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A Circular Business Model for 3D Concrete Printing with Recycled Fine Aggregates

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This is a circular economy business model for a 3D concrete printing facility that uses recycled fine aggregates from demolition waste to manufacture urban, memorial and garden furniture.

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Author Moshe Kinn & Nicholas Hurst

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List of Abbreviations

CAD	Computer Aided Design
CIRMAP	Circular Economy via Customisable Furniture with Recycled Materials for Public Places
LCA	Life Cycle Analysis
Mt	Million tonnes
MPM	Mixture Proportioning Method
NWE	North-West Europe
RFA	Recycled Fine Aggregates
t	tonnes
UMG	Urban, Memorial or Garden
WMC	Waste Management Company

1. Executive Summary

CIRMAP is an Interreg North-West Europe (NWE) funded project, focused on developing a Mixture Proportioning Method (MPM) for 3D printing mortars using Recycled Fine Aggregates (RFA). To demonstrate a successful application and commercial viability, urban, memorial or garden furniture (UMG) have been designed, 3D printed and installed in several locations across NWE.

3D concrete printing with RFA from local demolition waste is a new and novel use of a material that is otherwise only fit for landfill. The CIRMAP project establishes the closing of the circular economy model that gives RFA a new purpose as a new product.

For success, there is a need to continuously characterise and adjust the ratios of the aggregates that complete the mortar formula, with each multi-tonne batch of material that is received from a Waste Management Company (WMC). This is because the grade and variability of a buildings material that is found within RFA is determined to be different each time. Therefore, the MPMs developed in the CIRMAP project will support future progress for using RFA in 3D printing mortars.

The CIRMAP project was lab based and production was small, so therefore it was not possible to base this model on an operational manufacturing system that is commercial. Nevertheless, it has shown that a hitherto non-recyclable waste material, can be upcycled into durable long-lasting UMG furniture, and thus close the RFA circular economy loop.

2. Introduction

2.1 The background to this project

Organisations from France, Germany, United Kingdom, the Netherlands, and Belgium form the CIRMAP consortium. Between the five partner countries of the CIRMAP project, 65 Mt of Recycled Fine Aggregates (RFA) is generated each year from demolition waste. In contrast, 54 Mt of sand is extracted from marine environments and consumed each year by the CIRMAP partner countries. Furthermore, sand is the second most exploited natural resource in the world, and its over exploitation leads to degradation of landscapes, depletion of natural resources and when extracted from the seabed, becomes a marine environment preservation issue.

Using RFA in concrete, as a substitute for sand, would save natural resources. However, owing to the need for high performance and a requirement to adhere to rigorous construction regulations and standards, no market currently exists for RFA.

RFA is a local resource, with large differences in its composition. This inconsistency in its composition makes it unsuitable for mass production, which requires a standardised consistency of the materials characteristics. But, RFA could be used at a smaller scale, for the manufacture of concrete products needing neither to comply with construction standards, nor needing to possess high performance characteristics. For example, RFA could be used in the manufacture of bespoke concrete Urban, Memorial or Garden (UMG) furniture.

Traditional precast concrete cannot be used for small scale production, or for bespoke UMG furniture, because of the high costs for moulds, which can typically range from 50% to 80% of the total cost of the project. However, 3D concrete printing allows for the manufacturing of customised shapes, that would otherwise be difficult to produce through conventional methods and could be showcased by customers as a sign of their personal or corporate identity.

As such, the CIRMAP project identified an opportunity to develop a 3D printing mortar that uses RFA. The research conducted throughout the project has resulted in a new Mixture Proportioning Method (MPM) for a 3D printing mortar. Furthermore, a minimum of 25 customised UMG furniture shapes have been installed across North-West Europe (NWE) demonstrating a successful application.

Popular design trends within the 3D concrete printing industry include modular construction methods, to build more complex structures, and parametric modelling, as a digital design tool to modify design and printing parameters. Additional benefits include, shape optimisation, therefore reducing overall material consumption, and localised production, meaning that products can be printed near or at the location for installation, reducing the impact on carbon emissions from transportation.

NWE has many urban and inner-city areas in need of redevelopment. To do this, old buildings will be removed and replaced by new attractive districts with an expanding urban population. Urban facilities, which include UMG furniture are an important component of these new developments.

The typology of constructions is very similar amongst the countries in NWE and there is a common need for urban centre regeneration which provides a common resource of RFA.

Here lies opportunity for a new circular economy business model focussed on 3D concrete printing UMG furniture using RFA.

2.2 Focus of this business model

Within the CIRMAP project, only non-commercial small prototyping and bespoke printing facilities were created. Therefore, it is not possible to write a full circular economy business model based on a profitable commercial entity that operates within a circular economy. However, this business model attempts to lay out the commercial and societal aspects of diverting RFA from landfill and using it to 3D concrete print UMG furniture.

This business model is based on the Business Model Canvas found in the Appendix.

3. The value propositions

3.1 Introduction

The Business Model Canvas for a circular economy 3D concrete printing business using RFA is shown in Figure 1.

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7.2 Who are the local WMCs that will partner with the company?

7.3 What trade, non-profit organisations, or societal organisation, can help with the promotion and proliferation of products?</td><td colspan="2">8.1 To make products from RFA.

8.2 Sell the RFA formula for 3D concrete printing.

8.3 To provide a full design and installation service.

8.4 To provide education about this recycling and sustainability proposition</td><td colspan="2" rowspan="3">1.1 How can a company solve the recycling problem of RFA waste within a circular economy business model?

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Figure 1 The Business Model Canvas for a circular economy 3D concrete printing business

3.2 What is the problem this business model is trying to solve?

When a building is demolished, there is a variety of waste that will be recycled or disposed of. Typically, building waste is crushed into large aggregates that can be reused as ballast, backfill, and foundation works.

However, RFA, classified as less than 5mm in size, are also produced from the demolition process. Due to technicalities such as water absorption, and current building regulation and codes, there is no application for RFA within the construction industry. Currently, the only place for such waste is landfill and 65 Mt of RFA will be disposed of each year in the five partner countries of this project.

To avoid strict building regulations and demonstrate a successful end use application of mortars containing RFA, the CIRMAP project has identified UMG furniture products as the ideal market opportunity. This is because high compression strengths are not required and further offers the prospect to replace virgin sand completely in these products and therefore save on natural resources.

Furthermore, combined with 3D printing and design optimisation, less materials can be used when compared to conventional pre-cast designs. For example, an object can be printed with a hollow interior, otherwise known as 'hollow form'. See Figure 2 of a hollow form chair.

Figure 2 A hollow form 3D printed chair using mortar

As a digital design tool, 3D printing also offers the opportunity to create bespoke shapes otherwise difficult to manufacture through conventional means and mass production methods. A popular digital design tool within the 3D concrete printing industry is parametric modelling (Li et al., 2023).

By applying parametric modelling techniques, the tool path of a 3D printer can be modified according to parameters defined by the user, resulting in unique geometries and textured surfaces. See Figure 3.

Altogether, designs can be printed to the design specification of the architect or customer. A prototype, in small scale, or one-to-one scale can be printed in a matter of hours, and if necessary, on site and in situ. This reduces the time that prototyping, and production of UMG furniture can be made.

Figure 3 Weave pattern on bench made by The Manchester Metropolitan University for the CIRMAP project

Advantages of using RFA to 3D print UMG furniture

- RFA can be used in mortar as a substitute for equal amounts of virgin sand
- No moulds are required to produce products
- Unique designs, at 50%-80% lower costs when compared to precast products
- Fast realisation with on-site printing
- Complex geometry implementation
- Can include a strong corporate identity
- Weight and shape optimisation, hollow forms rather than solid forms
- Less mortar used compared to precast products
- Computer control to compensate material variability
- Localism within the circular economy if production is close to urban centre demolition

3.3 What need is 3D concrete printing with RFA fulfilling for its suppliers?

Fine aggregates are a waste by-product of the demolition process. At this time there is no pathway for fine aggregate waste to be recycled, so it is sent to landfill.

While this type of waste is classified as inert, and in the UK only charged at £3.25 per tonne for landfilling tax, there is the transportation cost to the Waste Management Company (WMC) to deliver this heavy waste to the landfill. If this heavy aggregate can be transported a much shorter distance, and used in mortars for 3D printing, it has the potential to save the WMC on transportation costs and reduce its carbon footprint. By doing this the WMC will increase its corporate social responsibility score and show its customers that it is a caring company. Depending on distances that are travelled, the WMC may also clear the demolition site quicker and save on fixed and variable overheads.

3.4 What need is 3D concrete printing with RFA fulfilling for society?

As discussed, up to 65 Mt of fine aggregates will be disposed of at landfill between the five partner countries of the CIRMAP project. On the contrary, up to 54 Mt of sand will be mined each year for the same five countries, and sourced from offshore marine environments, from inland rivers and terrestrial mines, causing damage to marine life and depleting natural stock levels.

This CIRMAP project has developed a MPM and several mortar formulations, that can incorporate a significant volume of RFA, as a proven substitute for virgin sand.

Therefore, for every tonne of RFA that can be incorporated into new concrete products saves on natural resources. Furthermore, each tonne of RFA used as a substitute for virgin sand, is saving the carbon footprint of the whole mining, desalinating, processing, and transporting of virgin sand, every time it is recycled and reused.

3.5 Circular economy business models

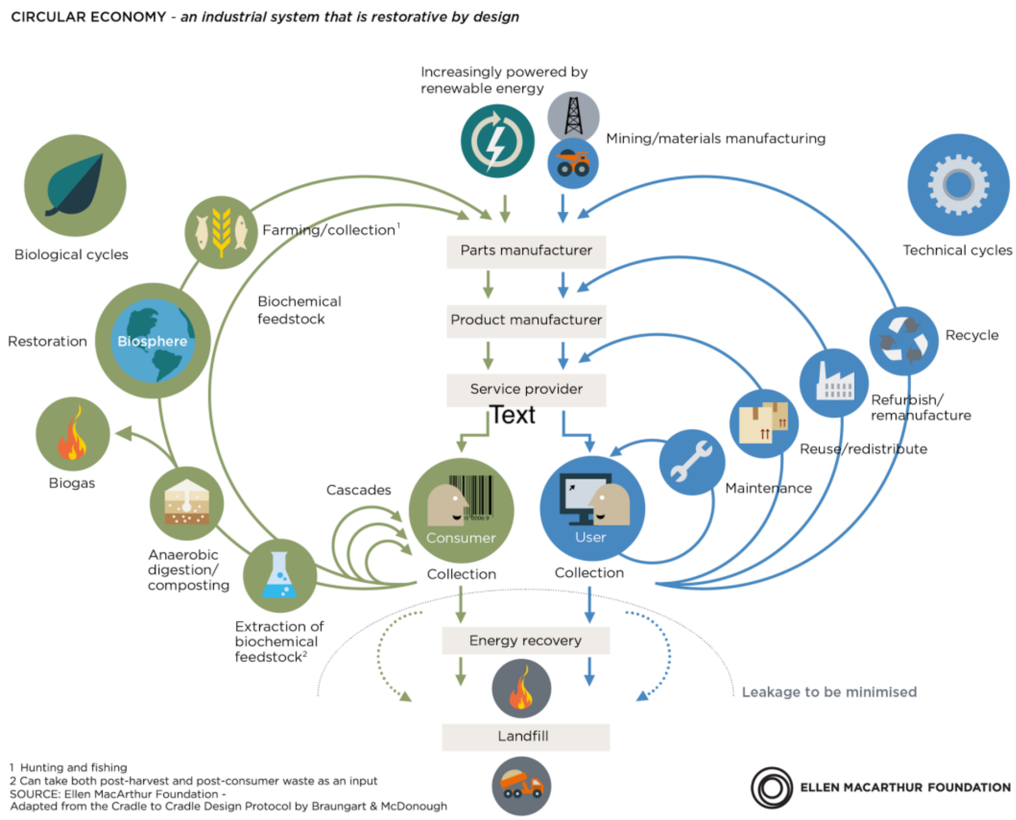

Figure 4 The circular economy butterfly diagram (Ellen MacArthur Foundation, 2023)

The linear economy, as shown through the centre of Figure 4, is manufacture, use, and then discard. The aim of the circular economy is to be at the bottom right-hand side of the model, with concrete products in constant use. What this shows is that recycling takes a product out of the market and is then reintroduced as another product. While this is preferable than landfill, it involves energy usage and in many cases a loss of materials in the recycling process.

The circular economy also considers the interplay between the manufacturer, the customer, and the product. The challenge for the circular economy is how to close the circle. For example, what mechanisms are used to return the product so that it can be re-manufactured? Furthermore, how will the product remain in service in relation to its capacity lifespan, i.e., who and how will it be maintained or repaired if needed?

Altogether, there are five circular economy business models.

1. Product as a service – instead of the customer buying the product outright, the ownership of the product is retained by the manufacturer. Therefore maintenance, replacement parts and after use disposal are all carried out through the manufacturer.

2. Sharing platform – mainly for the IT sector.

3. Circular supplies – usually a company may have a limited number of suppliers that provide the feedstock for the business. However, in the circular economy all customers are the suppliers of their waste as a feedstock to the company. Therefore, either the product comes back directly to the manufacturer, or after use, the product is crushed and reused in its entirety.

4. Product life extension - this is about fixing products so that they can continue to be used for the same purpose that they were made for. This could be by reusing or repurposing prototypes, at a different location.

5. Resource recovery - products are designed to easily be disassembled into their constituent components. This means the design uses interlocking components rather than bonding them together.

3.6 The circular economy flow of RFA

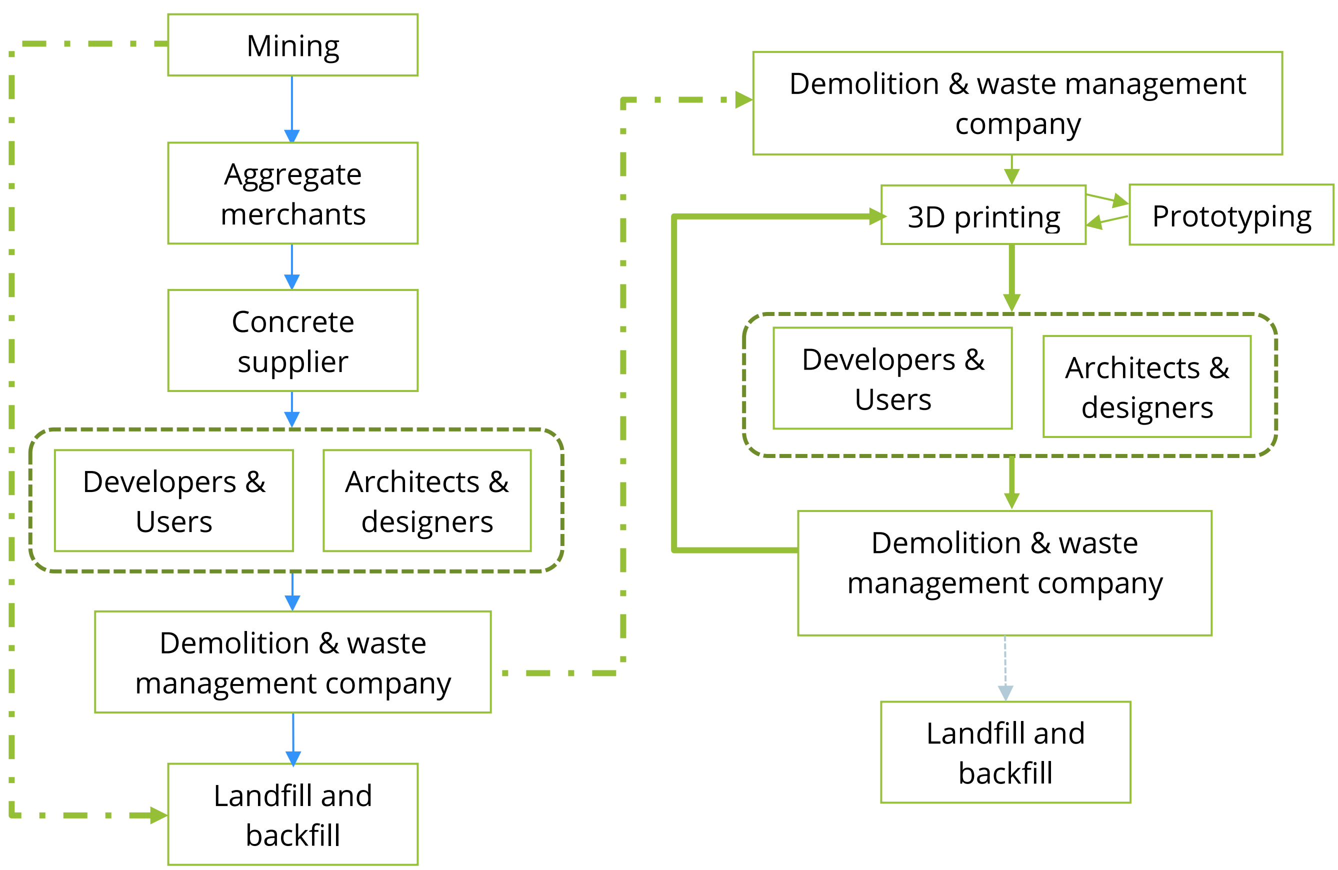

Figure 5 Left side is the linear economy of RFA. Right side is circular economy of RFA.

3.6.1 Material flow in the linear and circular models

Aggregates are a key material in concrete production used throughout building and construction industry. Developers and building owners, together with architects, are key to the design of the built environment and are the specifiers of the materials used. Therefore, in the design stage, there is the need to understand what materials will go into the construction, as well as end use considerations for demolition, to ensure the maximum number of materials can be recycled and reused.

When a building comes to the end of its use, and is demolished, the demolition company together with a WMC will remove the building and the demolition waste. Materials that can be reclaimed and recycled are, however RFA will be sent landfill. This is the linear pathway for RFA, as it is used once within a building and then disposed of.

In a circular model, the RFA will be upcycled and repurposed into new products with a new lifespan. The CIRMAP project diverts RFA from landfill and toward the 3D concrete printing industry, providing opportunity for the material to form a new product. The RFA can be repurposed in two ways, as an end use UMG furniture product, or for concrete structure prototypes.

In a true circular economy, no RFA should end up in landfill. However, when the carbon footprint and the sustainability of upcycling the RFA are outweighed by the carbon footprint of transportation and processing, in may be more sustainable to landfill the RFA. Therefore, in our model there is a faint blue pathway to landfill.

3.6.2 Products are designed for circularity

Design for circularity using RFA manifests itself in three ways: *design for modularity, design for recycling* and *design for durability and performance*.

Design for modularity
The product can be designed for modularity, whereby the product is made using interlocking shapes that can be disassembled and reassemble somewhere else. For example, a park bench can continue to be used as a bench after it has been relocated to somewhere else, or a long undulating bench can be disassembled and used as two shorter benches.

Design for recycling
The products and used materials can be ground up and reused again. However, the technical issue of water absorption will need to be addressed each time.

Design for durability and performance
In theory, the duration of the products should be the same as conventional concrete products and should therefore have the same lifespan as the building or urban setting it is in. However, as these items can be furniture, an art installation, or a sculpture it may be removed when the area is remodelled. Therefore, the item may be forced to end of life even though it is still usable. It is hoped, that in such a scenario, an architectural reclamation company, that recycles usable products from building prior to demolition, would take the object for repurposing.

3.6.3 Material recovery for circularity

Material recovery, from 3D concrete printed products, may happen at several places along the value chain, during manufacturing, or before/during installation at the customers site, and at end of life or end of use. It is important that these materials do not result in landfill.

Material could find its way back into the demolition and waste management system, crushed and recycled again into large and fine aggregates. In theory, these aggregates could be recycled again and used for new products. This means that as an afterlife material, which was once unusable as a fine aggregate, is now in its second iteration.

3.6.4 Further opportunities for circularity

Other circular economy business options are as follows.

Access
A big opportunity to boost sales is envisaged if products are not directly sold but are leased out and paid for by monthly or quarterly subscription. This means *access* to a product is provided, and the manufacturer remains responsible for product maintenance, repair and collecting the products at end-of-life. Municipalities often have a fixed budget. When products are paid for through a monthly subscription fee, this helps the customers' cash flow situation. However, such a business model is only possible if the company can finance the costs of production from the cash flow of its own business. The company could build up a business that sells access for a limited time, i.e., it rents out its creations for a timed duration.

Repair and maintenance
If it is a product still owned by the manufacturer, then the manufacturer will be responsible to repair and maintenance. For example, if the customer is paying a subscription for the product, fixing any damage may be free, or if chargeable the fee could be waivered. It must be noted that urban furniture may be prone to vandalism. And the council may find it convenient for the manufacturer to fix or maintain it as they have the expertise rather than themselves.

Refurbish
If products are returned to the company at end-of-use or end-of-life, the whole product, or some parts of it may still be usable and can be repurposed for the same or similar usage.

Local circular economy- Localism
Circular opportunities are seen to further enhance a local circular economy. Therefore, 3D printing businesses should be situated close to the availability of feedstock. The outcome will be products made from local demolition waste. For this end, the manufacturing of products using RFA should be located near or in big cities where there will always be an availability of RFA. A further selling point is the making of products from local waste which reduced the flow of waste to the local landfill, thus reducing its environmental impact. If the RFA came from a specific building which perhaps was a local landmark for many years, making urban furniture from its demolition waste will provide a memento with a good feel factor for the users and the local council.

4. The customers

The customers will be the following:

- Local public authorities, include council, parks department, cemeteries, etc.
- Corporations that own large buildings that use urban furniture.
- Urban architects that need prototyping
- Garden furniture for the consumer
- Metal and stone sculptors can use 3D printed concrete forms to create shapes

5. Distribution channels - getting products to the customers

There are three modes for installing 3D printed concrete products. The first is third party contractors, the second is the manufacturer with its own team of installers, and the third is the user themselves. Much will depend on what the end use product is. For projects like a new playground, or a landscaping project within the grounds of a large public or private building, the manufacturer will be very much involved in the design and installation of the project. The installation may be printed in situ or at the plant and transported on a truck to be installed.

However, for consumer end-user products, the consumer can either buy it directly from the company or via a third-party reseller. In either case, and depending on the item, the customer can collect it or have it delivered. Installation may be done by a local building contractor, or depending on complexity, by the consumer themselves. Examples of third-party resellers are garden centres and building merchants.

6. Growing a customer base

The 3D concrete printing market with RFA, is an emerging market that is at this time niche, and compared to conventional precast concrete products, is a small market. Therefore, during the next five to ten years, the growth process must be manufacturer driven. The pilot projects carried out by partners within the CIRMAP project have proved that the technology, formulations, mortar, and control software work. As a result, UMG furniture has been installed for public use and demonstrates a successful application.

Going forward, companies should make direct sales to grow customers and use past installations as case studies to communicate the advantages of 3D concrete printing UMG furniture with RFA. Direct sales should focus on bespoke items customised for individual consumers.

7. Income revenue streams

7.1 How will profits be made?

Under the law and regulations across the four EU countries and the UK that the CIRMAP project is relevant, there is a cost to the WMC for handling and processing a tonne of waste aggregates. If the cost to the WMC can be reduced by delivering RFA for 3D concrete printing, as opposed to delivering it to a landfill site, then this will provide a free delivery for free waste. This is a success for both the 3D print manufacturer and the WMC.

7.2 Value adding to maximise income

The goal here is to value add to the waste materials, such that its value as a bespoke design and manufactured item will maximise its entire value. This means it can be a bespoke product designed to fit within a specific installation. Income to the company will include design and consultancy fees, as well as installation, maintenance, and repair, if needed. The purpose is to work closely with the customer to provide a service that includes design, manufacture, and installation of the product. Thus, a 'project' is what is sold.

Lower value product lines of 'generic designed' products, that are not made to order, but are made for inventory, and sold via a catalogue and online store, should also be developed. These generic designed products can be made in high volume and can be sold via third party companies. They will provide a lower profit margin per product to the company; however, the goal is to sell them in higher volumes.

7.3 What value is the customer paying for?

If the customer is going through the design prototyping stage, then the customer will get a cheaper and quicker route to the completion of a prototype. Furthermore, the prototype can be printed on site so that its perspective with the installation site can easily be measured.

For bespoke items the customer is buying a product package that includes, consultancy, design, as well as the installation and in required maintenance of the product.

Buy buying one of the company's products, the customer has the good feel factor that the product is part of a local circular economy business that made it from local waste, i.e., the waste has a local history talking point, and is sustainability as it does not use virgin sand.

8. Key resources required for a 3D concrete printing plant

CIRMAP is a proof-of-concept project, that by 2023, has several working pilot plants across the five regions of the project. Figure 6 shows **Error! Reference source not found.**a robotic 3D concrete print system developed at one of the pilot plants.

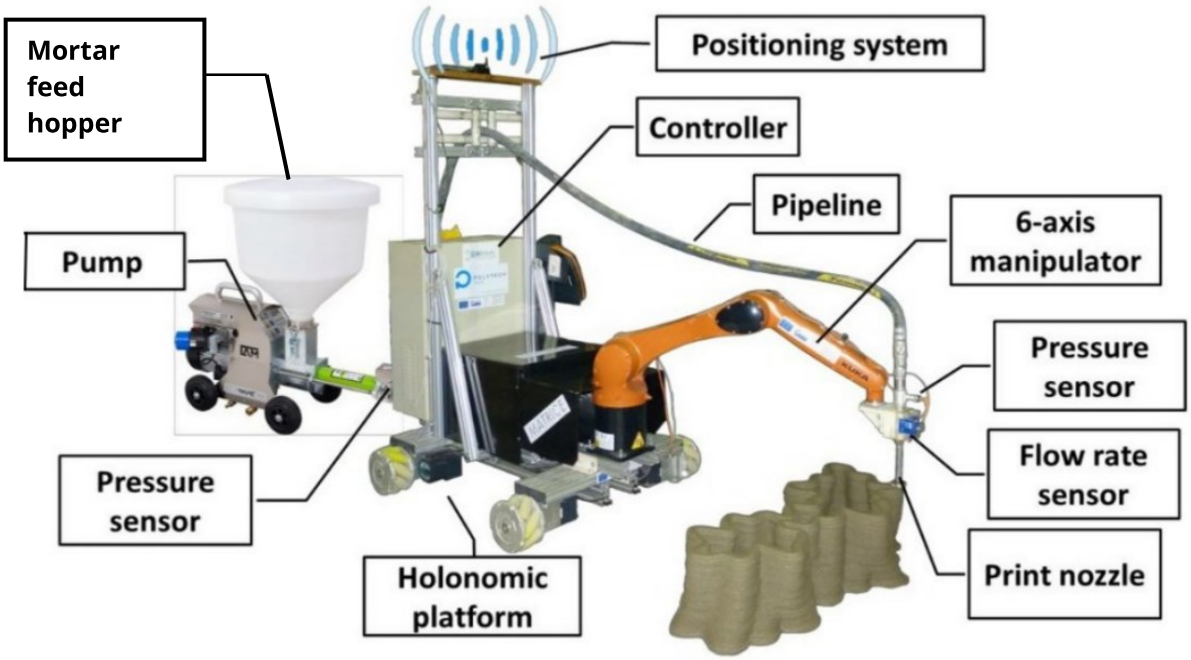

Figure 6 Layout of robotic 3D concrete printing system

8.1 Details of the 3D printing equipment

3D concrete print systems can be modified in several ways depending on the desired output of the 3D printed structure.

Typically, the system requires a manipulator, for example a 3-axis large format 3D printer, or a 6-axis industrial robotic arm, retrofitted with a nozzle large enough to deposit mortar, usually 15-20mm in diameter. Such machines are widely available and can vary in size, and therefore build volume, which is one of the main limitations that should be considered. For the CIRMAP project, a robotic arm with a reach of 1.45m has proved sufficient for printing UMG furniture such as a small bench, or modular components of a larger structure, but other systems can include a mobile track or platform which can increase the overall footprint of the machine. In terms of axis, a 3-axis machine is sufficient for most 3D concrete prints, however as users become more advanced, they may wish to experiment with a 6-axis machine.

At the other end of the system is a mortar pump. Again, such devices are widely available and come with a variety of specifications. Here users will need to consider the size of the aggregates that the device can pump and the working pressure of the system. For the CIRMAP project, a system with a working pressure of 25 bar has proved sufficient for the structures printed. The length of the hose should also be considered, and it was identified that a shorter hose length of 5m is best for 3D concrete printing UMG furniture. This is to limit any waste material that is still in the system after a 3D print.

In terms of quality control users may wish to monitor the system in real time through flow rate and pressure sensors incorporated within the pump system, or online monitoring and rheological measurement systems that are incorporated at the printer's nozzle. To achieve this the CIRMAP project developed a Master Control Command system.

Altogether, the equipment discussed can be purchased directly from major manufacturers. However, if the user is not competent with robotics or 3D concrete printing, then it is recommended that they source their equipment from a third-party supplier specialising in 3D concrete printing. There are several businesses across NWE that can support with this, and provide custom built systems, training, and on-going technical support for new enterprises.

8.2 Software

The software used for 3D concrete printing will depend on the type of machine that is being used and what programming language the machine will respond to. Typically, the Computer Aided Design (CAD) design to 3D slicer workflow still applies for 3D concrete printing. Any popular CAD software can be used to generate a 3D model which can then be sliced for 3D print.

However, the user should be aware that the choice of slicing software will likely be determined by the programming language of the machine. For example, a machine that responds to GCODE will require a standard 3D printing slicer with a modified printing profile. This approach is favoured for printing basic shapes and is a shallow learning curve.

In contrast, an industrial robot will respond to other programming languages such as RAPID code. Here it is recommended that the user build their own slicer or purchase a custom-built slicer through a third-party 3D concrete printing company. A custom-built slicer is made using a visual programming tool such as Grasshopper. It is with such tools that the user can also unlock parametric modelling techniques, create unique geometry, and modify printing tool paths.

8.3 Size of plant

The aim at the CIRMAP pilot plants was to recycle 5t of RFA, per partner country, by 2023. Building a commercial plant was not required, however, VICAT, who are a cement manufacturer and a project partner do operate in the commercial world (Vicat, 2023). Therefore, if an 80 kg/h to 100 kg/h printer was deployed that would be a yearly output of 200 to 300 tonnes per year. The output volume will vary depending on the operational procedures implemented.

The scope for 3D concrete printing with RFA is big due to the availability of the feedstock. This means that the size of the business is not constraint by the technical capabilities of the plant, but rather by the availability of sustainable feedstocks and by the capacity of the market.

8.4 Location site

The CIRMAP project is about implementing localism as part of a circular economic business model. As part of such a model, the goal is to locate the business such that the travelling time of both the feedstock and the products, is kept to a sustainable minimum. This implies that the business should be in or near an urban area.

Furthermore, from the Life Cycle Analysis (LCA), produced for the CIRMAP project it was identified that the optimal distance for RFA to travel, to save only on the transportation carbon footprint, would be a distance that is at least 10 km or less, than what is needed to travel for virgin sand. However, before deciding about transportation distance, the ecological cost of extracting new sand must also be taken into consideration.

8.5 Feedstock

The main feedstock is RFA waste, that at this time is not recycled and will go to landfill. The feedstock is used as a substitute for virgin sand and quantity will vary for each formulation. For example, the formulation developed at The Manchester Metropolitan University, contains 50% RFA by total volume. The remaining materials in the formulation include cement and water and can also include the use of additives such as hydrated lime, plasticisers, viscosity modifying agents and accelerants.

8.6 Storage

There will be a need to store enough RFA feedstock. The ideal conditions to store RFA are in a dry, indoor environment, however silos and airtight drums could also be used where conditions are damp or outdoors. Also, as the business operates on circular economy principles, all prototypes, failed prints, and unsaleable products will need to be stored until they can be recycled and crushed back into RFA to begin a new life as a new product, or as larger aggregates for the construction industry.

8.7 Manual or machine pre-sorting

RFA will need to be sieved to ensure a consistent aggregate size. In a large commercial operation, an automatic sieve will be employed to increase the throughput. This will also avoid any potential damage to the pump and 3D printing system should large aggregates enter the system.

8.8 Characterisation/MPM adjustments

Each time a delivery of RFA is received from a WMC, several characterisation tests will need to be conducted for greater understanding of the material and to determine any amendments to the MPM, such as the water content. Therefore, it is important that the 3D concrete printing plant has suitable laboratory facilities and equipment to collect this data.

The tests are based on existing British and European standards and can be split into two parts, essential tests, and further tests. Essential tests include, particle size distribution, which is designed to BS EN 933-2:2020 standard; Density, which is designed to BS EN 1097-6:2013 standard; And water absorption, designed to the same BS EN 1097-6:2013 standard.

Further tests include, water content, which is designed to BS 812-109:1990 standard; organic content, which is designed to BS EN 15169:2007; elemental distribution and crystal structure; and particle morphology.

Data collected from essential testing can be used in fresh state and hard state simulations developed by the CIRMAP project to validate the materials success prior to printing.

8.9 Mixing the formula

High speed paddle mixers are recommended to ensure a reliable consistency.

8.10 Additives

In general, it is recommended that no plasticisers, or accelerants are added to the mortar. There is a possibility for some additives to reduce compressive strength, durability, and longevity of the final product. However, for practical usability and technical issues, accelerants have been used by project partners to overcome design and manufacturing constrains.

8.11 Enhancements needed for the commercial plant

It is recommended that a commercial plant should include an in-house rock crusher to grind up waste materials. This is to ensure that products received back by way of the circular economy can be crushed and processed into further iterations of UMG furniture products.

9. Strategic alliance partnerships

The RFA feedstock will be sourced from a WMC. Therefore, the most strategic partner for a 3D concrete printing business will be local WMCs. Suppliers of professional services, for example, building architects, landscape architects, landscapers, and even gardening contractors, will all be strategic partners who can recommend the company's products and services to their clients. Large garden centres, or building materials wholesalers, for example Travis Perkins in the UK, would be strategic resellers for the large volume generic products.

10. Key Activities

To summarise, the key activities to launch a 3D concrete printing business using RFA feedstocks are as follows:

- Full list of the machinery, office equipment, vehicles, and spare parts
- Full design of the plant
- Procurement of capital finance

- Plant setup
- Hiring staff and training
- Securing feedstock partners
- Building customer base
- Customer service and onsite maintenance
- Advertising
- Building strategic partnerships

11. Cost structure

As previously discussed, full costing for a 3D concrete printing system can vary depending on the specifications of the printer, pump or software used. As such, the following costing is loosely based on equipment and material purchases suitable to print shapes or components of scale suitable for street furniture. It should be noted that all costs do not include transportation costs.

Equipment	**Estimated Costs**
3D Printer or Robot	€20,000 – 50,000
Pump System	€5,000 – 10,000
Software (Per License)	€1,000 – 5,000
Hardware (per PC)	€1,000 – 5,000

Table 1 Estimate of costs for equipment.

Material	**Cost per tonne**
RFA	€10-15
RFA Treatment (Sieving and Drying)	€30-40
Cement	€347
Hydrated Lime	€878
Water per m^3	€2.23

Table 2 Estimate of costs for raw materials.

The fixed overheads include the following:

- Rent & Council Tax
- Electricity
- Wages

The variable expenses will include the following:

- Maintenance

- Training
- Insurance
- Cleaning
- IT costs
- Marketing and selling
- Waste disposal

The cost will be different in each country and will also change depending on the location of the plant within or outside a town or city.

12. Conclusions

The concept of 3D concrete printing UMG furniture, with RFA from local demolition waste, is a new and novel use of a waste that is otherwise only fit for landfill. It establishes the closing of the circular economy model that gives demolition waste new life as a new product.

For success, there is a need to continuously characterise and adjust the ratios of the aggregates that complete the mortar formula, with each multi-tonne batch of material that is received from a WMC. This is because the grade and variability of a buildings material that is found within RFA is determined to be different each time. Therefore, the MPMs developed in the CIRMAP project will support future progress for using RFA in 3D printing mortars.

It is also presumed that the RFA from 3D concrete printed installations could be used again in further mortar formulations, thus increasing its lifetime circularity. However, as this has not been tested, exactly how many lifecycles RFA can undertake is not yet known.

Altogether, it was not possible to base the business model on an operational manufacturing system in commercial use, as the CIRMAP project was lab based and production was small. Nevertheless, it has shown that a hitherto non-recyclable waste material, can be upcycled into durable long-lasting UMG furniture, and thus close the RFA circular economy loop.

13. References

Ellen MacArthur Foundation. (2023). *The butterfly diagram: visualising the circular economy*. Retrieved 30/03/20223 from

Li, S., Nguyen-Xuan, H., & Tran, P. (2023). Digital design and parametric study of 3D concrete printing on non-planar surfaces. *Automation in Construction*, *145*, 104624.

Vicat. (2023). *Putting people at the center of things*. https://www.vicat.com/

14. Appendix

Harvard Business school, from https://hbr.org/2013/05/a-better-way-to-think-about-yo