as part of the research project 'PROSIT - Projecting in Sustainability: qualification and digitization in construction', PO FESR 2014–2020 - Specific objectives 1.2.1 - expression of interest for the 'realization of technological platforms under the program agreement: High-tech districts, aggregations and private public laboratories for strengthening the scientific and technological potential of the Campania Region, awarded to STRESS scarl insert. The activity involves among the project partners the Department of Architecture and the Department of Structures for Engineering and Architecture of the Federico II University of Naples, the public-private consortium STRESS s.c.a.r.l. and the Municipality of Naples. Authors thank the all participants for the contribution to achieve the research findings.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan, COM2019", 2019.

[2] European Commission, "EU construction and demolition waste management protocol," 2016. https://single-market-economy.ec.europa.eu/news/eu-construction-and-demolition-waste-proto-col-2018-09-18_en Accessed on Nov 30, 2022.
[3] P. Altamura, "Costruire a zero rifiuti. Strategie e stru-menti per la prevenzione e l'upcycling dei materiali di scarto in edilizia, Franco Angeli, 2015. [Italian]
[4] E. Antonini, "Residui da costruzione e demolizione: una risorsa ambientalmente sostenibile," In E. Antoni-ni (Ed.), Il progetto VAMP ed altre esperienze di valo-rizzazio-ne dei residui. Franco Angeli, 2001. [Italian]
[5] M. Rigillo, and M. T. Giammetti, "Management of the C&D waste in the urban regeneration Project," Journal of Technology and Environment, Vol. 22, pp. 240–-248, 2021. [CrossRef]
[6] ISPRA, "Rapporto Rifiuti Speciali", 2021. https://www.regione.puglia.it/web/ufficio-statistico/-/is-pra.-rapporto-rifiuti-speciali.-edizione-2021 Ac-cessed on Nov 30, 2022.
[7] J. Cárcel-Carrasco, E. Peñalvo-López, M. Pas-cual-Guillamón, and F. Salas-Vicente, "An overview about the current situation on C&D waste manage-ment in Italy: Achievements and challenges," Build-ings, Vol. 11(7), Article 284, 2021.
[8] FAOLEX Database, "Art 205, Legislative Decree 152/2006," https://www.ecolex.org/details/legisla-tion/legislative-decree-no-152-approving-the-code-on-the-environment-lex-faoc064213/ Accessed on Nov 30, 2022.
[9] PVC Forum, "UNI/PdR 75:2020: Selective decon-struction - Methodology for selective deconstruc-tion and waste recovery from a circular economy perspective," https://www.pvcforum.it/pvc-hub/news/unipdr-752020-selective-deconstruction/ Ac-ces-sed on Nov 30, 2022.
[10] R. Cossu, V. Saliebri, and V. Bisinella, "Urban min-ing: A global cycle approach to resource recovery from solid waste, CISA Publisher, 2012.
[11] M. Dri, P. Canfora, I. S. Antonopoulos, and P. Gaud-illat, "Best envi-ronmental management practice for the waste management sector," JRC Science for Po-licy Report, EUR 29136 EN, Publications Office of the European Union, Luxembourg, 2018. [CrossRef]
[12] K. Ghosh, "Urban mining and sustainable waste management," Springer, 2020.
[13] Un Monda Fatto Bene, "UNI 8520-2 Aggregati per calcestruzzo - Istru-zioni complementari per l'appli-cazione della EN 12620 - Parte 2: Requisiti," 2016. https://store.uni.com/uni-8520-2-2016 Accessed on Nov 30, 2022.
[14] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, "Mix design and fresh prop-erties for high-performance printing concrete," Ma-terials and Suctures, Vol. 45, pp. 1221–1232, 2012. [CrossRef]
[15] B. Gang, W. Li, M. Guowei, S. Jay, and B. Mingke, "3D printing eco-friendly concrete containing un-der-utilised and waste solids as aggregates," Ce-ment and Concrete Composites, Vol. 134, Article 104742, 2021.
[16] J. Pasco, Z. Lei, and C. Aranas, "Additive manu-facturing in off-site construction: Review and fu-ture directions," Buildings, Vol. 12(1), Article 53, 2022. [CrossRef]
[17] M. Rigillo, S. Russo Ermolli, and G. Galluccio, "Dig-ital rule-based compliance processes. The urban re-generation of ex-Corradini, Naples (IT)," Agathon International Journal of Architecture, Art and De-sign, Vol. 10, pp. 120–131, 2021.