

## D8.3

# Report on the possibilities for re-use and recycling of the materials

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OSIRYS

"Forest based composites for façades and interior partitions to improve indoor air quality in  
new builds and restoration"



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## 1. Summary

The Deliverable D8.3 is a public document of the OSIRYS project, delivered in the context of WP8, Task T8.3. The OSIRYS project sets out to develop eco-innovative façade and inner partitioning products. They should improve indoor air quality, increase thermal and acoustic insulation and control breathability of the construction systems. Important constituents of the products are composites of natural fibres and bio-derived plastics, bio-composites. The objective of task 8.3 is to assess the reuse and recycling potential of OSIRYS products, both regarding design and necessary infrastructure. Recycling of bio-composites has been examined in lab studies and required reuse structures and recycling routes have been examined through literature studies and interviews. The conclusions in chapter 8 on how to enable reuse and recycling in a systems perspective are valid for many building products and should be considered in product development.

Enabling reuse or recycling of building materials and products is a challenge. It put special requirements on product design as well as systems of services such as databases on product properties and quality assurance. There is a legal incentive to reuse and recycle through the European Construction Product Regulation and the Directive 2008/98/EC on Waste. Reuse of a product is usually preferable from an environmental point of view, but in some cases recycling may be more feasible from a practical and economical perspective.

### **Critical design factors for reuse or recycling of OSIRYS products**

A key design factor to enable reuse is the possibility for disassembly. Components with shorter technical lifespan should be able to replace and larger modules easy to move without damage.

If a product is designed for a long lifetime with reuse in mind, content of some hazardous substances may not be a major issue. But all products will eventually end up as waste and hazardous substances may obstruct recycling. The possibility of disassembly is still predominant, but to produce waste fractions of unmixed material not undamaged products.

Although labour intensive, deconstruction rather than demolition can be cost effective if landfilling is avoided and suitable joining methods is used. Boards glued together may cause more crumbling than would nails or screws. Using clips or channels is most preferable.

Additives will affect the properties of recycled material, making recyclers more reluctant to accept waste fractions or elevate the cost of recycling. An additive that may be hazardous poses a mayor barrier to recycling. Generally, the economic reality of recycling means that pure materials can be sold to recyclers who produce high quality recycled materials whereas additives will lower the quality and thereby the economic incentive to recycle.

The reuse and recycling potential of OSIRYS products and sub-products/materials has been assessed in chapter 3.3. The potential varies among the different products and materials but is generally low due to their intrinsic characteristics. Some alterations in design could raise the potentials but may be at the expense of other characteristics, such as replacing glue with sturdy mechanical joining techniques or focus on thermoplastics rather than thermosets.

### **Reuse structures**

Reuse of façade or partitioning products is very rare in Europe today. Reuse traders may buy products from demolishers or allow them to drop off products that can be reused. Sale channels are specialized department stores or web shops, small scale operations mainly dealing with other kinds of products. There are also examples of houses having been erected using salvaged material from previous structures on site, local reuse where the design phase has been adapted to local limited supply. Neither of these could be a mayor reuse service provider for reuse services without significant development.

Critical to the reuse potential of products is that there is relevant information available prior to disassembly or demolition. An emerging technology for providing essential information is BIM (Building Information Modelling). This means a digital model of the building is created, providing information of the building components years later. Other smart technologies for identifying building products are tagging with barcodes or RFID (Radio Frequency Identification). At the very least, the different parts of the products should be permanently labelled.

There is also a future need to develop methods of quality assurance for reused products. With the right information of product properties and how to assess the current state at the time of building demolition, reuse traders may handle these products. Manufacturers should assist in developing quality insurance plans from planning deconstruction to inspection of salvaged products.

A recommendation from this study is however not that reuse traders should be the main provider of reused products, or of collection for recycling, in the near future. Due to the novel characteristics of OSIRYS products, the most capable provider of these services may be manufacturers or suppliers. A take back scheme is suggested, where the manufacturer or supplier of a product takes control of the aftermarket. They know quality assurance, have access to the right markets and could widen the product portfolio to also include reused products, at lower prices and to boost their green image. It also enables a business model that safeguard the supply of raw material by recycling.

### **Recycling routes**

The bio-composites developed within the project cannot be recycled in current commercial processes. Several recycling initiatives of composites have been started but are not adapted for bio-composites. Because these are new materials, systems of quality assurance need to be developed so that buyers of recycled material know its content and properties. That is a complex process involving actors along the supply chain.

Previous trials have shown that thermoplastic bio-composites can be reprocessed several times. Thermosets cannot be reprocessed but may be used as fillers in concrete, mortar or other composites, which is low quality utilization. Lab studies have been carried out in order to evaluate the potential for reprocessing of the bio-composite structures.

Bio-composites are sometimes promoted as being compostable, but that is an unlikely scenario as the composting industry will not risk contamination from construction sites. To utilize the novel properties of OSIRYS products, collection for recycling into new products needs control so that materials are not mixed.

OSIRYS bio-composites could share recycling processes with other materials, such as cardboard packaging or other bio-based construction materials such as cellulose wool insulation. This however needs further development of materials, processes and design of recycled products.

For gypsum and cork, recycling routes exist, but some adaptation of the collection system or product design may be needed. Separation of different materials is necessary to enable these recycling routes.

Because recycling routes are currently not available, waste-to-energy may be the most feasible option. Content of gypsum however may hinder even that waste management. It is therefore important that design of OSIRYS products is at the very minimum adapted for waste-to-energy by incineration by enabling easy disassembly of gypsum containing material.

### **Conclusion**

Bio-composites may be inherently difficult to reuse because they may be damaged by scraping or blows during use or disassembly. Recycling is difficult due to the basic fact that composites are a combination of materials. This necessitates initiatives regarding both design and involvement in the aftermarket to assure reuse and recycling of OSIRYS products. This report points at certain issues and possibilities that could be explored to further develop the environmental benefits of these novel products.

## 2. Introduction

The construction sector in Europe is the largest user of material in the economy and the solid waste from the sector amounts to almost a third of all generated on the continent, not counting mining and quarrying. Much is landfilled, leading to unsustainable resource use (Iacovidou et al. 2016).

The OSIRYS project sets out to develop eco-innovative façade and inner partitioning products. Important constituents of the products are composites of natural fibres and bio-derived plastics, bio-composites. The potential to lengthen product lifespan by reuse or replacing new raw material by recycling are important issues to lessen the environmental impact of production. There are many product requirements except for reuse and recycling possibility, see deliverable D3.2, most notably to improve indoor air quality, increase thermal and acoustic insulation and control breathability of the construction systems. It has not been possible to fulfil all requirements during product development; this report evaluates how the waste management requirements have been considered.

Reuse initiatives can be divided into three different categories (Gorgolewski 2008):

- Adaptive reuse refers to mayor renovation of an existing structure on the site, possibly add to it or extend it. It normally implies a change of function resulting from building obsolescence.
- Relocation is when an entire building is moved to a new location. Much can be learned on how to design for reuse from these kinds of initiatives.
- Component reuse implies that selected components are extracted from a building to another. This means valuable components that have not yet reached their technical end of life can be further used even though the building is being demolished.

This report mainly deals with component reuse, as the aim of the project is to develop building products. The design recommendations provided herein is however helpful also for adaptive reuse and relocation, as design for disassembly is crucial.

Recycling implies that a material, not a product, is reused. The report examines several recycling options for the different materials. Most wanted are recycling routes where a material's special characteristics can be utilized, usually by producing similar products from unmixed waste streams, often called closed loop recycling. Open loop recycling (downcycling) on the other hand implies a material is utilized, but many characteristics are lost lowering its value, such as utilizing special composites as filler material in concrete.

A change in attitude towards reuse as well as development of infrastructure for reuse is necessary in the construction industry. This report focuses on what product manufacturers can do to boost the reuse and recycling potential of their products. This means adapting design to the needs of available reuse traders and recyclers, but also taking a larger responsibility in developing the necessary infrastructure in cooperation with these.

### 3. Critical design factors for reuse or recycling

Enabling reuse or recycling of building materials and products is a challenge. It put special requirements on product design, discussed in deliverable 3.2 of this project, as well as systems of services such as databases on product properties and quality assurance.

Reuse of a product is usually preferable from an environmental point of view, but in some cases recycling may be more feasible from a practical and economical perspective. An explanation on when reuse or recycling is preferable refers to the reason for end of life (Ashby 2009).

- Physical or technical end of life means the product is worn out, but could be repaired.
- Functional end of life or loss of desirability means that more modern replacements exist, rendering the products unwanted.
- Economic end of life means that new products could lower operative costs, making a replacement cost-effective.
- Legal end of life means the product is no longer legal to use for certain applications.

Products with a functional end of life or loss of desirability should be designed for recycling, because there will be no demand for these second hand. The other four kinds of end of life means design for reuse could be successfully implemented, although an economic or legal end of life probably means the product can be reused for less demanding applications. This will lower the value making recycling a more feasible option. If design for reuse or recycling fails, or if proper infrastructure is lacking, waste-to-energy is much more preferred than landfilling for bio-based materials. Therefore, design for waste-to-energy is also considered.

This chapter covers important aspects of product design and how these have been handled in the project, whereas chapters 4,0 and 0 discusses what systems are needed to enable reuse and recycling.

#### 3.1 Design for reuse

A key design factor to enable reuse is the possibility for disassembly. Products that are reused today are mainly those that are held in place simply by weight and shape or by a few screws. Removing the products has to be easy and without damaging them. If adhesive is used, disassembly and reuse will be very difficult (Henderson et al. 2013). If different sub-products are glued or mechanically joined into larger elements and these elements are fastened with reversible joints such as screws, reuse may be more cost effective than handling many smaller products (Gorgolewski 2008, Iacovidou et al. 2016). The joints also have to be easily visible and accessible. What is regarded as “easy” to disassemble varies, but workers health and safety regulations are becoming stricter. What is acceptable during assembly today may not be acceptable during disassembly in the future. Weight and measurements should thereby be kept small.

Another design factor is the use of standard dimensions and standard joining techniques. If special screws are necessary to fasten modules, reuse may be hindered due to lack of screws even though the module is in good condition. Standard dimensions of panels and

profiles make it easier to match supply and demand. The design process when building with used products is easier when designers don't have to adapt plans due to special dimensions of available products.

If a product consists of several parts, it should preferably be designed to allow for component replacement. The parts likely to reach end of life first could be designed for technical upgrade. The outer layer of a façade or partitioning panels could be designed with replacement in mind.

If a product is designed for a long lifetime with reuse in mind, content of some hazardous substances may not be a major issue. As long as the product is intact there is little exposure. The legal end of life could however be a risk and the best practice is of course not to include any substances that are listed as (or could potentially be) hazardous. Also, all products will eventually end up as waste and hazardous substances may obstruct recycling.

### **3.2 Design for recycling**

Design for recycling is different from design for reuse on a few aspects. The possibility of disassembly is still predominant, but to produce waste fractions of unmixed material not undamaged products. A European handbook on best practices in deconstruction techniques of plasterboards has been developed (Burgoyne et al. 2015) and several of its conclusions are translatable to OSIRYS products. Several methods for separating layers of walls are identified, mainly manually. Practical tools where pickaxes, shovels, saber saws and similar or automatic screwdrivers depending on the wall design, see Figure 1.



*Figure 1. Manual tools generally used to deconstruct gypsum-based systems. Tools used from the picture 1 to the picture 7: shovel, wrecking bar, cutting chisels, automatic screwdriver, saber saw, sledgehammer and pickaxe (Burgy et al. 2015).*

Although labour intensive, these methods can be cost effective for materials such as plasterboards where recycling is much cheaper than landfilling. How easy disassembly is depends on how large pieces that can be broken loose intact. Boards glued together may cause more crumbling than would nails or screws, Figure 2. Using clips or channels is most preferable. Workers health and safety is of course important during deconstruction. Regulations may be stricter when buildings are deconstructed in the future, ruling out manual handling causing more mixed waste fractions.



*Figure 2. An example of deconstructing sandwich structures glued together using a shovel for leverage, in this case plasterboard and expanded polystyrene attached to a bearing wall. The materials rather than the glue line breaks rendering contaminations in the waste fraction. It is labour intensive and cause crumbling of the material (Burgy et al. 2015).*

The material composition is also more important for recycling than reuse potential. Additives will affect the properties of recycled material, making recyclers more reluctant to accept waste fractions or elevate the cost of recycling. Generally, the economic reality of recycling means that pure materials can be sold to recyclers who produce high quality recycled materials whereas additives will lower the quality and thereby the economic incentive to recycle.

If materials contain substances that are not proven safe for humans and the environment, the precautionary principle means that the material should not be recycled, but disposed of. This means material loss and higher cost.

### 3.3 Properties of OSIRYS products

Based on the principles of design for reuse or recycling a survey has been conducted to relevant project partners. The potential to reuse or recycle the different materials and products has been assessed in the tables below. There are also comments on how to improve these potentials. Potential for waste-to-energy is also noted.

As the survey was conducted in parallel with product design, project months 32 to 37, it does not necessarily concern the final design decisions. It should however inform on possible future development to enhance reuse and recycling potentials.

#### 3.3.1 External cladding of the multi-layer façade

Although the external cladding, Table 1, may be the easiest OSIRYS product to disassemble unharmed from a building, the reuse potential is low as it is specially designed for a particular building. It will usually not be removed until the building is quite old. If recycling routes can be found, collection of the external cladding will be quite efficient. High value recycling routes is however not very likely for thermosets.

*Table 1. The reuse and recycling potential of external cladding of the multi-layer façade.*

Sub-product	Material	Joining method	Reuse potential	Recycling potential	Waste-to-energy potential
Vacuum infused panel	Thermoset bio-composite	Mechanical anchoring to core of the façade and building super-structure.  Quite easy to disassemble.	None – low  Special design for each building.	Low – medium  Not mixed with other material but thermosets are difficult to recycle other as fillers, downcycling.	High

### 3.3.2 Core module of the multi-layer façade

The core module could sustain some damage, such as scraping, without losing reuse value as this will not be visible once reassembled. This type of product, Table 2, is very seldom reused today, but markets could be created. Recycling requires separation of layers which is labour intensive. Recycling routes needs to be developed, which may provide business opportunities for manufacturers.

*Table 2. The reuse and recycling potential of core module of the multi-layer façade.*

Sub-product	Material	Joining method	Reuse potential	Recycling potential	Waste-to-energy potential
Whole module	Sandwich structure consisting of the layers below.	Bio-adhesive to build the sandwich.  Mechanical anchoring to other building elements.	Low  Quite easy to disassemble from building. Reuse potential depends on difficulty of quality assurance and market demand.	None  Separation of layers is necessary for recycling.  Removal of layers containing gypsum is necessary for incineration.	Medium – high  Content of some non-combustibles is acceptable at waste-to-energy plants.
Water tightness barrier	Plastic foil	Bio-adhesive	None	None - low  Difficult to separate the thin foil.	High

Fire proof panel	Thermoplastic bio-composite	Bio-adhesive	None – low  Might break when disassembled. Some adhesive will remain, but it could in some cases be incorporated into new products.	Low – high  No recycling routes exist, but could be created. Production of new panels possible.	Medium  High gypsum content will necessitate special treatment plants, raised price.
Cork insulation	Black cork	Bio-adhesive	None – low  Might break when disassembled. Some adhesive will remain, but it could in some cases be incorporated into new products.	Low – high  No recycling routes exist, but could be created. Production of new panels possible.	High
Profiles	Thermoset bio-composite	Bio-adhesive and screws	Low  Might be able to disassemble without damage. Low value.	Low – medium  Will contain residues of adhesives. Thermosets are difficult to recycle other as fillers, downcycling.	Medium  Some glass fibre content may raise prices.

### 3.3.3 Internal solution module of the multi-layer façade

The internal solution of the multi-layer façade, Table 3, is similar to the interior portioning product, Table 5. The former contains a water tightness barrier in the sandwich that will make separation of layers more difficult prior to recycling. In both cases, the whole module could be reused if the outer layer is unworn and undamaged. If separation without breaking is possible, inner layers and profiles may be used after the quality has been assessed, but this does not seem economically feasible.

*Table 3. The reuse and recycling potential of internal solution module of the multi-layer façade.*

Sub-product	Material	Joining method	Reuse potential	Recycling potential	Waste-to-energy potential
Whole module	Sandwich structure consisting of the layers below.	Bio-adhesive to build the sandwich.  Mechanical anchoring to other building elements.	Low – medium  Quite easy to disassemble from building. Reuse potential depends on difficulty of quality assurance and market demand.  Susceptible to physical damage during use.  Repainting possible	None  Separation of layers is necessary for recycling.  Removal of layers containing gypsum is necessary for incineration.	Low – high  Low potential if gypsum plasterboard is used and not separated.

Multi-functional coating	Coating	Coating	None	None	High
Gypsum or foamed wood wallboard	Gypsum or foamed wood	Bio-adhesive	None – low  Might break when disassembled. Some adhesive will remain, but it could in some cases be incorporated into new products. Low value.	Low – high  No recycling routes exist for foamed wood, but could be created. Paint will lower the value.  Recycling routes for gypsum are established.	None –high  Gypsum can be recycled, foamed wood is suitable for combustion
Foam or cork insulation	Black cork or commercial foam insulation	Bio-adhesive	None – low  Might break when disassembled. Some adhesive will remain, but it could in some cases be incorporated into new products	Low – high  No recycling routes exist, but could be created. Production of new panels possible.	High
Water tightness barrier	Plastic foil	Bio-adhesive	None	None - low  Difficult to separate the thin foil.	High

Profiles	Thermoset bio-composite	Bio-adhesive and screws	Low  Might be able to disassemble without damage. Low value.	Low – medium  Will contain residues of adhesives. Thermosets are difficult to recycle other as fillers, downcycling.	Medium  Some glass fibre content may raise prices.
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### 3.3.4 Curtain wall

Reuse of the curtain wall may be possible if disassembly into appropriate modules is possible. Disassembly into individual parts will be labour intensive. Unique designs will lower the number of potential applications.

*Table 4. The reuse and recycling potential of the curtain wall.*

Sub-product	Material	Joining method	Reuse potential	Recycling potential	Waste-to-energy potential
Whole module	Wall consisting of the components below.	Bio-adhesive between components.  Mechanical anchoring to other building elements.	Low  Special design for each building lowers reuse potential.  Susceptible to mechanical damage.	None  Separation of layers is necessary for recycling.	Medium  Some remains of glass is not a problem, but should be separated.

Profiles	Thermoset bio-composite	Bio-adhesive and screws	Low  Difficult to disassemble without damage.	Low – medium  Will contain residues of adhesives. Thermosets are difficult to recycle other as fillers, downcycling.	Medium  Some glass fibre content may raise prices.
Glass  (not developed in the project)	Glass	Bio-adhesive	Low  Difficult to disassemble without damage.	Low  Other glass than packaging is often not recycled.	None
Gaskets  (not developed in the project)	Rubber	Bio-adhesive	None	None – medium  Recycling routes exist for rubber, but mostly larger quantities.	High

### 3.3.5 Interior partitioning

The whole module could be reused if the outer layer is unworn and undamaged. If separation without breaking is possible, inner layers and profiles may be used after the quality has been assessed, but this does not seem economically feasible.

Table 5. The reuse and recycling potential of the interior partitioning.

Sub-product	Material	Joining method	Reuse potential	Recycling potential	Waste-to-energy potential
Whole module	Sandwich structure consisting of the layers below.	Bio-adhesive to build the sandwich.  Mechanical anchoring to other building elements.	Low – medium  Quite easy to disassemble from building. Reuse potential depends on difficulty of quality assurance and market demand.  Susceptible to physical damage during use.  Repainting possible.	None  Separation of layers is necessary for recycling.  Removal of layers containing gypsum is necessary for incineration.	Low – high  Low potential if gypsum plasterboard is used and not separated.
Multi-functional coating	Coating	Coating	None	None	High

Gypsum or foamed wood wallboard	Gypsum or foamed wood	Bio-adhesive	None – low  Might break when disassembled. Some adhesive will remain, but it could in some cases be incorporated into new products. Low value.	Low – high  No recycling routes exist for foamed wood, but could be created. Production of new panels possible. Paint will lower the value.  Recycling routes for gypsum are established.	None –high  Gypsum can be recycled, foamed wood is suitable for combustion
Foam or cork insulation	Black cork or commercial foam insulation	Bio-adhesive	None – low  Might break when disassembled. Some adhesive will remain, but it could in some cases be incorporated into new products	Low – high  No recycling routes exist, but could be created. Production of new panels possible.	High
Profiles	Thermoset bio-composite	Bio-adhesive and screws	Low  Might be able to disassemble without damage. Low value.	Low – medium  Not mixed with other material but thermosets are difficult to recycle other as fillers, downcycling.	Medium  Some glass fibre content may raise prices.

### 3.3.6 Common issues

An aspect relevant to all products is that of sealants and anchoring to other parts of the building. These may be site specific and a matter for the constructor or applied by product manufacturers. Anyway they may hinder reuse by making modules more difficult to disassemble without damage. If they are difficult to separate from other materials they will contaminate the waste stream to be recycled. Designers and builders should take this into account, not to lower the potential for reuse or recycling.

There is a risk of damage around mechanical anchoring when holes are drilled. The area of anchoring is also more susceptible to cracking or breaking as forces affecting the products will be focused there. Anchoring should have sufficient integrity not to be degraded if screws are loosened and reapplied.

Moisture damage will prevent reuse. This is a risk after dismantling and during transport and storage awaiting assembly in new buildings. There is also a risk of moisture damage in the interior layers of the sandwich if holes are drilled and that may be difficult to detect.

What kind of wastes that are generated depends on product design and the intended construction process. If OSIRYS-products are ready made modules delivered to the construction site, most waste should arise during module manufacturing where they can be sorted by material type. Finished modules that are discarded at the construction site will consist of a mix of materials. Cutting modules or sandwich panels into the right size at the construction site will produce small pieces of mixed materials that may be difficult to separate. If instead panels are cut and glued into sandwiches in situ, it may be possible to sort the different materials at the site. Waste from different parts of the supply chain will have different properties and will be generated in different amounts. Accounting these amounts in large scale manufacturing and construction is important to evaluate how the waste can be used as a resource, feeding back into production. In this stage of product development, minimizing waste of glued together panels should be a priority.

## 4. Existing reuse structures

Reuse of construction material or products is not common in Europe today. The main use is by private persons or small construction companies. The kind of products being redistributed is typically not façade or partitioning modules. There are however legal possibilities for reuse and some professional actors in reuse.

### 4.1 Legal conditions for reuse

Hemström et al. (2012) presents which EU-legislation that is relevant for the reuse of C&DW. Also national legislation is surveyed for a few member states. The Construction Product Regulation (CPR) and the Directive 2008/98/EC (European Commission 2008) on Waste was deemed relevant.

The Construction Product Regulation (CPR) applies for construction products that are placed or made available on the European market (European Commission 2011). It repeals the former Construction Product Directive (CPD) and aims at setting up harmonized conditions and rules on how to express the performance of essential characteristics of construction products. It also refers to CE marking as the only marking of conformity of the construction product and its compliance with European Union harmonized legislation. Other markings may be used, provided that they help to improve the protection of users of construction products and are not covered by existing Union harmonization legislation. The REACH-legislation (Registration Authorisation and Restriction of Chemicals) is mentioned as an example of a harmonized legislation to be used when applicable. The following basic works requirements (BWR) are covered by CPR:

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health and the environment
4. Safety and accessibility in use
5. Protection against noise
6. Energy economy and heat retention
7. Sustainable use of natural resources

The significance for the reuse of products is that in the CPR one basic requirement is that construction works should be designed, built and demolished in such a way that the use of natural resources is sustainable. In particular reuse or recyclability of construction works, the materials and parts after demolition should be ensured. If available, Environmental Product Declarations (EPD) should be used for the assessment of sustainable use of natural resources (European Commission 2011). This strengthens the reuse potential for newly produced construction works and products, but since the harmonized standards and legislation are not yet fully developed for this requirement, the actual practice of this requirement through the CPR is probably relatively small.

Because building products put on the market should be CE-marked, so should reused ones. Hemström et al. (2012) concluded that was not clear in 2012 whether materials needed to be CE-marked again during reuse, or if the previous marking was enough. Remarking does not seem to take place today by the rather small scale reuse traders in Europe.

## 4.2 Reuse traders

There are professional reuse traders today and more still that are run by municipalities or charity organizations. The reuse businesses in Sweden and Belgium are more developed than in other countries but is marginal compared to the conventional construction products retail. The costumers are usually private individuals and small construction companies. It is unusual that architects or structural engineers participate today. This means reused products are used in cottages and single family houses, not multi-family houses or commercial buildings.

Reuse traders may buy products from demolishers or allow them to drop off products that can be reused. Sale channels are specialized department stores or web shops. Liabilities or warranties are usually not given to the costumer. Because of the small scale of the operations and that the costumers have the possibility to assess the quality, these are working systems. It is however not systems adapted for collecting large amounts of OSIRYS products from commercial or multi-family buildings nor delivering to larger construction sites.

## 4.3 On-site reuse of demolished buildings

Several projects have been conducted during the last two decades where houses have been erected using salvaged material from previous structures on site, local reuse where the design phase has been adapted to local limited supply (Gorgolewski 2008, Iacovidou et al. 2016). These are cases where old buildings have been assigned for demolition and a similar building will be constructed afterwards, which is of course not always the case. These projects are good for developing design processes involving reused components.

Flexibility of the design process is important, but problems are alleviated with good information of what deconstructed buildings contain (Gorgolewski 2008). Even so much material are not reused but recycled, or rather downcycled, such as producing structure material under roads by crushing concrete. This may replace the use of new aggregate material and of course lowers the need for transportation.

These kinds of projects involving OSIRYS products will not be possible for years or decades. They will not be a major form of reusing these novel products.

## 5. New reuse structures

From the previous chapter it is evident that new reuse structures need to be developed to facilitate large scale reuse of OSIRYS products, assuming they are designed for reuse. To ensure reuse collaboration between manufacturers, designers, structural engineers, traders and constructors is critical. Coordination of the activities sourcing, testing and incorporation of components in new structures are necessary (Iacovidou et al. 2016). This is evidently out of scope for this project. This chapter will elaborate on what can be done by designers and manufacturers to create new reuse structures, through internal initiatives and partnerships.

Optimal reverse supply chains for C&DW have been suggested by Hemström et al. (2012) along with key development needs along the chain. Most relevant for this project are the suggestions:

- Centralization of information through database system
- Development of quality assurance systems for reused products
- Reuse related design, product development and construction concepts

The model for forward and reverse supply chain in Figure 3 is applicable to all construction products and materials. How it can be adapted to the novel products developed in this project is elaborated below.

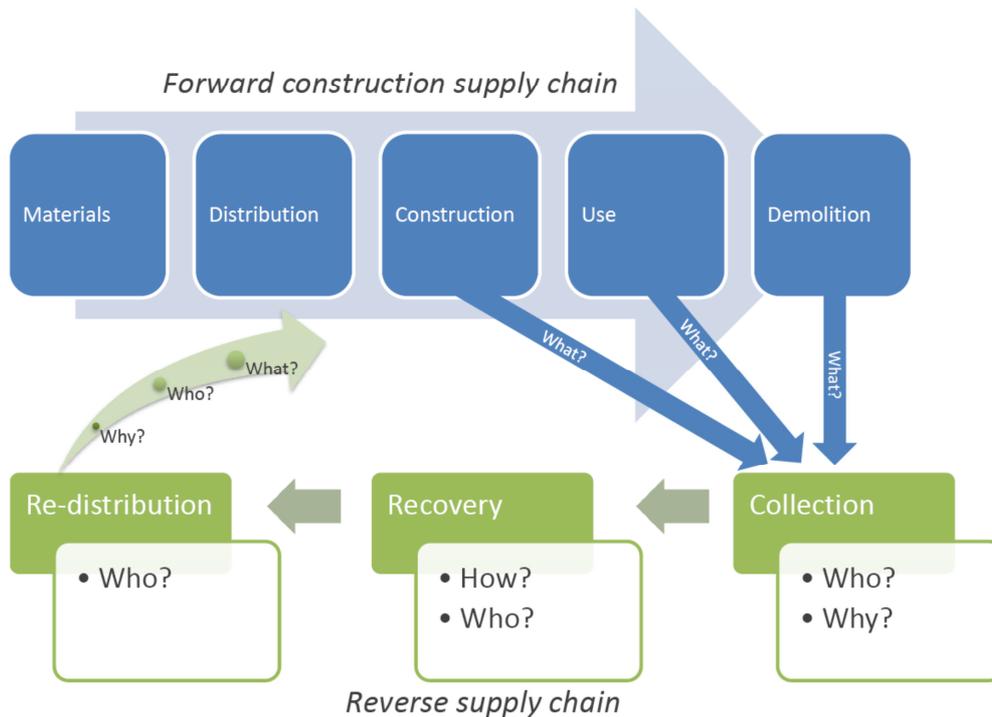


Figure 3: Model framework for characterization of supply chain for reused construction components in Europe. The supply chains for recycling or waste-to-energy comprises other steps. Here “What” refers to what products that are available from different stages of the supply chain. “Why” refers to the drivers for waste generation and reuse of products. “Who” refers to the fact that different actors can perform necessary actions in the reverse supply chain. The model was developed within the project IRCOW (Hemström et al. 2012)

## 5.1 The need for product information

Critical to the reuse potential of products is that there is relevant information available prior to disassembly or demolition (Gorgolewski 2008). Proper information eases the planning of disassembly because the demolisher knows what they should look for and builders may know what products that will be available in the future. Building plans or databases could provide quick information. An example of what information that can be gathered from building plans and drawings is the study by Huuhka et al. (2015) who compiled information on what type and dimensions of concrete panels that are currently used in 276 apartment buildings. The information can be used by designers of new buildings who need the information of what kind, dimensions and amount of certain products that will be available after deconstruction of old buildings.

If this kind of information regarding OSIRYS products was compiled in databases and made available prior to demolition, the supply of reused products would be more predictable. Whose responsibility it would be to manage these databases is another question, a reuse

oriented industry association has been suggested (Hemström et al. 2012). Manufacturers can help by providing information in an appropriate format.

An emerging technology for providing essential information is BIM (Building Information Modelling). This means a digital model of the building is created and adapted during the design and construction phase, including tagging and archiving properties of all components. With the help of this tool, material can be more efficiently managed during construction, but the model can also provide information of the building components years later. Other smart technologies for identifying building products are tagging with barcodes or RFID (Radio Frequency Identification) (Iacovidou et al. 2016). At the very least, the different parts of the products should be permanently labelled.

A shape of things to come may be the initiative by the Swedish government to investigate the possible consequences of compulsory log books of buildings. The two purposes would be to give knowledge of hazardous substances in building material and products and to facilitate higher rates of reuse and recycling. Three alternatives with different legal demands were considered. The softest alternative is to provide guidelines for how to write logs and the hardest concerns mandatory logs delivered to a national authority. The logs should be updated when renovation is performed. The mid-alternative concerns mandatory logs are to be kept updated, but how they are written is up to the builder and monitoring is performed by municipalities (Swedish National Board of Housing, Building and Planning, [boverket.se/loggboken](http://boverket.se/loggboken)).

Information of what goes in to a building is one thing, the state and characteristics of them after use is another. A general inspection of the building will be valuable to assess the feasibility of reclaiming any products for reuse and after disassembly structural tests should be performed to assure characteristics. Industry codes and standards that identify accepted procedures and good practice for component reuse would provide reassurance for clients and designers (Gorgolewski 2008). To develop these codes and standards for OSIRYS products, means of quality assurance should be developed by manufacturers.

## 5.2 Quality assurance

In other work packages a quality insurance plan for new products is being developed. There is also a future need to develop methods for reused products. Some starting points are these:

- Moisture might affect each layer of the sandwich; one way of examining this is by dimensional analysis, measuring thickness, width and height of the sandwich. Disassembly of the sandwich will allow analysis of each layer but is labour intensive and may harm the products. These procedures are likely far too labour intensive to be economically feasible for sandwich structures in the façade, where moisture damage may occur. It may be more feasible for the less complex products, such as interior parts of the façade or partitioning.
- Visual inspection should reveal cracks, scratches and broken corners. Cracking and debonding of any paint also matters.
- Panels and profiles require a certain amount of care and should be supported at several points along their height (more relevant for very long products such as in the Tartu demo) during storage and transportation. During temporary storage, use

polystyrene and foam wedges between elements. Elements should be packaged in closed crates with polystyrene (foam) blocks between the elements. The latter will be placed so as to avoid the elements coming into contact with each other and moving inside the crate. Elements should avoid direct contact with water and be protected from sunlight or accidental damage.

### **5.3 Take back scheme**

A take back scheme means that the manufacturer or supplier of a product takes control of the aftermarket. It can be regarded as a voluntary extended producer responsibility regarding waste management or as a business models that safeguard the supply of raw material by recycling. This kind of scheme is mentioned in the assessment of optimal supply chains for reuse of C&DW in the IRCOW-project (Hemström et al. 2012) as an innovative construction concept. The manufacturer assures the collection of construction waste or even end of life products for reuse or recycling.

OSIRYS products do not resemble other materials on the market, meaning recycling companies will be reluctant to handle these. Before a market is established, there will be high barriers to initiate reuse or recycling schemes. The ones that are best suited to overcome these barriers are producers, thereby improving the environmental performance of its products.

Examples of take back schemes for construction material are Paroc's Rewool® for rock wool insulation and Desso's Take Back™ for carpets. Rewool® enables closed loop recycling of mainly construction site scrap but also demolition waste if minimum quality can be assured (PAROC 2015). Carpets are a more complex product. Desso have developed a special line of carpets in combination with separation and recycling processes. Recovery of used carpet tiles is regulated through a maintenance contract with the customer. During renovation or demolition the tiles are sent back to the manufacturer where 50 % is recycled into new carpets and 30 % that is not suitable for recycling is utilized for waste-to-energy. Because the manufacturer has maintenance contracts with the customers the remaining 20 % was reused in other buildings (WRAP 2013).

#### **5.3.1 Reuse**

OSIRYS products will not be commonly used for some time and knowledge of its properties is of course low at a start. This means the products may also be in low demand on the second hand market. The ones who have knowledge of the products are suppliers and manufacturers. They have access to the right markets and could widen the product portfolio to also include reused products, at lower prices and to boost their green image. By having a take back scheme, there would be control of the supply of reused products, providing a better sourcing service to customers.

Manufacturers and suppliers may be the most suitable actors to do quality control of returned products, having gained this knowledge from the production lines. By testing and selling used products alongside new ones provides confidence in the quality.

Different kinds of OSIRYS products are wasted along the supply chain and the possibility to include these in a take back scheme varies. Façades may be maintained for decades before

being deconstructed, having reached their technical end of life. The demand for these on the second hand market will be low and the take back service may not be provided by the original manufacturer. Surplus orders of profiles on the other hand may be collected from construction sites and have the same quality as new ones.

Manufacturers and suppliers should identify niche markets where a take back scheme is most feasible. This would be buildings that are renovated or changed over shorter periods of times than the technical lifetime of the products. There should also be reasonable time to maintain contact between building owner and suppliers. In the case of Desso's carpets, maintenance contracts have been in place since the 1990's (WRAP 2013). Possible niche markets are for example office buildings where new tenants wish to move interior partitioning or shopping centres wishing to change curtain walls as stores are changed. For these niche markets, special designs could be developed to ease disassembly.

### **5.3.2 Recycling**

A take back scheme may provide products that can be reused in other structures. Another objective with such a scheme may be to collect material waste for recycling. Scrap will arise during production and construction as products are cut to the right size or broken. These waste flows will likely be larger than the amount of products collected for reuse. The material will also be available years before used products can start to be collected. This means that recycling may in fact be the main result from a take back scheme.

The reason for developing a take back scheme for recycling is that the manufacturers are the ones that have knowledge of and use for the novel materials. Before similar products have a large market share, it will be difficult for waste collection companies to offer adapted services and proper recycling routes due to small amounts. The risk would be higher that OSIRYS-products are simply collected for combustion or landfill. But manufacturers could of course collaborate with waste collection companies to develop take back services. This is for example the case with Paroc's Rewool® scheme where customers can either have scrap material collected by the manufacturer or the recycling company Ragn-Sells (PAROC 2015).

A take back scheme would provide large amounts of materials and enable more cost effective recycling processes. Under the right conditions and design, the material could be recycled into new or similar products. Much waste will consist of different material glued together, see chapter 3.2. Even though separation may be difficult, developing processes will be more feasible in large scale.

What kind of wastes that are generated depends on product design and the intended construction process. If OSIRYS-products are ready made modules delivered to the construction site, most waste should arise during module manufacturing where they can be sorted by material type. Finished modules that are discarded at the construction site will consist of a mix of materials. Cutting modules or sandwich panels into the right size at the construction site will produce small pieces of mixed materials that may be difficult to separate. If instead panels are cut and glued into sandwiches in situ, it may be possible to sort the different materials at the site. Waste from different parts of the supply chain will have different properties and will be recyclable to different extent. With a take back system, manufacturers will get better knowledge on waste generation and can better utilize it as a resource.

## 5.4 Reuse traders

A study on the amount of concrete panels currently installed in Finnish 1970s mass housing (Huuhka et al. 2015) found that the reuse potential is high as large amounts of similar dimension wall units will be available following deconstruction. There is then a need for reuse traders that collect, store and sell the products. Supplying sufficient amounts of reused products is important to enable design with reused products without project delays (Iacovidou et al. 2016). If reuse traders would also handle OSIRYS products, the availability of façade and inner partitioning products will increase.

Reuse traders need to be competent in quality insurance plans of these specific products. Although guidelines could be provided through BIM or other databases, but gaining much experience will be difficult unless reuse is in relatively large scale.

There is a need for codes and standards in the building industry for using reused materials. When procedures are lacking, designers and builders will be reluctant to use these materials (Gorgolewski 2008). This applies to reuse of all material, not just OSIRYS products. To enable reuse of OSIRYS products specifically, manufacturers need to cooperate with relevant stakeholders to develop procedures such as quality assurance and best practices for deconstruction.

## 6. Possible recycling routes

As discussed in chapter 3.2, recycling into high value products requires sorting or separation into pure material fractions. This chapter examines possible recycling routes for the materials used in OSIRYS-products under the assumption that the different layers are possible to separate from each other. Utilizing mixed material to produce new products has not been examined and does not seem feasible. This means separation is necessary. Separating the layers one by one is possible but requires much manual labour making it expensive. Separation after grinding may be mechanized but it is a large effort to develop efficient processes. In neither case would the resulting materials be pure as the glue will not come loose from the panels.

Recycling can be many things. Utilizing a material for its original purpose is called closed loop recycling. This is most preferable as it implies high quality and value of the recycled material. This is however not possible for many materials due to losses of material and properties during the recycling process. Utilizing recycled material for a less demanding application, such as ground composites to reinforce concrete, is called downcycling and implies lower value. Downcycling may be in several steps but the quality of the virgin material will not be regained. Waste-to-energy by incineration will prevent landfill, except for the ash, but all material characteristics will be lost. Several recycling routes are possible for the different materials developed in the project.

### 6.1 Current recycling of composite material

Two main kinds of fibre-reinforced plastic composites is used today, glass and carbon fibre. Recycling processes for these are not as developed as for example paper recycling, but commercial processes exist. Most developed are processes for carbon fibres, which are expensive materials, making recycling economically feasible. It utilizes the thermal treatment pyrolysis to decompose the plastic matrix while the fibres remain. Despite recycled carbon fibre being cheaper than new ones, the market is underdeveloped as manufacturers have been reluctant to change their supply methods (<http://www.compositesworld.com/articles/recycled-carbon-fiber-update-closing-the-cfrp-lifecycle-loop>). This is an example of the difficulties of establishing material cycles involving designers, manufacturers, costumers and recyclers.

There are some examples of glass fibres being recycled to replace aggregates in mortars or concrete. This is done by adding the composites to the cement kiln, using the plastic as fuel and the fibres as structure material. This is downcycling of the composites and produce cement of lower mechanical properties, although durability is unchanged (Yazdanbakhsh et al. 2014).

There have been many studies on mechanical, chemical and thermal recycling processes but few have reached commercialization. A review by Yang et al. (2012) states three overarching fields where development is needed to enhance recycling:

1. New easy recyclable composite materials.
2. More efficient separation and purification technologies.

3. Production techniques that can at least partially use the recycled fibres instead of only new fibres.

Bio-composites are not as common as glass or carbon fibre composites and there are no commercial recycling initiatives. Utilizing the pyrolysis process or cement kiln would not result in recycling as bio-composites would combust.

## 6.2 Recycling of bio-composites

During the last decade, there has been great interest in developing thermoplastic bio-composites rather than thermoset, as the first generally has a good recyclability. However many blends have not been trialled for recycling (Soroudi et al. 2013).

Bio-composites have a lower recycling potential than pure polymers, because composites are more sensitive to thermomechanical degradation than corresponding plastics. The recycling trials that have been conducted on different blends however show that thermoplastic bio-composites can be reprocessed several times. A review of trials by Soroudi et al. (2013) shows that composites has been recycled three to eight times into products before quality is lowered. The quality is however often changed: Thermal stability and moisture resistance may increase because of the improvement of interfacial bonding between fibre and matrix. Different degradative effects can also happen due to length reduction and chain scission in the synthetic thermoplastic matrix, which leads to a decrease in the molecular weight and an increase in crystallinity. Some trials have shown the need for some additives to increase interfacial adhesion (Bourmaud et al. 2007).

There have also been trials of recycling bio-composites into fillers for mortar and concrete, rather than reprocessing into new composites. This kind of downcycling can of course only be done once, but may produce low cost mortars (Soroudi et al. 2013). The studies above concern thermoplastic bio-composites. Grinding thermosets can also be used as filler material. There exists successful experiments of even thermosets replacing new fibres to some extent (Palmer et al. 2009), but not for bio-composites.

Bio-composites are sometimes promoted as being compostable, implying a safe waste management with harmless residues. Composting could be a final waste management option after a few cycles of reprocessing (Le Duigou et al. 2008). Successful composting of such materials would however be an industrial process to control temperature, pH and moisture (Soroudi et al. 2013). Composting of such materials is however not being conducted today and it is an unlikely scenario. Plenty of clean plant matter such as municipal garden waste and agricultural waste is available to the composting industry. Construction waste poses far greater risks of contamination and will not be considered (Conroy et al. 2006).

### 6.2.1 Recycling of OSIRYS bio-composites

For thermoplastic bio-composites developed within the project, reprocessing into new composites is the most preferable option as this could result in a high value product. Some thermoset bio-composites could also be used as filler in new bio-composite parts. Reprocessing trials are described in chapter 7. The possible applications of these recycled

materials have not been assessed, if they can be utilized in OSIRYS products or other applications.

The fire panel developed in the project contains plasterboard scrap in its core layer. This could most likely be replaced by grinded thermoplastic composites or even the thermoset profiles. It has not been tested and how it would affect the fireboard properties are not known. OSIRYS materials could also be grinded and used as reinforcement in mortar, concrete or other composites. This kind of downcycling is possible for all OSIRYS products, but product development is necessary to find applications for these new materials.

A key to recycling of these novel materials is that they are available to the competent companies. For production scrap, this will not be a problem as the recycler may be the manufacturer. But circulating waste from construction and demolition is a bigger challenge. For years, these materials will not be very common and they should not be mixed with other composite materials as cost-effective recycling requires unmixed waste fractions. A manufacturer take back scheme could be an option, described in chapter 5.3.

OSIRYS bio-composites will not comprise just fibres and plastics, but also additives such as flame retardants. This may limit applications of recycled materials, but if recycled into new OSIRYS products the intended application is the same as before. This would constitute a controlled cycle of material where characteristics of the additives are desired instead of considered a burden for mixed composite recycling.

To sum up, there are no current recycling routes for OSIRYS bio-composites or any other bio-composite for that sake. There is however a potential to develop such services and processes. What manufacturing processes the recycled material could be utilized in also needs to be further developed. Lastly, quality assurance is paramount to ensure high value recycled material. The buyer needs to know just what the material contains and its properties.

### **6.3 Recycling of gypsum**

The use of gypsum plasterboard instead of foamed wood board in the pilot buildings has been suggested. Plasterboards are common in construction and recycling routes exist, although there are some limits due to lack of regional infrastructures or economic feasibility of sorting at the site. A main barrier to plasterboard recycling is that deconstruction has not always been considered, plasterboards are inseparable from other materials (Burgy et al. 2015).

Several European companies collect and recycle gypsum. Some impurities are acceptable, such as pieces of wood, wallpaper and nails which are sorted out during the recycling process. The recovery rate is high, effectively preventing waste to landfill. The recycled gypsum is sold to producing companies and incorporated into new plasterboards ([http://gipsrecycling.biz/15841-1\\_GypsumRecycling](http://gipsrecycling.biz/15841-1_GypsumRecycling)).

Unlike other materials used in OSIRYS products, gypsum is non-combustible. If it would be treated in an incinerator anyhow, sulfuric acid is formed causing acidic emissions. Waste incineration plants do not accept waste containing too much gypsum. It is therefore very

important that, if gypsum is used, it is easily separable from other materials during deconstruction. This enables recycling and avoids landfilling of the entire OSIRYS product.

## 6.4 Recycling of cork

A major constituent of the multilayer façade and inner partitioning is cork, more specifically black cork manufactured from a process involving heat treatment. It is possible to use new or recycled cork to produce black cork for OSIRYS products.

It is possible to mechanically recycle black cork into other agglomerated products, but it has not been examined which applications that may be feasible. According to the project partner Amorim, the recycled black cork will not be sufficient for use in new OSIRYS products. During manufacturing of sandwich modules, bio-adhesives will penetrate some way into the cork and is therefore difficult to remove. Although the bio-adhesive may not disrupt the recycling process, it may have an effect on the properties of the produced material, ruling out some applications.

The cork that is recycled today is mainly cork stoppers collected from consumers in some countries, but also old insulation cork boards and other cork materials. If recycling of cork from OSIRYS products is initiated, there is also a need to develop the application of the recycled material.

## 6.5 Other recycling methods of bio-composites

### 6.5.1 Shared recycling routes with other bio based products

Other bio based insulation materials are for example those made from flax or hemp fibers and cellulose wool insulation, made from paper fibers. These materials have a shared recycling issue with the products developed in the project, that they are based on biological fibers that are most likely recyclable but that they also contain other substances which will lower the value of the recycled products. Most notable here is flame retardants. A weight ratio of 20 % flame retardants or more is common in hemp and flax thermal insulation (Kymäläinen et al. 2008). Cellulose wool insulation typically contains boric acid, borax and metal hydroxides. Boric acid and the borax substances have been identified as Substances of Very High Concern (SVHCs) and been included on the Candidate List according to REACH legislation. Future use of these substances should be limited (Larsen 2012). Other less hazardous flame retardants are also used, but predicting how these will be regarded in the future is not possible.

Recycling of these materials may be prevented, if not by legal obligations then by consumer demand, if it cannot be guaranteed that phased out hazardous substances are removed. There are three reasons for further examining the development of similar product such as flax, hemp and cellulose wool insulation:

1. Recycling initiatives that are developed for these products, producing safe new products with known and controlled chemical content, may be applicable also to OSIRYS products. This can be done by techniques that remove additives or by creating products for specific use where the hazard is controlled.

2. Recycling routes may be shared. As rather large quantities of material are needed for cost efficient recycling, mixing these materials may lower handling costs. Development is then needed on what can be produced from the recycled material, containing different kinds of biological fibers.
3. By having a similar content, waste from one manufacturer may be used as raw material for another. Content of flame retardants may not be a problem then, as these would have been added in the production process anyhow. OSIRYS bio-composites may for example be recycled into cellulose wool insulation, replacing recycled paper.

These scenarios are far from realization but may be necessary to enable large scale recycling of these products. The increasing amount of bio-based construction products being developed open up a new field of research and development on what new products can be produced from the increasing waste flows.

### **6.5.2 Paper and cardboard recycling**

The foamed wood board developed in the project has similarities with paper packaging regarding material composition. At the time of writing, July 2016, the suggested composition of the wallboards are:

- Chemical pulp (Northern bleached softwood kraft, NBSK), 98.8 %
- Fire retardant (FireFain XMP), 1 %
- Surfactant and binding agent (Polyvinyl alcohol, PVA), 0.2 %

It would be beneficial for the recycling potential of the material if current processes of paper and cardboard recycling could be utilized. Paper packaging typically consist of not just wood fibers, but also plastic layers and some impurities such as ink. This means recycling processes are adapted to produce pulp and a reject fraction containing most impurities (Suhr et al. 2015).

At a first glance, it seems technically feasible to process foamed wood boards in paper recycling facilities. There are however some notable barriers:

- The boards are harder and thicker than paper packaging which would require pre-treatment such as grinding before mechanical pulping.
- In the wallboard fibres and plastics form a matrix, whereas in packaging it is often different layers. The wallboard will not dissolve as easily, which will lower the efficiency. Also, the plastics will not be present as flakes making them more difficult to separate from the fibres (Suhr et al. 2015).
- It is not known to what extent the fire retardants will be washed out during regular processing. Paper packaging typically do not contain these and recyclers will be reluctant to accept materials wit “new” impurities.

Introducing wood-plastic composite into current paper recycling processes is an interesting possibility and should be investigated further. It should however not be seen as a viable current option.

## **6.6 Waste-to-energy**

If recycling efforts should fail or not be available in certain regions, waste-to-energy by incineration is a better option than landfilling. The incineration infrastructure is well developed in several northern European countries and they also import waste from other parts of Europe.

Even though OSIRYS products are resistant to flames to some extent, they will combust at high temperature given their organic nature. In construction or demolition sites they could be sorted as combustible waste along with wood, plastics etc. Sending material to a waste incineration plant is associated with costs for both transport and treatment.

What may hinder utilizing waste-to-energy is content of non-combustible material. The incineration plants are designed to combust municipal waste, which means a few percent inert materials such as metal are not a problem. Incorporating some glass fibres into OSIRYS profiles or flame retardants may not prevent the material from being accepted by incineration plants, but the higher ash content may increase the treatment price further. Content of gypsum however may lead to the material being rejected and instead landfilled. If gypsum is used in the fire panel or if plasterboard is used in sandwich structures, it is very important that these layers can be separated or the whole sandwich may be landfilled. Consequently, waste-to-energy is not an obvious last resort of OSIRYS products if recycling fails.

## 7. Lab tests on recycling bio-composites

### 7.1 Reprocessability of scrap of thermoplastic bio-composite

A lab study of the reprocessability of industrial scrap of the bio-composite structures has been carried out in order to establish the percentage of recycled bio-composites may be incorporated in parts by compression moulding and extrusion. Polylactic acid (PLA) was selected as thermoplastic material, due to it was the initial material defined (Deliverable 2.1)

The biocomposites of thermoplastic matrix (PLA) have been studied as fillers to produce parts using thermoplastic biocomposites. The different steps that were carried out to prepare the laminates from natural fabrics, the thermoplastic resin and the fillers are explained as follows:

1. Preparation of samples by compression moulding with biaxial fabric from BIOTEX (40 % w) and 2 layers of PLA sheet (60% w)
2. Preparation of ground material: 3 mm and 6 mm (Figure 4). From microscopy, the most suitable particle size to the process was decided as 3 mm.(Figure 5).
3. Incorporation of recycled material as filler by extrusion process (Figure 6). A good dispersion of the filler is not obtained by this process.
4. Next trials of reincorporation of recycled material were carried out by processing in ONE STEP in a compounding machine (Figure 7). Sheets with recycled material from 10% to 30 % were prepared.



*Figure 4. Sequence to prepare ground material*

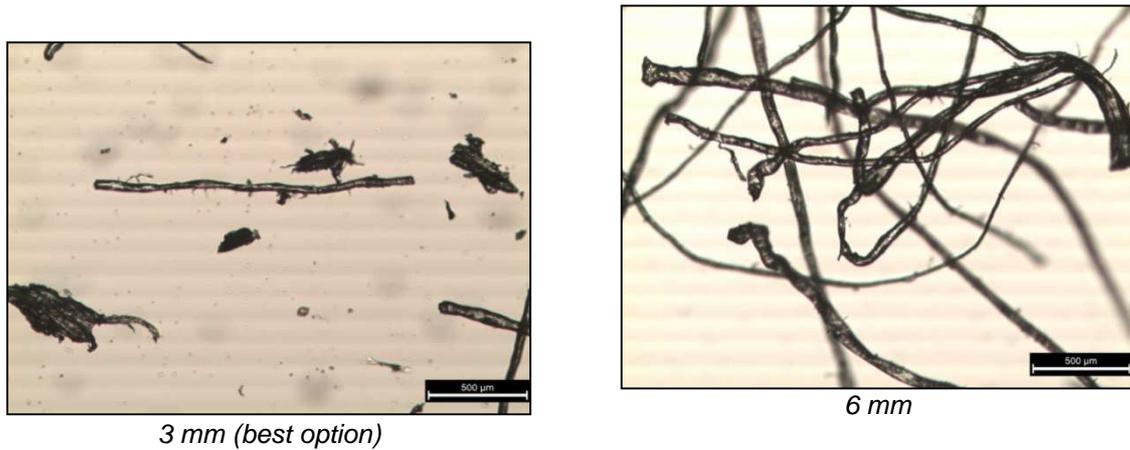


Figure 5. Evaluation of ground material (3 mm and 6 mm) by microscopy

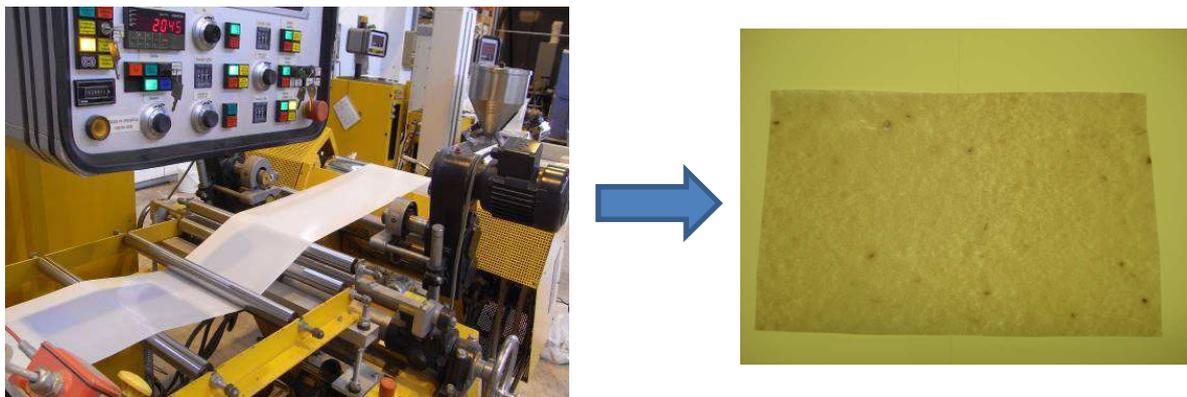


Figure 6. Processing of recycled material by extrusion



Figure 7. Processing of recycled material by ONE STEP process in compounding machine

From sheets prepared by One-step process in compounding machine, different laminates were prepared by compression moulding in order to compare mechanical properties. The composition of these laminates is 2 biaxial fabrics from BIOTEX (~ 40 % w) and 3 PLA sheet

films with recycled material (~ 60% w). The processing conditions to obtain the laminates are:

- Temperature = 153°C
- Time = 2 minutes
- Pressure = 87 kN

In Figure 8 and Table 6, laminates prepared with recycled material are detailed.

*Table 6. Mechanical results of laminates with recycled material*

Sample	Description
1	Laminate of 3 sheets PLA sheets (10 % ground) and 2 BIOTEX Flax +/-45 biaxial fabric
2	Laminate of 3 sheets PLA sheets (15 % ground) and 2 BIOTEX Flax +/-45 biaxial fabric
3	Laminate of 3 sheets PLA sheets (20 % ground) and 2 BIOTEX Flax +/-45 biaxial fabric
4	Laminate of 3 sheets PLA sheets (25 % ground) and 2 BIOTEX Flax +/-45 biaxial fabric
5	Laminate of 3 sheets PLA sheets (30 % ground) and 2 BIOTEX Flax +/-45 biaxial fabric
6	Laminate of 3 sheets PLA sheets (blank) and 2 BIOTEX Flax +/-45 biaxial fabric
7	Laminate of 2 sheets PLA sheets (blank) and 1 BIOTEX Flax +/-45 biaxial fabric



*Figure 8. Laminates prepared with recycled material*

Once laminates were obtained, these are mechanized Figure 9-a) and tested Figure 9-b) in order to obtain values of tensile strength, as it is described in Table 7.

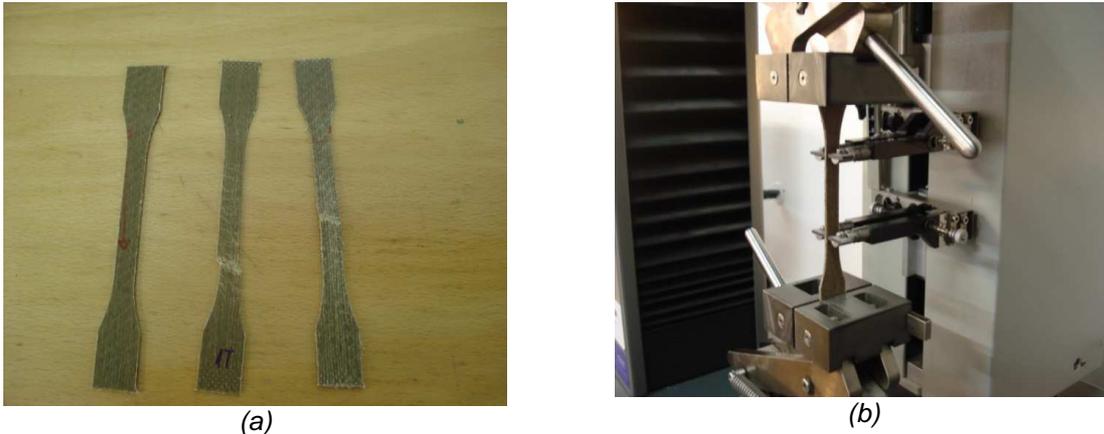


Figure 9. Specimens and tensile tests of laminates with recycled material

Table 7. Mechanical results of laminates with recycled material

Reference	Sample Description	Tensile Strength (MPa)	Tensile Modulus (MPa)
1	10 % ground	71,7	7940
2	15 % ground	74,2	8290
3	20 % ground	66,8	8010
4	25 % ground	70,7	8190
5	30 % ground	71,1	7000
6	Not recycled (3 sheets of PLA)	69,4	5220
7	Not recycled (2 sheets of PLA)	75,5	5510

Mechanical results obtained with laminated with between 10 – 30% (phr) of recycled material, show that the use of industrial scrap of biocomposites of thermoplastic matrix and their processability is feasible and obtain similar tensile strength to non-recycled material.

## 7.2 Reprocessability of scrap of thermoset biocomposite

### 7.2.1. Preparation of ground material

Regarding to assessment of reprocessability of thermoset biocomposites, laminates were prepared by using four layers of biaxial ( $\pm 45^\circ$ ) flax fabric and commercial unsaturated polyester resin. Catalyst system was composed of 0,2% cobalt octoate and 1,5 % methyl ethyl ketone peroxide. The laminates were processed by infusion and they are prepared in

order to evaluate the viability to use scrap of biocomposite in new biocomposite parts at lab scale.

Particle size distributions were obtained depending on the equipment used for material milling: an automatic grinding mill and an ultra centrifugal mill for 10 mm and 1 mm sizes respectively. Figure 10 shows the ground material obtained from both equipments. Additionally, blends of 50% w/w each were prepared to evaluate the effect of these sizes combination on the mechanical properties.



Figure 10. Equipment used for material milling and different sizes obtained for recyclability tests

### 7.2.1 Preparation of filled recycled biocomposites by compression moulding

Once the ground material was prepared, it was added to the unsaturated polyester resin in order to evaluate the influence of particle size and recycling material amount on the mechanical properties obtained from different laminates reinforced with flax biaxial fabric. Three percentages were considered for biocomposites preparation: 0,5 and 1,5 %, being this last value the greatest amount possible for samples preparation. For higher filler contents, an increase of resin viscosity was observed leading to bad resin impregnation of natural fabrics. For the preparation of laminates, 4 layers of biaxial ( $\pm 45^\circ$ ) flax fabric were firstly impregnated with the filled unsaturated polyester resin by hand lay-up and further processing by compression moulding at  $40^\circ\text{C}$  and 60 kN for 20 minutes. Catalyst system was composed of 0.2% cobalt octoate and 1,5 % methyl ethyl ketone peroxide. Natural fibre content of these laminates was around the 20 %.

### 7.2.2 Filled recycled biocomposites characterization

The influence of recycled material on flexural mechanical properties of the biocomposites obtained was determined in accordance with the standards UNE-EN ISO 178 and UNE-EN ISO 179 respectively. Flexural modulus was tested for different particle sizes over those compositions that showed better impact properties. In the evaluation of flexural properties, it was decided to prepare two groups of specimens with parallel and perpendicular orientation regarding the material structure (fibre orientation), defining orientation "O1" as  $0^\circ$  (fibre

direction) and orientation "O2" as 90° (perpendicular to direction "1"), as it can be seen in Figure 11.

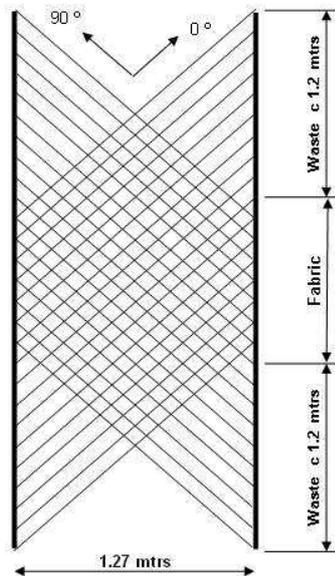


Figure 11. Scheme of specimen directionality to test mechanical properties.

The results of these characterizations are gathered in Table 8.

Table 8. Influence of recycled material on the mechanical properties obtained from biocomposites characterization

Test	Grinding (%)	Particle Size (mm)	Flexural Modulus (MPa)	
			O1	O2
0	---	---	O1	2340
			O2	2460
1	1,5	10	O1	2440
			O2	2500
2	0,5	1	O1	2760
			O2	2700
3	0,5 + 0,5	10 + 1	O1	2330
			O2	2490

As it can be seen from this table, in the case of flexural properties, the best results can be observed for small particle sizes. The influence of test specimens' orientation on flexural modulus is, however, negligible.

### 7.2.3 Lab study from OSIRYS material

From previous results, evaluation of reincorporation of scrap of OSIRYS profiles was carried out. OSIRYS profiles are composed by bioepoxy resin, graphene and natural and glass fibers.

In Figure 12, images of grounded material obtained from OSIRYS profiles is detailed



*Figure 12. Ground of OSIRYS profiles*

Once the ground material was prepared, 0.5% of scrap of OSIRYS profiles was added to the bioepoxy resin in order to evaluate recyclability of this material and assess mechanical properties obtained from different laminates reinforced with flax biaxial fabric. Four layers of biaxial ( $\pm 45^\circ$ ) flax fabric were firstly impregnated with the filled bioepoxy resin by hand lay-up and further processing by compression moulding at 150°C and 60 kN for 20 minutes. Natural fibre content of these laminates was around the 40 %. After that, a postcuring was established at 80 °C along 8 hours.

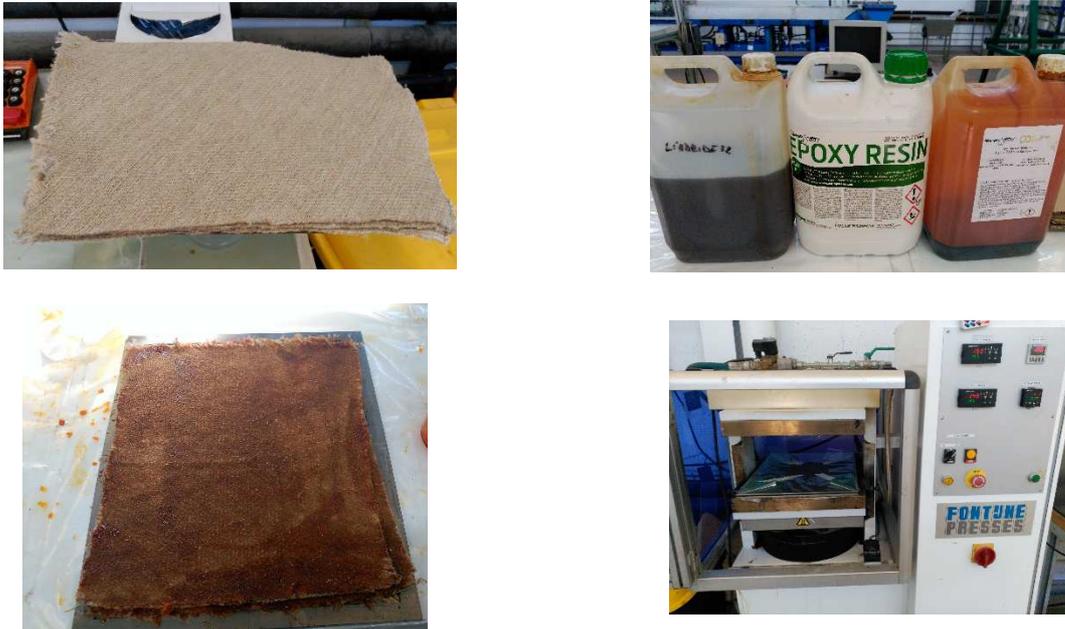


Figure 13. Different steps of the lab study on recycling OSIRYS profiles

Obtained laminates (Table 9) will be evaluated by tensile tests in order to assess mechanical properties.

Table 9. Laminates prepared from OSIRYS profiles scrap

Test	OSIRYS profile scrap (%)	Description of OSIRYS pultrusion profile scrap	Laminate	% of natural fibre
0	---	---	Bioepoxy resin Biaxial flax fabric	≈ 40 %
1	0,5	Bioepoxy resin Graphene Natural fiber Glass fiber	Bioepoxy resin Biaxial flax fabric + 0.5 % of scrap	≈ 40 %

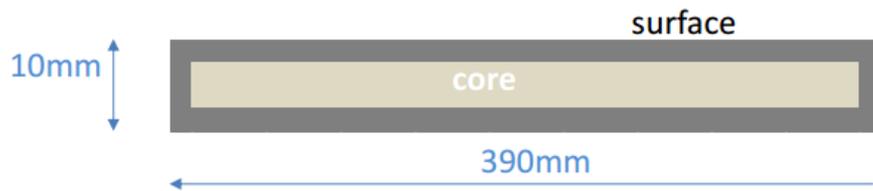
Mechanical tests are being performed. Results will be included in next interim report.

### 7.3 Industrial scrap of OSIRYS biocomposites

From technical results of lab studies in AIMPLAS facilities, CONENOR, OMIKRON and AIMPLAS is working on preparation of samples from industrial scrap of OSIRYS products.

CONENOR will prepared following structure (Figure 14) in its facilities in order to obtain recycled panel from OSIRYS products. In core of the structure, industrial scrap from OSIRYS thermoset pultrusion profiles (OMIKRON) will be included. And in the surface of the structure, industrial scrap from thermoplastic OSIRYS parts (CONENOR) will be recycled.

There are different options on which extruder to use, which will produce planks of different dimensions. The produced composite material does not have any application, the trials are just to verify that scrap material from OSIRYS products can be reprocessed.



*Figure 14. OSIRYS Recycled panel to be processed by CONENOR. The dimensions are a suggestion.*

The results from this study will be included in the next interim report.

## 8. Conclusions

Bio-composites may be inherently difficult to reuse because they may be damaged by scraping or blows during use or disassembly. Recycling is difficult due to the basic fact that composites are a combination of materials. This helps to explain the rather low reuse and recycling potential of the OSIRYS products. But it does not lessen the importance of the material efficiency gains of reuse or recycling.

Design is a key issue to enable both reuse and recycling of construction products. This regards to the possibility of easy disassembly, into unharmed modules for reuse or pure material streams for recycling. But because reuse structures are underdeveloped and recycling routes are lacking there is also a need to develop infrastructure.

### Design for disassembly

To enable reuse, the products installed into buildings should be easily removed modules. Components of these modules that are most likely to be damaged should be able to replace. This means glue could be used to join some parts, but reversible mechanical anchoring such as durable screws is preferred for most applications.

The possible recycling routes identified assume that all the different materials in OSIRYS-products are somehow separated from each other. It is important to note that this separation is difficult once panels have been glued together. How much of the waste arising from the supply chain that is in the form of glued together materials depends on systems design and minimizing this kind of waste should be a priority when designing production processes. After separation, glue will also contaminate waste streams collected for recycling. How this will affect the recycling processes needs to be tested.

Disassembly is not just a possibility of providing raw material by recycling but may be necessary to prevent landfilling. Waste-to-energy may be a valid option if cost effective recycling is not possible. That however necessitates that non-combustible material such as glass and especially gypsum is separated. In regard to this gypsum should not be used at all.

### Confidence in reuse

Designing products that could be reused will not assure reuse if the potential costumers are unsure of the quality. Providing as detailed information on reused products as for new ones will improve the perception of reuse. Databases where information on specific buildings can be compiled are a preferred way, but at least proper labelling is necessary. Manufacturers can help by providing information in an appropriate format and by cooperating in industry initiatives to develop codes and standards.

As these are complex products, manufacturers should also assist in developing quality assurance plans from planning deconstruction to inspection of salvaged products. If this can be achieved at low cost, reused OSIRYS products could be an alternative to new ones in many applications.

### Developing recycling routes

There are certainly many potential recycling routes of OSIRYS products. Thermoplastic bio-composites could be recycled in a closed loop into new products whereas thermosets could be downcycled as fillers in similar products. The options are further expanded as these

materials could be fed into combined material streams, such as thermoplastic bio-composites and cardboard or paper, producing cardboard, or in combination with other bio-based building products. Today however, no recycling routes exist.

Content of potentially hazardous substances will hinder recycling as recyclers are more reluctant to accept these or will do so at a lower prize. This problem is ameliorated if closed loop recycling is achieved, the special substances needed can be recycled back into their intended purpose rather than contaminating other products. OSIRYS products manufacturing could be further developed to incorporate a proportion of scrap material.

It is not possible at this stage of development to assess what amount of different wastes that will arise from the supply chain. Assessing this should be a priority when large scale production is initiated. This will aid in improving system design and enabling utilization of waste material in production processes.

### **Take back scheme**

Reuse structures, such as demolishers and reuse traders, will evolve due to increase in demand and awareness. The recycling industry is also evolving, using new processes to recycle more materials. Special façades and interior partitions will however not be the first new product categories to be traded second hand, nor will novel bio-composites be the first new materials to be circulated by industry processes. Some economies of scale are necessary. Therefore a take back scheme is suggested, that the manufacturer or supplier of a product takes control of the aftermarket.

The main operation of a take back scheme may be to return construction scrap to production processes, but also to offer some reused items in its product portfolio. The basis for this is that manufacturers may be the ones most competent in material utilization and quality assurance. Setting up such a scheme is not the easiest option for manufacturers but may be the most feasible way of ensuring some reuse and recycling, improving the environmental performance of OSIRYS products.

### **Waste-to-energy**

The aspects mentioned above regarding difficulty of disassembly and the lack of reuse and recycling routes means that OSIRYS material waste will not be easily recovered. The most feasible waste management option will be incineration, which does not require disassembly and an infrastructure is present, especially in northern Europe. Even though the energy content can be recovered, the novel material features will be lost.

Gypsum creates acidic emissions when incinerated. If it is used in the fire panel or if plasterboard is used in sandwich structures, these layers should be separated or the whole sandwich may be landfilled. Incineration is costly and content of non-combustible material will increase the price of waste management. This provides an economic incentive to improve design and develop processes for higher value material recovery, enabling reuse and recycling.

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## 10. Abbreviations

BIM	Building Information Modelling
C&DW	Construction and demolition waste
IRCOW	Innovative strategies for high-grade material recovery from construction and demolition waste
OSIRYS	Forest based composites for façades and interior partitions to improve indoor air quality in new builds and restoration
PLA	Polylactic acid