The H2020 CINDERELA Project — A New Circular Economy Business Model for More Sustainable Urban Construction

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Abstract The municipal sector and different industries, including construction and demolition activities in urban areas, generate waste streams that could provide excellent secondary raw materials (SRM) to replace traditional raw materials in construction applications. The CINDERELA project develops a business model (CinderCEBM) aided by a one-stop-shop (CinderOSS) service to help construction companies increase profit and deliver value by using SRM from urban waste streams in building and civil engineering applications. The model and the platform will be tested in different socio-economic environments to ensure technological, systemic and economic viability across Europe through demonstrations involving manufacturing and construction with the use of SRM-based materials supported by building information modelling (BIM) and advanced solutions combining disruptive technologies (3D printing) and SRM cascading recycling systems (phosphorus extraction from wastewater prior to sewage sludge use in construction).

Keywords: CINDERELA project, circular business model, secondary raw materials, waste recycling, urban construction.

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1 Introduction

The construction sector is one of the largest consumers of raw materials; therefore, an increase in raw material efficiency in construction is of great importance. According to OECD data (2018), the construction sector is expected to more than double between 2017 and 2060 globally, with its use of materials increasing to almost 84Gt in 2060. In Europe, the construction sector, including buildings, consumes about half of all raw materials and energy extracted and one third of the total amount of water used. At the same time, construction waste accounts for one third of all waste generated (European Commission, 2014). Construction is also an important economic sector, representing ca. 9 % of Europe's GDP and directly employing 18 million Europeans (European Commission, 2019). With these numbers, the transition of the construction sector from linear to circular is a major step towards making the European economy more sustainable.

The construction sector presents enormous potential for implementing circular economy business models that will facilitate a decrease in its environmental impact and encourage resourceful use of materials. Such an approach envisages, among other things, the use of secondary raw materials (SRM) recovered by recycling of different waste types generated in urban areas, including construction and demolition waste (CDW), industrial waste, waste from extractive and processing activities and some waste types generated by municipal sector (for example, sewage sludge from urban wastewater treatment, and heavy fractions remaining from municipal waste treatment). This approach provides a pathway to new consumption patterns and value chains relevant for urban areas where valuable raw materials can be recovered for construction purposes. New patterns include the use of cascading recycling approaches, e.g. extraction of critical raw materials (CRM) such as phosphorus (P) from wastewater before it enters the treatment plant, so that the sewage sludge as process residue can be later used as SRM for construction without losing the value of the phosphorus contained in it. Other approaches combine techniques offered by disruptive technologies such as robotic 3D printing to use plastic recycled as SRM from municipal waste for manufacturing construction

elements of advanced geometries and design as elements of small urban infrastructure.

Building and infrastructure construction in urban regions are very important activities linked with intense urbanisation and consequent expansion of cities. It is estimated that by the year 2050, nearly 86 % of the world's population in developed regions (64 % in less developed regions) is expected to live in urban areas (UN DESA, 2012). This means intense investments in infrastructure and buildings and revitalisation of urban space, including transformation of degraded areas. Many urban centres across Europe are already the scene of intensive construction works because of increasing numbers of inhabitants and services. At the same time, cities are geographically and administratively closed units (using short transport routes), and generate large quantities of various waste types, with a potential of the use as SRM for construction. All these features make urban environments an excellent "living laboratory" for verifying the effectiveness of sustainable construction and circular economy models based on SRM.

Sustainable urban construction based on closed local raw material circulation from waste to products is the main topic of the CINDERELA research and demonstration project entitled New Circular Economy Business Model for More Sustainable Urban Construction.

2 The CINDERELA project

2.1 About the project

CINDERELA is a 4-year large scale demonstration project implemented under the flagship of the European Union's Horizon 2020 research and innovation programme (contract no. 776751). The goal of the project is to make circular economy an industrial concept in the construction sector. CINDERELA is coordinated by the Slovenian National Building and Civil Engineering Institute and involves 13 partners from seven European countries (Slovenia, Spain, Italy, Poland, Serbia, The Netherlands and Croatia): NIGRAD, Foundation Gómez Pardo,

TECNALIA, AEDHE, Polo Pordenone, Opencontent, Bocconi University, IETU, BEXEL, TUDelft, KplusV and 6.MAJ. A multidisciplinary consortium jointly designs and demonstrates under real conditions a CINDERELA circular economy business model (CinderCEBM) based on the manufacturing and application of SRM-based construction materials which are recovered from local waste streams.

2.2 Building a new circular business model – CinderCEBM

Companies need a solid framework for creating and innovating circular business models that combine economic profits with environmental and social values. A CinderCEBM is the central theme of the CINDERELA project that, on one hand addresses the environmental challenge of waste management, and on the other offers sustainable and profitable urban construction solutions for businesses based on the recycling of various wastes. With appropriate technologies that are sufficiently simple, economically viable, financially acceptable and technically compatible with existing construction and production equipment, waste (Figure 1) can be recycled into SRM-based construction products that have the appropriate characteristics for their intended use. New circular business models have a better environmental footprint than conventional products, while offering a similar price point. In this respect, the most promising SRM-based construction products are recycled and manufactured aggregates, building composites (green concrete, geotechnical composites, asphalt) and recycled soil. The largest quantities of recycled waste can be used in low grade applications, such as geotechnical embankments and fillings. On the other hand, upcycling (recycling into products of higher quality or value than original, such as green concrete) is considered as more desirable; however, the uptake of waste is generally lower than in the case of downcycling.

Figure 1: Construction and demolition waste (CDW) is one the most voluminous waste streams in the urban environment.

In support of the CinderCEBM, circular business model, the project is developing a multiservice CINDERELA "one-stop-shop," called CinderOSS. CinderOSS combines many different services that can help entrepreneurs implement and accelerate their waste-to-construction product circular business model, as well as helping governments and other stakeholders in participating or stimulating these business models. CinderOSS offers information on product development services, market creation, including complementary measures, proposals for new regulatory and administrative procedures and information about the production and construction of circular construction products with the associated Building Information Modelling (BIM) libraries. Finally, CinderOSS will include a digital marketplace called the CINDERELA Digital Business Ecosystem (CinderDBE), where waste-to-product flows are traced, offering transparency and an efficient environment for stakeholders to meet and trade materials.

Both CinderCEBM and CinderOSS will be tested in real environments in six European countries (Spain, Italy, Slovenia, Croatia, Poland and the Netherlands). Through the basic conditions for the implementation of a business model, such as the prices of waste handling and of SRM, the availability of materials, non-

technological barriers (such as legislation and social acceptance of SRM) and incentives, will be checked.

2.3 Assessing waste-to-resource opportunities in urban and peri-urban areas

Getting the right information on the types, location, availability and flows of SRM as well as the actors behind them is a critical enabler of CinderCEBM. Using an innovative, open source, GIS supported tool named GDSE (Geodesign Decision Support Environment), CINDERELA provides a holistic protocol for material flow analysis in urban and peri-urban areas. The tool is used to predict optimal waste-to-product solution based on waste availability, quantity and location. For example, the tool combines a list of the NACE (Nomenclature des Activités Économiques dans la Communauté Européenne) codes of the economic activities with the appropriate codes from European List of Waste (LoW) and actors that generate them with the support of the ORBIS database (2018). The tool provides a material flow analysis representing waste stocks and flows (Figure 2).

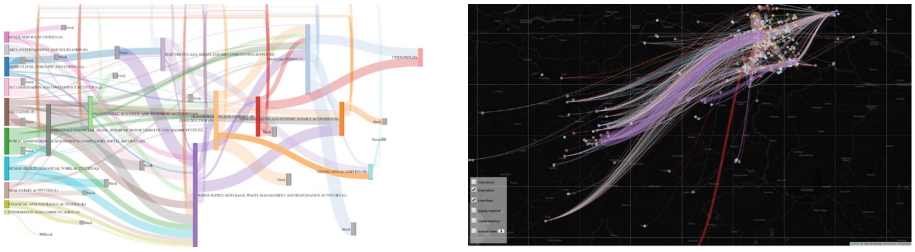

Figure 2: Visualization of the outcomes of the GDSE tool - left a Sankey diagram and right a Sankey map with an activity based spatial material flow analysis for selected waste streams in Maribor and surrounding municipalities, Slovenia.

This initial step of setting a business model in a local environment using analysis of existing waste flows was tested in six selected urban areas and regions in Europe: in the Maribor area (Slovenia), Istria (Croatia), Basque country (Spain), Amsterdam Metropolitan Area (the Netherlands), Trento area (Italy) and Katowice area

(Poland). Within the investigated regions, the largest quantities of suitable waste streams to be used as SRM for construction products included different fractions of CDW (group 17 from LoW such as concrete, brick, ceramic, mixture of CDW, and dredging spoil), waste generated by the municipal sector (heavy fraction after municipal solid waste treatment or sewage sludge from wastewater treatment), and other waste reflecting the local economy/industry (mining waste, waste from thermal processes (slags and sludges), and others).

Another important consideration for establishing key business processes related to CinderCEBM is the valorisation of waste potential for recycling into SRM-based construction products. CINDERELA is developing a set of criteria for the recycling of waste into SRM-based products for different intended uses in construction works, such as composition, quantity, quality, availability and recyclability of waste. For three case studies (Maribor with surrounding municipalities in Slovenia, Istria in Croatia and the Madrid – Henares corridor in Spain) laboratory testing of the selected waste (Figure 3) was performed in order to valorise their potential as SRM for the construction sector.

Figure 3: Visual appearance of mixed CDW (waste code 17 09 04 from LoW), and soil and stones (waste code 17 05 04) from Slovenian and Croatian case studies.

2.4 Design, development and testing of construction works with SRM-based products

CINDERELA focuses primarily on construction works (that is, building and civil engineering works (European Parliament and the Council, 2011)) with the application of SRM-based construction products and materials such as recycled aggregates (aggregates from recycled CDW), manufactured aggregates (aggregates from recycled industrial waste, originating from processes involving thermal or other modification), building composites (such as green concrete (Figure 4) with recycled and manufactured aggregate, geotechnical composites using sewage sludge and other wastes (Figure 5), asphalt with addition of aggregate from reclaimed asphalt) and recycled soil originating from selective excavation of soil. For the recycled wastes, CINDERELA defines a set of end-of-waste (EoW) criteria (such as limiting values of elements in leachate from composites) for different intended use of final products. As a measure stimulating the demand side of the CinderCEBM, the criteria will be incorporated into the CinderOSS.

Figure 4: Green concrete with reclaimed bituminous (left) and tar asphalt (right).

Figure 5: Composite from sewage sludge and ash.

Laboratory test data of SRM-based construction products will serve a double purpose; firstly, to design and establish modular as well as mobile pilot production plants for recycled and manufactured aggregates, building composites and recycled soils, and secondly, to demonstrate their use in large scale pilot demonstrations involving geotechnical works for revitalisation of a degraded area, construction of small scale facilities and for road construction. To build trust and encourage designers of and investors in construction works to use SRM-based products, BIM libraries will be developed. They will include all relevant data on SRM-based construction products (including mechanical properties, type of incoming materials, chemical and mineralogical composition, and environmental impact) to enable the use of the BIM tools for designing, constructing, managing and demolishing (reuse and recycling) of construction work with SRM-based materials during their life span. Through BIM, the CINDERELA pilot demonstrations, which will be built in Slovenia, Spain and Croatia, will showcase the added value of using SRM-based construction materials compared to traditional raw material based products.

Demo 1: Extraction of valuable materials - phosphorus extraction

Phosphorous (P) is one of 27 CRMs in Europe for which supply security is at risk and economic importance is high. The current P extraction approach is usually implemented in centralised wastewater treatment plants (or up the chain), as a measure to reduce the operational and maintenance costs of the utility by preventing the clogging of the wastewater collection and treatment infrastructure with struvite. However, the approach is not wide-spread, because the recovered P-product is relatively new to the market and poses problems for utilities in terms of storage, valorisation and market uptake. In the CINDERELA project, P, along with other nutrients important for agriculture, is recovered directly from separately collected urine in the form of liquid fertilizer. The complete nutrient recovery (CNR) system consists of stabilization, purification and concentration of the urine. A CNR approach has a number of important advantages nitrogen and other valuable secondary nutrients (boron, iron, nickel, etc.) are recovered along with the phosphate; the full waste is treated, with full removal of micropollutants, pathogens, and bad odour from urine; a liquid high-grade organic fertilizer is produced, which can be used directly for hydroponics/urban farming, and distilled water is obtained as a valuable by-product. After the CNR process, urine enters the sewage path again where sewage sludge without the extracted P and other nutrients can still be recycled into SRM-based construction products, generating value as input material. Modular and mobile units for extraction of nutrients from urine will be tested in Amsterdam (The Netherlands) and in Maribor (Slovenia). To showcase the full cascading recycling approach, sewage sludge, after phosphorus extraction, will be applied to production of SRM-based construction materials (geotechnical composite) at the Umag demonstration pilot.

Demo 2: Pilot production of SRM-based construction products

Some recycled materials, such as recycled aggregates, are already used in European construction; nevertheless their use, especially in countries with an abundance of natural aggregate, has not yet become an everyday business. The potential of many other waste materials remains unexplored, in particular when taking into

consideration their immense possibilities in terms of mass flows and synergic effects for production of new construction composites.

Three pilot production plants of SRM-based construction products in Maribor, Umag and Madrid will be developed as part of the CinderCEBM demonstration. In these pilot plants, different types of wastes will be recycled into SRM-based construction products, which will be later used in construction pilot demonstrations. All pilot plants are designed to be modular and mobile with capacities of 10,000 tons/year on average and a maximum of 70 tons/day. They will be a combination of crushing, screening and mixing devices combined, depending on the type of the final product.

3D printing of street furniture with recycled plastics from municipal solid waste is another demonstration of innovative technology and use of materials within the CINDERELA project. To demonstrate the potential of this material and technology together, CINDERELA will develop a 3D printed building component that will showcase the principles and benefits of circular economy, especially when focusing on the manufacturing process with the use of disruptive technologies. This will be a small scale project, demonstrating the potential development of production of SRM-based construction materials in the future.

Demo 3: Large-scale demonstrations of construction with SRM-based construction products

In order to demonstrate the business case and technical feasibility, large scale construction pilots with SRM-based construction products will be implemented in Maribor, Umag and Madrid, using sustainable building materials produced during the project. BIM will be utilized to support all phases of designing (Figure 6), constructing, using and reusing/recycling of construction works (or part of them), from the preliminary planning of work to facility management and deconstruction. For each of the projects, case-study analyses – clash detection, quantity take-offs, 4D (model-based time planning), 5D (model-based time and cost planning), and 6D facility maintenance (model-based maintenance planning) will be performed.

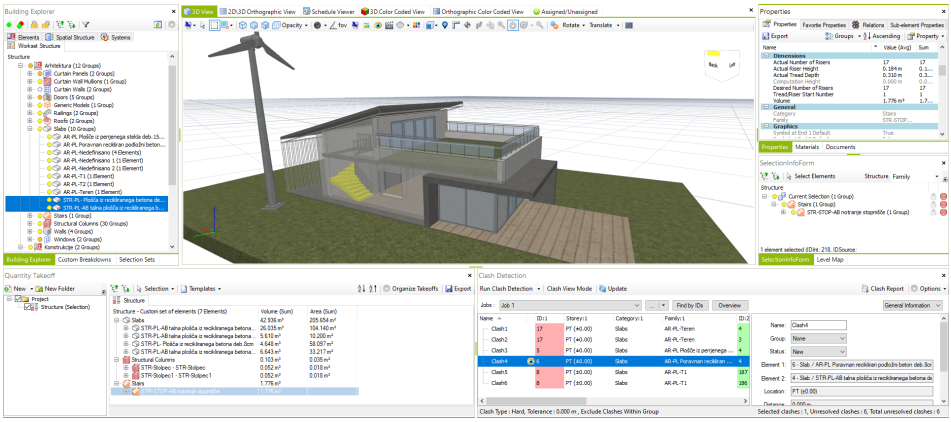

Figure 6: Planning of information-supported pilot construction in the CINDERELA project.

Geotechnical works

The largest quantity of SRM-based construction products replacing virgin materials can be utilized in the case of different geotechnical works. Revitalization of degraded urban areas through geotechnical works will be performed using the following steps: (1) site surveying and sampling, (2) analysis of existing materials (natural soils, anthropogenic soil, including dumped materials), (3) excavation and separation of waste materials, (4) recycling of waste and production of SRM-based construction products, and (5) construction and revitalization of the site. SRM-based material will be placed in layers and compacted in order to reach adequate intrinsic properties for geotechnical works. During the revitalization process, monitoring equipment will be installed for monitoring of eluates in piezometers. The monitor readings will be recorded directly into the BIM.

Construction of demo facilities

In Maribor, a one storey facility will be built with the use of SRM-based construction products. The facility will include a conference room, a laboratory, offices, toilet facilities and a stairway to the roof. The floor and the walls will be made of green concrete made with recycled aggregates. The foundation floor will be prepared and

fortified with the use of recycled soil; thermal insulation under the foundation will be made of recycled brick or glass. In Umag, a fence surrounding a degraded area will be constructed using modular prefabricated building blocks made of green concrete with recycled and manufactured aggregate, and in Madrid, a small facility will be constructed as a ground floor building. It will serve as the main control room for delivery of waste and the entrance to a waste treatment plant. The construction materials will include reused construction elements (doors and windows) and recycled aggregates recovered from the demolition of an existing building.

Road construction

SRM-based construction products developed in the CINDERELA project can successfully replace virgin materials and decrease the environmental impact of road construction/maintenance works. Recycled aggregate is excellent material for subgrade and base courses, and manufactured aggregates and reclaimed asphalt for surface courses. In Maribor, Umag and Madrid, a road construction project will take place after revitalization of degraded areas is completed.

2.5 Environmental, economic and social assessment

To ensure that the business model will deliver not only economic but also environmental and social added value, CinderCEBM will be assessed using life cycle approaches including environmental Life Cycle Assessment (LCA) and related methods such as Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC). This comprehensive assessment will help to evaluate how the new solutions proposed in CinderCEBM compare with the current "business as usual" situation in terms of environmental added value, economic viability and social implications. To facilitate their marketability, confirm innovation and performance along with the environmental benefits, new SRM-based construction products and technologies will also be assessed using the environmental technology verification (ETV) approach.

2.6 The role of stakeholders in the CINDERELA model and service

In order to further improve the model and service, stakeholders, actors and potential end-users for CinderCEBM and CinderOSS will be engaged. Through project activities, different target groups can acquire new knowledge and skills for more sustainable waste management and their use in construction in urban environments. Local, regional and national decision makers will be provided with information on new circular services and materials, value chains and decision-making tools. Policy makers will receive information about various barriers and incentives and proposals for new incentives for the circular economy. Waste holders will become more competitive by introducing new business models that include recycling waste into construction products rather than landfilling. Waste managers and processors as well as construction companies, as potential users of CinderOSS, will be the first to receive information on how a business model works in different environments, thereby increasing the chances of setting up a comparable model in their own environment. Construction companies, the most important players in sustainable urban construction, will receive information on the production of sustainable construction products based on SRM, their properties, methods of installation and maintenance, as well as BIM-supported tools for more modern and faster construction. The project is also of interest to the general public, which the partners see as an important player in the implementation of new circular models, since it depends to a large extent on their active participation and acceptance.

3 Conclusions

Sustainable urban construction, based on the closed local circulation of raw materials from waste-to-products, is an opportunity for many actors in urban areas, as well as for the general public. However, despite the potential advantages of circular approaches in the construction sector involving recovery and use of SRM from urban waste streams, it is still a challenging task to implement for many companies because of lack appropriate knowledge, technologies, good practices and incentives. For Europe, the CINDERELA project brings many new developments, innovations and a solid knowledge base that can stimulate demand and supply, and encourage

actors with circular ambitions involved in the construction sector to take action and bring circular business models into real life. In Slovenia, where the circular economy is one of the main domains of Smart Specialisation Strategy, testing the new business models and services that will emerge from the project is of particular interest to city managers, as well as industry and entrepreneurs, because of the country's small size in terms of geography and administration, as well as openness to new, more sustainable products and services. In this way, Slovenia can further strengthen its position as a frontrunner in the transition from linear to circular economy providing an example to other European cities, and becoming an important player and competitor in global sustainable development.

CINDERELA

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