

Framework for Reuse of Secondary Products in New Constructions



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Table of Contents

Abstract	2
1.1. Introduction.....	2
1.2. Literature Review.....	2
1.3. Problem Statement.....	3
1.4. Research Methodology.....	3
2. What is Reuse	3
2.1. Why Reuse.....	4
2.2. Barriers to Reuse.....	5
3. Theoretical Concepts	6-9
4. Working Framework	9-35
4.1. Identify Replaceable Materials.....	9-11
4.2. The preliminary Investigation.....	11-13
4.3. Decision to Reuse or Recycle.....	14-19
4.4. Product Health Assessment	19-21
4.5. Testing Framework : Case-study Application.....	21-35
5. Conclusion	36
6. Limitation	36
7. Recommendation	36
References	37-38

Abstract

Reuse of building material is an integral part of making the product circular. However, there is lack of working frameworks and practical tools which can quantify the feasibility of reuse over other choices such as virgin material use or recycling for that matter. Therefore, this research focuses on the development of such a working framework which can guide and assess the feasibility of reuse in new building construction. The tool is so developed that it guides from the very basic step of material selection to its assessment to the quantification of economic as well as environmental benefits of reuse. A case study is used to verify the application of the model. The results show how reuse is possible in the case of open loop recycling and not in the case of close loop recycling indication recycling to be a preferred option in the latter case. Barriers such as lack of information of the product life cycle (use) is found to limit the reuse possibilities. Lastly the intangible aspects of reuse such as aesthetic and emotional value addition are also discussed, and its impact is visible in the case study

1.1. Introduction

Resource depletion and environmental degradation has been on a surge since the industrial revolution. The situation has worsened due to the linear methods of production wherein materials are extracted from the ground, processed, used and then thrown away untreated or landfilled. Construction industry contributes to 38% waste production, 40% CO₂ generation and consumes as much as 50% of the total natural resource reserves ([Elma Durmisevic, 2017](#)).

One way to tackle this menace is to close the material loop such that the same material can enter various life cycles without compromising on the functional performance. This is a more circular way of material flow wherein materials/products are used for longer time with proper repair, maintenance, refurbishment and reuse, thus minimizing the demand for virgin materials. Reuse is a preferred strategy for reducing virgin material extraction and for reducing demolition waste generation. Reuse of a product saves most of the embodied energy in terms of labor, cost and manufacturing ([Circle Economy, 2015](#)). However, there is hardly any reuse of End-of-life (EOL) products. It is because of the associated challenges such as availability, quality and performance of the EOL product, price and repair costs. Another major hurdle is the lack of a working framework to assess the reuse possibilities.

To overcome these prevailing challenges, this study aims to develop a working framework to quantitatively and effectively assess the reuse potentials of EOL building products in new constructions. The framework is developed keeping in mind the practical challenges that one may face while incorporating product reuse. Therefore, the methodology is substantiated with a case study example.

1.2. Literature Review

The literature on reuse major has futuristic design explorations as to how the new constructions be designs so that they can be reused at EOL. Such papers are focused on design strategies, broadly the Design for Disassembly (DFD) concept ([Gerding, 2018](#)) ([Durmisevic, 2008](#)) ([Elma Durmisevic, 2017](#)). Additionally, one can also find exploratory and descriptive research with respect to reuse of building materials in terms of challenges and potentials ([Gilli Hobbs, 2017](#)), ([Jullian M Allwood, 2010](#)). For instance, Durmisevic studied the associated barriers which prohibit the reusability of products after EOL such as lack of accessibility to components, fixed integration of load-bearing and non-load bearing parts, interdependence and inflexibility of load bearing structure ([Durmisevic, 2008](#)). Authors have also emphasized the lack of decision-making tools that prohibit companies to evaluate the trade-off between virgin and EOL products ([Ton Bastein, 2013](#)). However, there lacks a working decision-making tool that could guide the designers and constructor to assess the reuse feasibility in a project.

1.3. Problem Statement

Reuse in construction is dealt with as a futuristic approach, something that can be achieved in the future if we design circular today. Reuse in construction sector is taken to be an afterwards activity requiring innovative thinking and design (D. P. (Ditte) Gerding, 2019). For instance, Design for Disassembly (DfD) is one such futuristic approach wherein a new construction is designed such that it can be disassembled at EOL and elements can be salvaged for reuse. However, it does not solve the challenge of reusing secondary material today instead of virgin material.

For Netherlands to achieve its circularity goals by 2050, it is imperative to stop extracting virgin materials and disposing the EOL products. It can be achieved by reusing the elements/components in a circular way. However, there is no working framework or guiding methodology which enables designers and engineers to make reuse a practical case.

Research Objective: To develop a working framework for designers and engineers to assess the reuse feasibility of secondary materials in new constructions

Research Question

1. Which materials to reuse in a new construction?
2. How to quantify if reuse is a feasible option?
3. What are the strategies to make reuse economically as well as environmentally feasible?

1.4. Research Methodology

A two- step approach is adopted. In the first stage, a working framework is developed to systematically assess the reuse feasibility of the secondary products in the new construction. In the second step, the verity of this framework is analyzed with help of a case study approach.

First the study discusses why reuse is a preferred EOL treatment than recycling and material recovery. It then emphasizes on the existing barriers which impede the reuse of secondary materials in the new construction. A stepped methodology is then developed based on the conceptual concepts which serves as a tool for designers and engineers to assess the feasibility and possibilities to reuse EOL products in the early design phase.

The assessment methodology is tested for the restorative flow (material portion of a product that comes from reused sources) from intersectoral waste with the help of a case study in Schiedam. The results of the study are aimed at providing some guidance to the designers as to what parameters to consider while exploring reuse possibilities and how to make it a practical choice in a new project.

2. What is Reuse?

Reuse of a material is a way of pushing the EOL waste back into functional cycles. The act of bringing a discarded product back to use is called reuse. In creation of a product, material, energy and labor is deployed. Reuse should be such that it recovers maximum value in each of these domains. As shown in figure 1, reuse can be practiced on system, component/product and material level. System reuse is most efficient and possible only when the function of the built facility is identical. For instance,

scaffolding system, railway sleepers and modular storage yards are ideal system reuse where the same system is used multiple times but for the identical function. System reuse in buildings is less common unless the unit is built on temporal base with a future relocation plan.

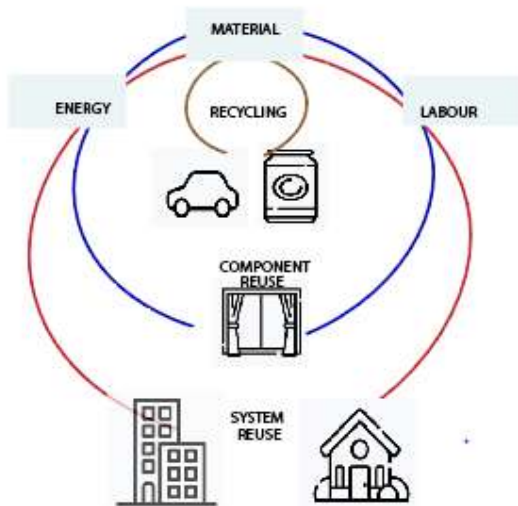


Figure 1: Level of Reuse, Adopted from (Circle Economy, 2015)

However, for a new construction, it is less likely to have same requirements as another demolishing structure. In fact, component reuse is more prevalent in these situations where not the entire system but part of it can be reused. It can be so that different parts can be reused in different projects which preserves the material, processing energy as well as the labor but requires some re-conditioning due to new performance requirements. Lastly, material reuse in reality is achieved by recycling the materials which is not a preferred strategy but widely adopted. However, the high value conservation is achieved by system and product reuse only (Circle Economy, 2015)

2.1. Why reuse?

There are environmental as well as economic motivations for reuse. Using secondary materials reduces the environmental impact by limiting emissions released in processing and manufacturing virgin materials. Often so the procurement of secondary products is cheaper than primary ones, however, one needs to evaluate the cost balances as many a times recycling can override the costs and risks involved in the reuse.

On one hand, recycling reduces the primary energy and carbon emission of production processes. For instance, steel making from scrap requires one third of the primary energy and emits less than a quarter CO₂ as compared to steel making from the ore; aluminum production from scrap reduced the production energy by 20 times (Cambridge, 2010). On the other hand, it is less effective than reuse that preserves the energy deployed in production as well as manufacturing which is lost in recycling. About 70% of the environmental impact of the new constructions are caused due to embodied energy from manufacturing of products (BioRegional, 2011). The

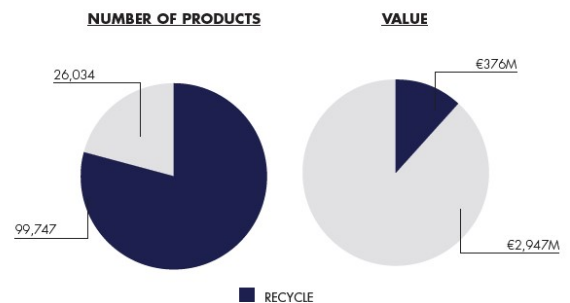


Figure 2: Reuse Vs Recycling in metal and electrical products sector Source: (Ton Bastein, 2013)

value generated during the production process is mostly lost if the product is not put back to use. It is applicable for most of the sectors such as consumer products (Green Alliance, 2013), metal and electrical sector (Ton Bastein, 2013) as shown in figure 2. Recycling is found to preserve the value only at material level saving about 10% cost and 50% energy use whereas reuse focuses on value recovery of labor, energy and investment amounting to 40% cost and 80% energy savings (Circle Economy, 2015). In fact, recycling requires energy and remains an energy and carbon intensive process due to high treatment temperatures (Cambridge, 2010). However, reuse is much more efficient strategy. For instance, as much as 1 ton of embodied CO₂ can be saved through reuse of 0.5 ton of structural steel (BioRegional, 2011). Reuse of 1 ton of steel and aluminum saves as much as 1.8 and 8.2 tonnes of CO₂ respectively (Jullian M Allwood, 2010).

In a LCA study done by Cleveland Steel and Tubes Ltd (CST), the environmental impacts of reused coated steel tubes were compared to primary steel welded tubes, reclaimed steel was found to have about 95%-97% CO₂ equivalent savings when compared to virgin steel (Cleveland Steel and Tubes Ltd, 2018). Detailed breakdown is shown in the table below

Impact category	Unit	Virgin steel tube	Concrete tube	Plastic tube	Epoxy tube	Bitumen tube	Uncoated coated tube	Average saving
Acidification (fate not incl.)	kg SO ₂ eq	17.99	3.64	2.51	2.45	3.46	2.00	84%
Eutrophication	kg PO ₄ eq	1.75	0.51	0.36	0.63	1.47	0.28	63%
Global warming (GWP100a)	kg CO ₂ eq	7725	365	277	275	293	212	96%
Photochemical oxidation	kg C ₂ H ₄ eq	2.19	0.13	0.09	0.09	0.09	0.07	96%
Ozone layer depletion (ODP)	kg CFC-11 eq	-3.25E-06	1.01E-04	8.15E-05	8.08E-05	6.34E-05	3.98E-05	-2157%
Abiotic depletion	kg Sb eq	0.01	<0.001	<0.001	<0.001	<0.001	<0.001	95%
Abiotic depletion, fossil fuels	MJ	83,551	8,407	6,814	6,751	5,411	3,290	93%
Water	M ³	1010	1.82	1.22	1.21	1.09	0.722	99%

Table 1: GWP comparison of recycled tubes vs primary steel
Source (Cleveland Steel and Tubes Ltd, 2018)

Despite these benefits, reuse is very limited in building industry and has been declining rapidly in past 70 years (Gilli Hobbs, 2017). A lot of factors contribute to this declining preference which are discussed in the following section.

2.3. Barriers to Reuse

There are various barriers which impede effective reuse. Foremost challenge impeding reuse is the lack of availability and robustness of data (Gilli Hobbs, 2017). When a product reaches EOL, there is generally a dearth of information regarding the composition, durability and exposure conditions that the element was subjected to while in use. Another barrier is the lack of knowledge and established market. Unlike automotive sector, the secondary product market for building materials is not established and functions as fragmented units. Intellectual property concerns and involvement of multiple suppliers in the product chain leads to knowledge barriers (Circle Economy, 2015). Also, it is geographically difficult to map the availability of secondary components for reuse. Once spotted, it is very probable that there is no or little information available about the first life use and technical specifications of the product use. Furthermore, companies do not have the decision making tools to evaluate the trade-off between virgin and EOL products (Ton Bastein, 2013). Contractors prefer demolition instead of deconstruction due to the inherent time consumption in disassembly (Jullian M

Allwood, 2010). It is followed by the reluctance on part of the contractors to use a material without certification and performance details. Testing is not commonly a feasible option as it adds cost to the product net savings and damages the material. Demand- supply inconsistency is another major issue (Gilli Hobbs, 2017) as the amount of material needed may not be the same as the secondary product available since the storage facilities are limited. Another big deterrent is how to select the material, based on which parameters if specifications are not known and where to apply it in the new building since there is no specification code for secondary products. . Lack of policy framework for reuse also halts the process. Since there are no legal obligations which mandate reuse of secondary components, there is even less initiative to apply it. Contractors and clients find new materials more-safer and hassle-free. The reason for missing policy guideline is that there is no one size fits all approach and therefore it is not integrated in the main tenders and contract clause. (BioRegional, 2011). Lastly consumer behavior and mind-set towards EOL products limits reuse acceptability in the society. Quality, safety and health concerns the consumer and ingrains the impression that reuse is a degraded material use(Circle Economy, 2015)

3.Theoretical Concepts

This section explains the fundamental concepts/ key terms which are used in the formulation of the working framework. These concepts in one or the other way are fundamental considerations for a reuse plan i.e, the concept of embodied energy and embodied carbon, technical life and functional life and the concept of layer of application. Although related, there is no hierarchy or order of significance of application for these concepts since the preference is varies on a case by case situation which will be discussed in section 4.1.

a. Embodied Energy (EE) and Embodied Carbon (EC)- Embodied energy is the amount of energy deployed in manufacturing the material (cradle to gate). It is important to define here that this study considers product stage (A1-raw material supply, A2- transport to factory and A3-manufacturing) as system boundary for primary embodied energy consumptions (not gross energy). This is because stages A4 and A5 i.e. the transport and installation processes are project specific and do not allow for standard comparisons. Although embodied energy and embodied carbon are related to each other, embodied carbon depends on the type of fuel mix used for processing the material. With the use of renewable energy sources, it is possible to have zero carbon emissions while the material still possesses EE. (Andrew Miller, 2013).

What is high EE & EC?

One can argue on the limit of the value of “high” and “low”. This comparison is fundamentally relative. For instance, an example is shown below between structural steel, iron and concrete. It must be noted that there are situations wherein selection based on EE is not possible since the materials involved can be of the same nature. For example, comparing the data from ICE, Concrete (RC40) has EE of 1.17 MJ/kg and which is about 97% less than that of virgin steel (35.30 MJ/kg) and 86% lesser than that of timber (8.50 MJ/kg) respectively. Further, the EC of concrete is 0.169 kgCO₂/kg which is 94% less emission than virgin steel (2.75 kgCO₂/kg) and 63% lesser than that of timber (0.46 kgCO₂/kg).

High EE material should be preferred for reuse over low energy materials as energy savings are higher for the former. In fact, high EE materials take high energy in recycling as well as disposal. Metal parts are a good choice in that sense, but it can sometimes be more economic to recycle them than to reuse. For instance, based on the given values one can identify steel to be energy intense and preferred to be reused after EOL but one can argue that recycling of steel is more economic in many cases. Therefore, it is difficult to achieve a conclusion solely based on embodied energy. To further narrow down to the most ideal choice for reuse, one needs to consider other paraments such as technical and functional life as discussed in next section.

b. Technical life Vs Functional Life

There are broadly two types of lives that a built facility is supposed to serve, functional life and technical life. Technical life is the actual life that a component can serve based on its strength and composition whereas functional life is the life for which the component is used to serve the intended purpose and after which it is rejected for disposal or recycling. A project is best utilized when its technical life = functional life. However, most of the products are pushed out of service due to various reasons, thus having a shorter functional life.

One of the reasons for a shorter functional life is obsolesces. A built facility or a product for that matter can face five types of obsolesces i.e., functional, technical, physical, locational and fashionable and it is the combination of these obsolesces mechanisms that a product is withdrawn from services even when it has the potential to perform longer (D. P. (Ditte) Gerding, 2019). Apart from technical and physical obsolesces, all other have nothing to do with the performance and durability but with the exterior aspects. Buildings which are designed for a service life of 100 years are found to be functional for about 50 years only (Daniel R. Cooper, 2013).

From a reuse point of view, one should identify the materials/products which have highest difference of technical and functional life as it indicates substantial remaining service life of the component. Also, as a rule of thumb, it is known that products which are more durable and are designed for longer service life are produced by energy intensive methods. Therefore, reusing these products is recommended.

c. Layer of Application

Stewart Brand described a building to be a buildup of different layers i.e, site, structure, skin, service and space. Each of these layers have different life in a building. For instance, the site and structure have the longest functional life (generally until demolition) than other fast changing layers such as service and space which are often replaced frequently during the service life of the building. Figure 3, depicts the compilation of functional life of different layers by Crowther.

LAYER				REFERENCE
Structure	Skin	Services	Space plan	
50	50	15	5-7	Duffy 1989
30-300 (typically 60)	20	7-15	3-30	Brand 1994
40	15	3	5-8	Cook 1972
25-125	25	5	5	Kikutake 1977
60-100	15-40	5-50	5-7	Curwell 1996
60 (assumed max. life of building)	20	7-15	3-5	Storey 1995
65	65	10-40	5	Howard 1994
50 (assumed max. life of building)	30-50	12-50	10	Adalberth 1997
40 (assumed max. life of building)	36	33	12	McCoubrie 1996
-	15-30	7-30	-	Suzuki 1998
40 (for brick veneer house)	12-30	30-40	8-40	Tucker 1990

Figure 3 : Functional life of Different layers by Crowther, 2001

It can be deduced from the figure above that the structure layer i.e. the foundation and load-bearing elements lasts between 30-300 years (typically 60 years) followed by the skin, services and space which are changed approximately every 20, 10 and 3 years respectively.

It is interesting to note that the same material can have different functional life depending on the layer of application as depicted in Figure 4, where in an office building the technical life of steel in the internal layer, services and internal planning is about 10-13 years whereas in the roofing and façade it is 45 years and that in the structure is as high as 110 years (Daniel R. Cooper, 2013)

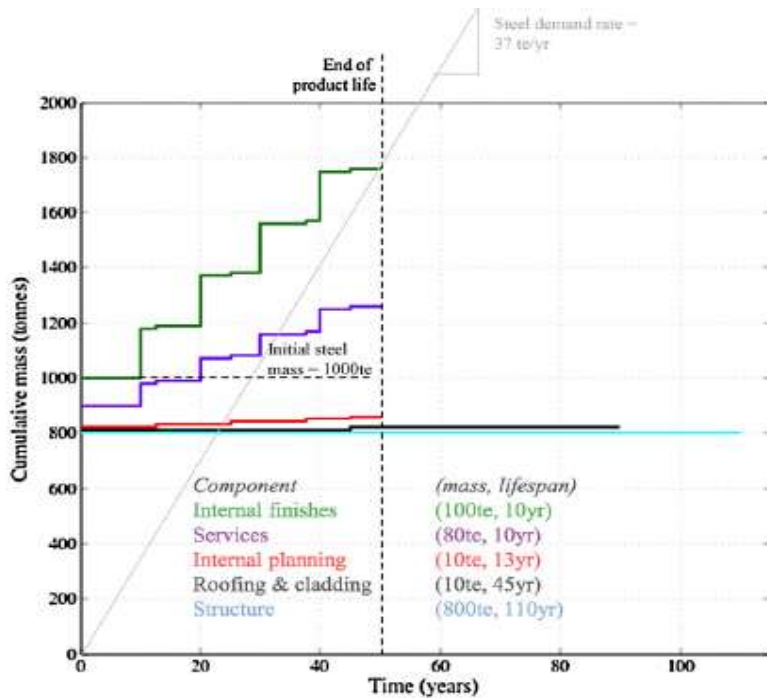
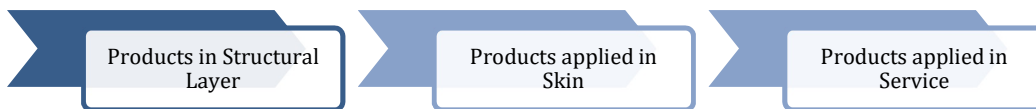


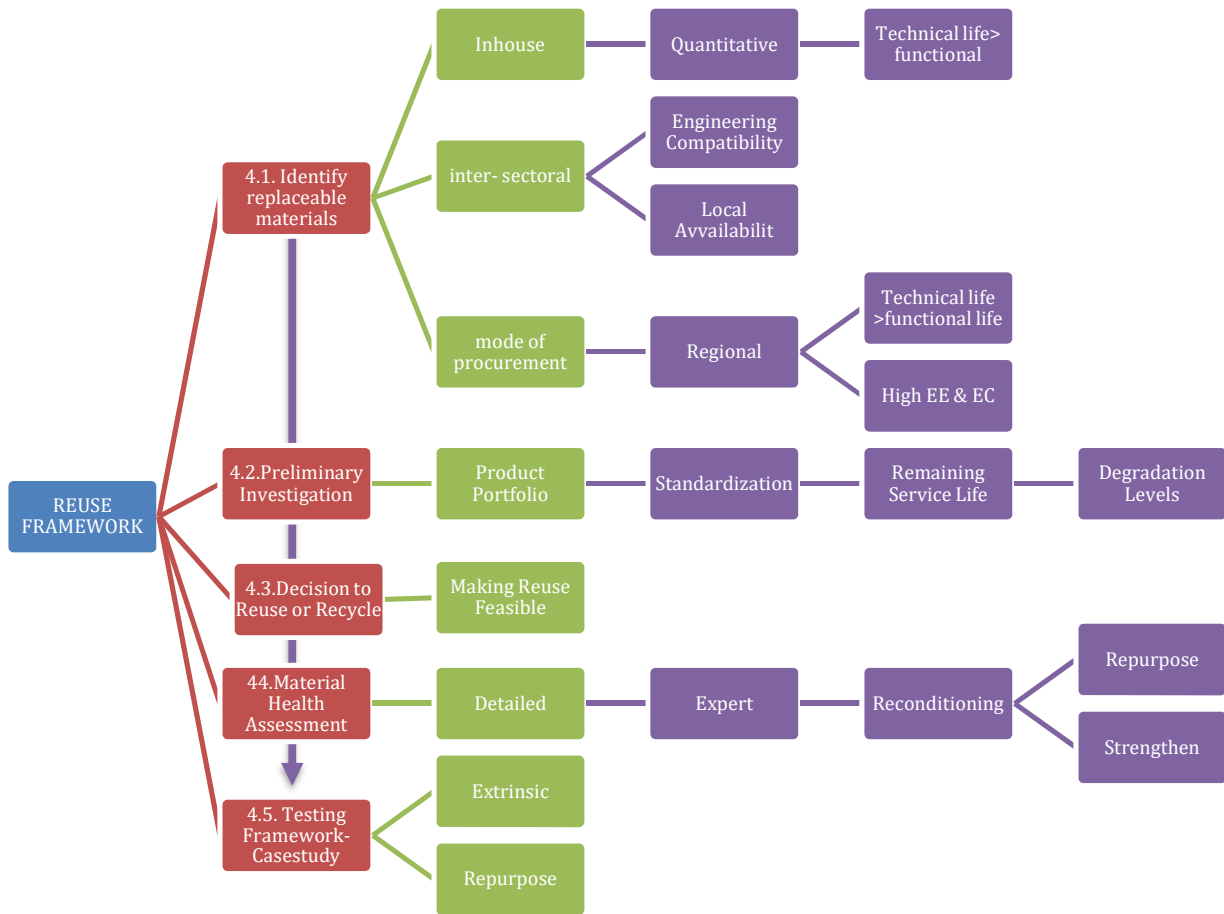
Figure 4: Technical Life of Steel in Different Layers by (Daniel R. Cooper, 2013)

Hence, when the building is demolished, there are plenty of products with residual technical life. These materials when reused perform substantially well and save on both cost and energy of virgin manufacturing. Therefore, it is crucial to have the knowledge of functional life of different layers and products used in those layers to effectively select the most appropriate secondary material for reuse in new construction. From a reuse point of view, the preference of EOL materials in various layers is as follows



4. Working Framework

The framework consists of five stages. The methodology is developed in a sequential order and therefore every succeeding step is impacted and defined on the findings of the preceding one.



4.1. Identify Replaceable Materials

The first step in reuse of secondary materials is to identify which materials are most feasible to be reused in a new construction. It depends on several factors such as material selection in procurement mode, availability of secondary materials and the reuse feasibility.

The identification fundamentally depends on the way of procurement of the secondary products. It may seem that the decision on procurement methods is made after the material selection but the two processes when carried out simultaneously result in effective solutions due to the inherent interdependencies. There are broadly three ways to procure i.e. regional procurement, in-house procurement and inter-sectoral procurement. However, the underlying objective in all three is to replace virgin material with EOL secondary materials such that it is environmentally as well as economically beneficial

4.1.1. Regional procurement

The secondary materials are obtained from suppliers, stockholder, online markets, etc. It is termed regional since there are economic limitations on the distances from which one can procure as the transportation cost should not override that of virgin material. Therefore, it is important to integrate the reuse strategy well in the design phase itself. It can be broadly divided into the following

- a. **Direct exchange/in-situ:** the seller of secondary parts directly sells to the buyers ([Jullian M Allwood, 2010](#)). Documentation is more likely to be available since not many shareholders are involved. For example, 18 tonnes of structural steel was reused in University of Toronto which was reclaimed from demolition of Royal Ontario Museum ([University of Toronto](#)). Online market places like Excess Material Exchange ([EME, 2019](#)) and harvestmap.org can also be used where companies can exchange their EOL products.
- b. **Stockholder** - secondary materials are procured and stored by third party until a demand is generated for it. Relatively higher need for testing than direct exchange in dearth of engineering drawings and loading conditions. Trust between the buyer and the seller often plays a vital role in trusting the standards and certifications claimed by the stockholder. For instance, Cleveland Steel supplied 2500 tonnes of secondary steel for roof truss construction of London Olympic Stadium ([Government Europa, 2019](#)).

Benefits- Supply- demand inconsistencies can be avoided when procuring regionally since one can procure from multiple suppliers. It also puts the buyer in a dominant position than the seller for competitive price delivery due to competition in the regional market.

Disadvantage – potential delays can occur since buyers depend on the suppliers, involvement of multiple stockholders to maintain proper supply can have other issues such as increased data discrepancy since the procured product belongs to different owners and different systems of quality assurance.

Selection Criteria-

1. materials with high embodied energy and high embodied carbon-
2. reuse materials with technical life > functional life

Since the products are bought from the market, it is preferred to list out the materials/products which will be most intensive in terms of EE & EC in the new construction and then look for procuring these products from the secondary material stock to reduce the production and manufacturing energy. Another consideration, in the regional procurement mode is to reuse products which typically have high difference between technical and functional life as it allows for more durable products and lesser risk of failures.

4.1.2. In-house Inventory

In-house inventory refers to the materials already available with the user from previous application, e.g., a contractor or the builder can possess EOL products from demolished buildings internally. Here the secondary material does not enter the market for sale instead remains with the owner himself for second life use. However, in order to ensure proper reuse, maintaining the material database is crucial for easy identification in the future. An example of in-house reuse is the MEC Ottawa building where about 75% of the existing building (by weight) was reclaimed and reused for new building on site which accounted for 50% of the total material demand of the new construction ([Mountain Equipment Coop, Ottawa](#)). The design and other characteristics of the steel were determined with the maintained documentation.

Benefits- Maintaining in-house inventory can substantially reduce the procurement time and cost from external sources, minimizes demand- supply inconsistencies. Furthermore, in event of proper record keeping of the products, the quality assurance is also better facilitated with consistent information such as engineering drawings, loading conditions, etc.

Disadvantage- Thorough material scan is needed, reuse is limited and depended on the available stock. Storing the products requires space, maintenance as well as data keeping which is time and cost consuming. It is more of a supply driven selection wherein the reuse depends upon the type and quantities of secondary materials available within the in-house inventory.

Selection Criteria- While choosing a product for reuse from the available inventory, one must consider the following:

1. High quantitative application
2. Substantial residual life
3. Previously applied in temporary layer of building

Quantity is a determinant and most important factor for in-house reuse. Imagine a scenario where a contractor has steel profiles having substantial residual life which were previously used in the service layer. These present a perfect reuse-case; however, they cannot be reused if the quantity of salvaged profile is lesser than the demand. One way to solve the issue of quantitative application is to use a combination of new and secondary products but that itself possess challenges for the builder since the old and the new needs to be compatible in terms of performance, durability and even aesthetics sometimes.

4.1.3. Inter-sectoral approach

Availing EOL products from other sectors to be reused in new constructions is termed as inter-sectoral procurement. For instance firms like SuperUse repurpose waste such as aircraft sets, windmill blades, etc for using in buildings, parks and other places ([SuperUse, 2019](#)). This type of reuse stems from the ideology that a product rendered waste after EOL in one sector can be a resource for another industry. It acts as circular economy facilitator having large environmental savings. But at the same time, it can be very challenging to adapt the product for application in another industry.

Benefits: it is a cheaper procurement since the EOL product in one sector is sold at scarp or a little higher than the scarp value. Generally, a reduced transportation cost is associated with inter- sectoral procurement since the buyer buys from neighboring setups only unless very specific reuse is well defined in the initial design.

Disadvantage: the salvaged product can be unknown to the user and therefore demands investigation into the profiles and composition of the EOL product. Dimensional modifications are often needed to comply to the demand. Lastly adapted reuse calls for creativity and design ideas to effectively fit the product into new application.

Selection Criteria- While deciding which material to reuse in the new construction, one should look for materials with following properties

1. Engineering Compatibility:
2. Locally availability

Engineering compatibility represents how well the existing product can be adapted to its new function in terms of performance and application ease. It is imperative for an adapted reuse. Local availability is another important aspect since transportation and procurement cost of the EOL product must not override the savings and benefits of reuse.

NOTE: There can be special cases where a combination of procurement methods exists together. For instance, an owner who is involved in different business decides to reuse EOL from one business as raw materials for the other. In such a case, both the in-house inventory and inter-sectoral apply and the selection criteria is a combination of both. This will be dealt with in greater depth in the case study application in section 4.5.

4.2. The preliminary Investigation

Having identified the EOL product for reuse, one needs to assess the if it is feasible to reuse. The first step in this direction is preliminary investigation. The aim of this is to gather as much information about the product as possible. A practical approach is to first study the available documents followed by interviews with the concerned personnel and physical inspection of the product.

Documentation includes any source of information about the first life of product which can ascertain the strength and other mechanical properties of the product. These documentations are important in tracing down the material properties of the product. It can be in the form of engineering drawings, bill of quantities, inspection certificates, product markings or information stored in a software such as excel or BIM model. If proper information about the product is available, then it seldom needs detailed investigation unless signs of degradation are visible. However, it is probable that none of these documents are preserved at EOL of the product. In that case, site visit and personal interviews with the owner or the supplier can help trace the product history. It wise to draw write down the gaps in the information before an appointment with the personnel and product inspection. In case of doubt conservative assumptions should be made. Following are the four components of preliminary investigation:

4.2.1. Product Portfolio- It includes basic information about the product that must be collected beforehand with the help of document study, personal interviews and product inspection. It is important to know data such as the

- Type of product,
- Physical dimensions
- Quantity available for reuse
- Age of the material
- Information on former use
- Technical capacity
- EOL Scenarios

4.2.2. Is it a standardized product?

Standardization is a powerful tool to identify the properties of the material. Different materials have different standard products whose performance and properties are very well know. Matching these properties can reveal important information regarding the salvaged product at hand. To judge the level of standardization and IS specifications, market research is needed. One needs to study the available types of products in the market, their compositions and also the IS specifications the concerned product complies to.



4.2.3. Estimate Remaining service life

As a rule of thumb, remaining service life is the subtraction of the technical life (from market research) and the functional life already served. It can be very challenging to estimate the remaining service life of a product at the preliminary stage. However, it is possible to extrapolate this figure if the procurement is regional i.e., direct or in-situ as there is greater possibility of accessing the engineering drawings and loading conditions of the source buildings. In case of procurement from stockholders, it is a matter of trust between the buyers and the seller if he believes the figures and records of the stockholder. In- house inventory is further beneficial since the owner is the same and if he keeps proper documentation, remaining service life can be computed.

However, it becomes challenging when inter-sectoral materials are procured to track down the remaining service life since the material flow chain is extensive involving multiple stakeholders. It is dealt by combining both the available documentation and trust between the buyer and seller. When it is not possible to compute remaining service life at preliminary stage, one needs to carry out tests for the same. Depending upon the materials under consideration, the testing methods vary as well and are typically carried out by experts in the field.

4.2.4. Degradation level

Different materials have different degradation mechanism. It is imperative to research the common degradation mechanisms for the product type under consideration. Therefore, before inspecting the product, one should refer to the repair and maintenance guidelines for the product issued by manufacturers, product associations or even the government and the municipal co-operations. This gives an indication as to what typical defects/damages can be observed in the product. These can be visually identified by an expert in the field and then classified under the degradation categories of that material. For instance, in case of steel products, when signs of damage are observed during product inspection such as rust broken through coating, it becomes important to test the levels of degradation in the material prior to reuse. NEN-EN-ISO 4628-3 specifies the methodology to assess the degree of rusting and coating degradation in steel by comparing with pictorial standards as shown in Figure 3. Similar standards exists for different materials.

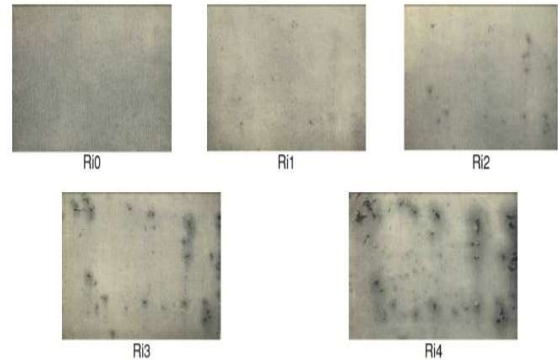


Figure 5: Photographic examples corresponding to ISO4628-3

The damage study is broadly carried out in three stages:

- i) **Types of damages**-What are the common signs/types of damages and degradation mechanisms? These very much depend upon the material or the product one is dealing with. For instance, rusting in metallic products, peeling and insect attack in wooden articles, stains in glass, etc., are the typical material specific degradation mechanisms. These mechanisms can be found in the standard repair and maintenance specifications for the product.
- ii) **Discard Criteria**-It is also called "removal from service criteria" which demines if the degradation level of the product is acceptable or intensive enough that the product/part needs to be discarded from service.
- iii) **Assessment**- Having listed out the types of possible degradations and knowing the discard criteria, one can assess the health of the product visually. Furthermore, it is also required to estimate the economic cost of repair at this stage which will contribute to the decision making in the next stage.

4.3. Decision to Reuse or Recycle

Having identified the materials which needs to be reused in the new construction and the procurement method and doing a preliminary level investigation, one gets sufficient information to make a decision if to go for reuse or not. It is feasible to reuse a component only if it has environmental and economic benefits which can be quantified making reuse a profitable business case.

Reuse is generally preferred over recycling in the waste management hierarchy as it retains the EE within the material and prevents emissions in the production of new products. For instance, reclaimed and reused steel sections are found to typically have a 25 times lower environmental impact than new even when the newer section have about 60% recycled content (BioRegional, 2011). However, there are instances when reuse ceases to be feasible over recycling, determined by the following factors:

1. **Value of Scrap:** Recycling is currently cheaper than reclamation since reuse is a more complicated and time-consuming process (BioRegional, 2011). This is particularly applicable for materials such as steel, where the recycling market is well-established and the process is hassle-free. About 90% used steel after EOL is sent back to recycling, 10% for some component reuse and less than 1% is sent to landfill (Ryerson University, 2006).
2. **Repair/ refurbishment:** Substantial levels of degradation such as corrosion, wear and tear can result in costly repair and refurbishment which then overrides the reuse cost savings.
3. **Quality and Safety:** many a times, there is no documentation and/or history of the salvaged product nor it is economic to test each individual element for quality and safety assurance. In such cases, the product is instead sent for recycling unless applied for a degraded application.
4. **Added value of degraded reuse:** For materials having open loop recycling, it makes degraded reuse more plausible than for materials with closed loop recycling such as steel. If steel is used for a degraded-application then it is essential to justify the value of this reuse as the same element can be fed back as recycled fraction for producing new steel.

Type of Recycling System: The first step in the LCI comparison is to determine what type of system of recycling it belongs to : an open or a closed loop recycling

As defined by ISO 14044:2006,

1. **Open Loop Recycling (OLR):** It is the system where the material is recycled in to a different product and not the parent itself. Here the inherent material properties are likely to be changed to serve the new function.
2. **Closed Loop Recycling (CLR):** It applies to systems where the product is recycled backed in the manufacturing of the parent product keeping the inherent properties of the recycled material intact.

Different materials have different types of recycling loop (if any). The value of recycling is evaluated based on the type of recycling system. For instance, in case of open loop recycling, it is not known where and for what purpose the recycled product will be applied but it is certain that it is not fed back to the virgin material stock. To estimate the value of recycling in this case, one should estimate the value of scrap. Economic value of Scrap value is different for different materials depending on the level of development of scrap market and recycling facilities. Whereas in case of a closed loop recycling, the net LCI of the product is reduced since the scrap replaces the virgin material. For instance, Steel can be considered as a closed loop recycling since the scrap is melted and fed back to the system in the steel making process.

4.3.1. Reuse Feasibility Method

Before reusing a product for its original or adapted function, it is imperative to substantiate that it is a better alternate to reuse and not recycle this product. Equations 1 & 2 are used to assess the reuse feasibility wherein letter A denotes virgin material and B denotes reused product. The environmental impact savings are expressed in terms of Life Cycle Impact (LCI) both in case of OLR and CLR

Reuse is feasible if

$$LCI_A - V_{scrap} + LCI_{scrap} > LCI_B + C_{TB} \dots\dots\dots \text{(in case of OLR)}, \dots\dots\dots (1)$$

$$LCI_A - LCI_{scrap} - V_{scrap} > LCI_B + C_{TB} \dots\dots\dots \text{(in case of CLR)}, \dots\dots\dots (2)$$

Where

- $LCI_A - V_{scrap} + LCI_{scrap}$ = Cost of recycling in OLR system
- $LCI_A - LCI_{scrap} - V_{scrap}$ = net value of recycling in CLR system
- $LCI_B + C_{TB}$ = Cost of Reuse
- LCI_A = Environmental Impact of Virgin Material
- LCI_B = Environmental Impact of Reused Material
- LCI_{scrap} = Environmental impact of recycling scrap
- V_{scrap} = Value (economic) of scrap
- C_{TB} = Additional cost of re-conditioning secondary material for reuse

This basic framework is the guide concept to be applied to the existing databases for arriving at the conclusions.

$LCI_B + C_{TB}$ = Cost of Reuse

LCI_B = 0 euro/kg, since no processing is required in the considered boundary of production stage for reuse. It is assumed that there is no over-dimensioning and strengthening involved. However, the variable is still introduced in the equation for systems where different boundary conditions are introduced.

C_{TB} = It accounts for the additional transportation and treatment cost of the reuse product. It is project specific and depends on the cost of procurement, cost of assessing the quality and health of the product, transportation distances and re-conditioning costs (if needed).

$C_{TB} = C_p + C_t + C_a + C_r$

C_p = Cost of procurement.

The reuse products are cheaper than the new products and generally a costlier than scarp due to their intrinsic value. However, these prices are highly subjective to the place and the availability of the material.

C_t = Cost of transportation, estimated during preliminary investigation

C_a = Cost of assessing the quality and health

C_r = Cost of Re-conditioning, estimated during preliminary investigation

It includes costs of repairs or refurbishment needed before applying the secondary material. These costs depend upon the condition of the product. However, they must be within the permissible limits not overriding the reuse savings.

4.3.2. How to make reuse feasible?

There is high possibility of reuse to not be feasible if not planned well within the system boundaries. Consider a situation where a used product is procured in a bad health without any documentation or background information from a far- off vendor and it is decided to test each member individually to assess quality. In such a situation it is almost certain that the reuse is not a feasible option. To avoid such situations, one should set boundaries to limit the costs. Principally the cost of reuse is the parameter **C_{TB}** which further have four components. Of these four, two components (**C_a & C_t**) can be

controlled with limiting systems whereas the other two remain more or less constant (**Cp & Cr**). One can argue that both the cost of procurement and the cost of re-conditioning are highly variable as they change in every project then how is it that they are entitled constant? Well, they are considered constant in a way that the control of the user is very limited on these costs. For instance, there is always a base price of the secondary material **Cp**, which can vary with negotiations but remains inevitable. Similarly, the cost of reconditioning **Cr**, is not controlled by the user as it depends on the product health. Although the buyer can choose not to buy it but if willing to reuse these costs are inevitable.

However, it is possible to reduce the net **C_{TB}** by using couple of strategies taking advantage of the interdependencies of the fixed (**Ca & Ct**) and the variable components (**Cp & Cr**). To do so, a concept of functionality is developed. Functionality as such refers to the future use (reuse) of the EOL product defined with respect to its previous function. Following three types are used in this study:

- a) **Intrinsic functionality**- when the future application is identical as that of the original one for which the product was initially produced. This preserves most of the value of the product in terms of energy, labor and production processes. For instance, doors from a retail shop are reused in another retail shop
- b) **Extrinsic functionality**- it is similar to the intrinsic functionality expect for the fact that the performance levels are not identical. For example, the door from the retail shops are now to be reused in a house. Here the performance levels are different since a smaller door size is needed for the house and hence modifications will be required in the secondary door. This process requires additional energy and cost, but it broadens the options of procurement as the product available in different configurations can be obtained now giving better control of prices and the demand-supply balances.
- c) **Repurpose**- when the future function is no longer the same as the original application of the product. The salvaged product can be upcycled or downcycled in this case. Upcycling is done when the product is applied for a superior application than original, it requires additional upgradation of the product but can be beneficial if the cost of virgin material is high. Downcycling is generally the case with repurposing wherein the product is put to an inferior application also called degraded use. Repurpose often has an element of creative reuse since the product is not used for its intended purpose.

Functionality type when combined with procurement methods can facilitate more realistic transportation boundaries within reuse feasibility limits. Two approaches can be used: procurement centric and functionality centric. For reuse proposal where functionality is defined first and then the mode of procurement is decided, is termed as functionality centric. For example, using EOL brick in the wall (intrinsic), applying primary EOL beams in secondary support structures (extrinsic) or using industrial EOL products for decorating interiors (repurpose). In all of these examples, the reuse is first defined in terms of functionality and thereby the following combinations are possible w.r.to procurement methods.

A. Feasible Functionality Centric Reuse

For a functionality centric reuse, the best practice is to locate the nearest source with the least fixed costs (**Cp & Cr**). In most of the cases the nearest sources is generally inhouse inventory and also has the least or no procurement cost, **Cp**. If the inventory is maintained well, it further reduces the re-conditioning costs, **Cr**. Next in the list for a defined functionality is the inter-sectoral procurement mode since it can be regionally located and the fixed cost component (**Cp**) is lower than that of regional procurement. However, **Cr** can be a determining factor to decide the preferred option.

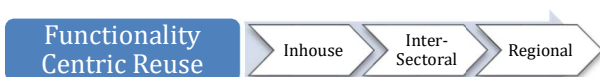


Figure 6: Order of preference_ Functionality Centric Reuse

B. Feasible Procurement Centric Reuse

In case of a procurement centric reuse where is it first defined where the product will come from and then the functionality, the order varies. For inhouse inventory, extrinsic is the one of the most idealist functionality since it allows to make modifications in the EOL product available at hand than to procure it from far off sources. Since the product type is same e.g. wooden profiles in the inventory of a builder, the fixed cost component C_r is lower than that required in case of repurpose or intrinsic reuse. Hence, the most idealistic is extrinsic since C_r is relatively lower followed by repurpose and then intrinsic since C_r is high in order to match same performance as virgin product. For inter-sectoral, intrinsic functionality is least attractive as it is very less likely for a EOL product of one sector to have same performance as the virgin product of another sector when applied there. For extrinsic, there will be C_r higher than that in repurpose. In case of regional procurement, there is no need to repurpose since the procurement is from a supplier who can deliver the required product nor is there as much a need to upgrade/ refurbish when the EOL product is available for intrinsic reuse. However, for intrinsic reuse, the EOL product is assumed to be in a good condition and can perform as good as a new material thereby having a high C_p , therefore a better strategy is to procure for extrinsic use in that case.

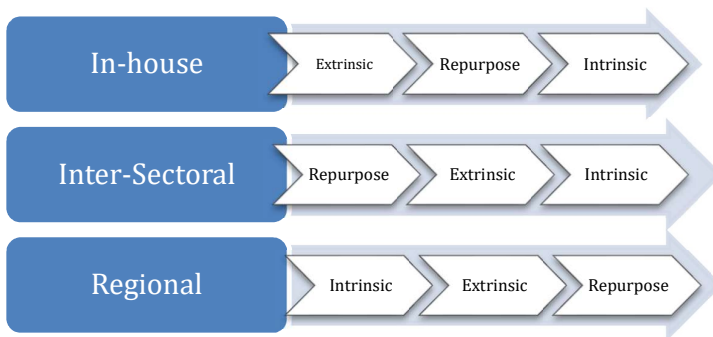


Figure 7: Order of preference_ Procurement Centric

C. Controlling Assessment Costs (C_a)

Certifications and testing can help boost the reuse of materials after EOL but they also incur additional cost and physical damages the test samples which is not preferred by the buyers or the sellers whosoever ensures these standards. Therefore, it is preferred to keep the testing within the economic boundaries. However, the extend of testing required is project specific and depends on many aspects such as functionality type and the trust between the supplier and the buyers, i.e. if buyers find the material source and information reliable or need to test for quality themselves. Other factors include the available information and durability conditions of the product.

What are the ways to ensure safety without testing/ certification?

In the past there have been reuse examples where testing and certification is circumvented with other measures such as coupon testing and over specification. Coupon testing is done on a smaller dimension sample and its failure mechanism is representative for the larger lot. For instance, in Olympic Park London, 25000 tonnes of secondary steel was deployed which represented 65% of the steel used in the roof truss and 20% of total steel used (Government Europa, 2019). Since it was not feasible to test each sample, coupon testing was used wherein smaller lengths of steel tubes were tested to determine the mechanical properties. It was done for each 12m tube (Jullian M Allwood, 2010). In over specification, elements used are of larger dimensions than required to ensure safe application.

How to assess the need and level of testing required?

In this section, an indicative framework is presented to highlight combinations where detailed and expert testing (explained in section 5.1 and 5.2) can be circumvented. The method is not absolute in a way it does not indicate yes or no for testing since the working circumstances are unique for each project but it does indicate a degree of recommendation for the same. It is developed taking into account the procurement type, functionality, product profile (standardization, remaining service life and degradation level) as summarized in table 2. Depending on the mode of procurement, different levels of information can be obtained regarding the product (Jullian M Allwood, 2010).

- I. **Regional mode:** For In-situ and direct exchange there is high possibility of accessing engineering drawings and loading conditions which reduces testing need, however, when stockholders are involved trust plays an important role to determine if the buyer believes the information provided by the seller or wants to test the material himself.
 - a. **For intrinsic/extrinsic:** Information on standardization complements remaining service life for regional procurement, i.e. if a product is standardized with unknown RSL, it can be extrapolated from info of the standard product and use phase. The positive combinations to avoid detailed testing (DT) and expert testing (ET) is the information on either standardization or RSL + low degradation (visual). This can be dealt with by coupon testing or over-dimensioning. However, high degradation with no info on standardization and RSL form the worst case where testing is imperative.
 - b. **Repurpose/ Downgrade:** Tracing back to the product standardization in relatively unimportant for downgraded reuse since the application is no longer the same or related but the information on RSL is needed to estimated life of the product in new application. In no case, it is recommended to go for expert testing for downgrade since it is most likely to override the costs – benefit balance.

Procurement	Functionality	Standardization	RSL	Degradation	DT	ET	Alternate Needed
Regional	Intrinsic/ Extrinsic	Yes	Unknown	Low	NR	NR	Coupon/Over-dimensioning
		No	Known	Low	NR	NR	Coupon/Over-dimensioning
		No	Unknown	High	HR	HR	-
	Repurpose/downgrade	-	Known	Low	NR	NR	Coupon/Over-dimensioning
		-	Unknown	High	R	NR	-
In-house	Intrinsic /Extrinsic	Yes	Known	Low	NR	NR	Coupon/Over-dimensioning
	Repurpose/downgrade	-	Known	Low	NR	NR	Coupon/Over-dimensioning
Inter-sectoral	Intrinsic	-	Known	Low	NR	NR	Coupon/Over-dimensioning
	Extrinsic	No	Known	Low	NR	NR	Coupon/Over-dimensioning
		No	Unknow	High	R	R	-
	Repurpose/downgrade	-	Unknown	Low	NR	NR	Coupon/Over-dimensioning

TABLE 2: Testing Requirement Assessment

HR = Testing highly recommended
 NR = Testing not recommended
 R = Detail testing recommended, expert testing may be circumvented

II. **In-house mode:** If properly maintained, one can document the type and durability conditions of the EOL products in stock e.g., with material passport. Degradation can further be prevented by appropriate storage conditions and maintenance if required. Therefore, the need for DT and ET is generally subsided.

III. **Inter-sectoral:** Since the procurement is from another sector, standardization is difficult to investigate (needs knowledge of the concerned sector) of the product is of lesser relevance here. Therefore, worse case it is assumed not to be standardized. For known RSL and low degradation, DT and ET can be avoided but recommended for unknow RSL and high degradation level.

D. **Role of Policy:** In many cases it is not possible to even after using the functionality and procurement optimization to make reuse economically feasible but it is always environmentally beneficial. In circumstances where it is not practical to circumvent the detail and expert testing to ensure quality and safe use, reuse then gets more expensive than recycling. This is when policy can play an important role. Policy amendments and government support can help bolster reuse. For instance, imposing tax on virgin material use, incentivizing secondary material reuse and subsidizing the ones actively reusing than mining are some of these actions which can make reuse both economic as well as environmentally viable with assured safety and quality.

4.4. Product Health Assessment

Reuse Potential Assessment (RPA) methodology is required to ensure safe and efficient of the secondary products in the new construction. The framework has four levels of investigation, preliminary (discussed in section 4.2), detailed, expert and remedial levels. It is pragmatic to work on the lines of estimating existing structures methodologies (B. Kühn, 2008) to further be extrapolated to secondary materials.

4.4.1. **Detailed Investigation-** In case, sufficient information is not available after the preliminary analysis but it is found feasible to reuse the EOL product, one needs to carry out detailed analysis. To ensure compliance with specifications, a quantitative inspection is done with the help of low-tech non destructive (NDT) testing methods. NDT methods are preferred over destructive testing (DT) methods as these do not sacrifice the test sample and are more economical than DT methods (Masanori Fujita, 2014). It is important to keep it low tech for capping the cost of testing (Ca) minimum and eliminating assessment by experts. It also depends on the future and previous use of the material as to which tests to be carried out. Although, NDT methods of testing are different for different materials, a basic framework applies to proceed with the testing. It should primarily test the following properties-

1. Mechanical properties
2. Chemical Composition
3. Degradation/ damage assessment

The aim of NDT is to be able to assign identity to the material under consideration and also to verify its properties with respect to existing standards.

4.4.2. Expert Investigation- This stage should be avoided as much as possible as it involves destructive testing methods by experts in the field. With no guarantee of the results, the costs make it unrealistic to go for these tests. For instance, the cost of testing steel profiles is estimated to be about a £100 per section (Jullian M Allwood, 2010). Again, testing methods at expert level vary depending on the product and the material it is composed of.

If the results of the investigation indicate a enough strength and remaining useful life of the product then it can be directly applied with required cleaning. However, if it is not found fit of use in the existing state, a set of re-conditioning/ treatment actions can be applied on the secondary material to make it fit for reuse.

4.4.3. Re-conditioning- Broadly there are two approaches for it, to invest in the product and make it fit for use by strengthening it or to alter the use (functionality) of the product and instead use it for an inferior use. The decision to repair or to reuse for degraded application is based on the level of effort in terms of cost and benefits. Both of these measures have their own limitations. While it can be costly to repair the product, it can be challenging to alter its application and fit it for another purpose. These strategies are discussed in detail below

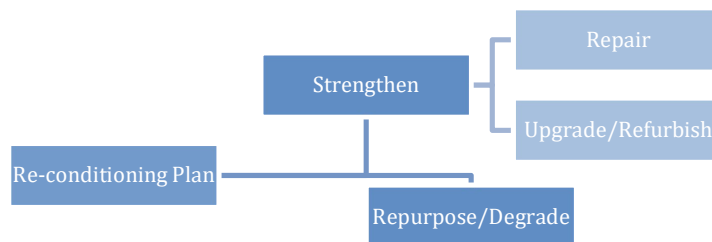


Figure 8: Re-conditioning Strategies

- a. **Repair:** Repair is a preferred and cheaper strategy of re-conditioning the secondary product. It is the additional operations needed to bring a faulty or broken product back to usable state (Circle Economy, 2015). General repair activities include repainting, washing, blasting, lubricating, etc. The level of repair is somewhat estimated in the preliminary investigation stage itself depending on the condition of the secondary product.
- b. **Upgrade/ Refurbishment:** It is relatively costlier than repair and applicable to products which have multiple separate components having different functional life. The value of a product is best recovered through direct use, then repair and then upgrade and refurbishment since they require breaking down and replacement (Circle Economy, 2015). Upgrade is generally in case of technical obsolesce of components which are then removed and replaced with new ones and the entire product is then reused. Whereas in case of refurbishment it is more the functionality of the component i.e. the component has reached EOL and needs replacement with newer one. Mostly upgradation is driven by legal policies which change over time and thereby the specification compliance changes as well. For instance, steel frame was reused in-situ in BMW sales and services center but it had to be strengthened in compliance to the updated seismic regulations (Jullian M Allwood, 2010).

The cost of repair/upgrade (**Cr**) needs a capping in the reuse feasibility equation not to override the reuse savings.

From equation 1 and 2,

$$LCI_A - V_{scrap} + LCI_{scrap} > LCI_B + C_{TB} \dots\dots\dots \text{(in case of OLR)}$$

$$LCI_A - LCI_{scrap} - V_{scrap} > LCI_B + C_{TB} \dots\dots\dots \text{(in case of CLR)}$$

Where

$$LCI_B + C_{TB} = C_{TB} \text{ (since } LCI_B = 0 \text{)}$$

$$C_{TB} = C_p + C_t + C_a + C_r$$

Allowable repair cost (Cr)

$$C_r < LCI_A - V_{scrap} + LCI_{scrap} - (C_p + C_t + C_a) \dots\dots\dots \text{(in case of OLR)} \dots\dots (3)$$

$$C_r < LCI_A - LCI_{scrap} - V_{scrap} - (C_p + C_t + C_a) \dots\dots\dots \text{(in case of CLR)} \dots\dots (4)$$

- c. **Degrade/ Repurpose:** Degrade is a type of repurpose, a typical case of downcycling. When it is not possible to assess the health and history of the product, one way is to estimate the degraded state of the product for reuse. For instance, in case of steel, if testing is not feasible, the grade of steel is downgraded to S235JR which is the lowest historical grade ([Jullian M Allwood, 2010](#)) and the product reuse is accordingly determined. Degrading is not a preferred re-conditioning strategy since it does not preserve the value created for a product to meet its original functional ([Circle Economy, 2015](#)). For degraded reuse, it is important to further estimate the value/ worth of this application. For example, it can so happen that the value of degraded reuse is lesser than the value of recycling the product or using the virgin material instead.

4.5. Testing Framework : Case-study Application

In order to validate the application of the conceptual framework developed so far, a case- study is selected where the reuse potential of EOL products is assessed by following the methodology developed. Two reuse scenarios are tried here, one with extrinsic functionality and the other with repurpose. The EOL materials are procured in an inter-sectoral mode from offshore industry and therefore identical application i.e. intrinsic functionality is not explored due to lack of engineering compatibility (as discussed in section 4.1.3). Furthermore, the reuse feasibility is calculated for the other functionality types to identify the optimum application.

Case study description

The case presented in a real time project with Saipem, a leading Offshore firm based in Schiedam, Netherlands. The existing establishment consists of two buildings A and B as shown in figure 8. Building A is the main office building with about 1400 m² whereas B forms the recent expansion of 400 m², located in Schiedam figure 9. Saipem wants to expand the current office buildings, to accommodate more employees and enlarge storage facility while maintaining a minimum environmental footprint for which a techno-economic feasibility is carried out.

The project is titled “New Green Office” emphasizing the importance of sustainability goals. One of the important sustainability goals for the expansion project is to use sustainable and circular materials with reuse of secondary products into the new construction. Additionally, the company possess offshore waste in large quantities and drives to sort a way to reuse this waste in the new construction. Combining these two objectives, the available EOL products from offshore are to the working framework to assess the reuse potential.



Figure 8: Existing Office Site, Part A&B



Figure 9: Google Map Location, Schiedam

4.5.1. Identify Replaceable Material

Type of Procurement: In-house inventory+ Inter-sectoral

Since the secondary products are from Saipem's off shore activities and are owned and stored by Saipem, this is a clear case of In-house inventory procurement. However, since the source of the material is not construction, it is also an implied case of inter-sectoral procurement.

Selection Criteria

- a) Engineering Compatibility
- b) High quantitative application
- c) Substantial residual life
- d) Local Availability

The firm possess different kinds of secondary products collected from its project sites. These materials are stored in containers by the company which are then numbered for data keeping. Photos of these containers provide details of what these containers have. However, there exists a gap in digital record keeping of each product. In order to identify the potential reusable EOL products according to the above-mentioned criteria, a thorough scan of the inventory was carried out.

The scan was done in two stages. In the first stage of preliminary scan, EOL material which were not-compatible for reuse were eliminated. For instance, products specific to intrinsic off-shore application which cannot be reused in a functional building such as cable carousal, electrical breakers, centrifugal pumps, etc. Local availability was not considered to be an elimination criterion since all the products are stored at the yard on the existing office site, making the transportation cost (Ct) zero. To further pin down the products from remaining lists, quantitative application and residual life were used. The results of second stage of scanning is presented in table 3, followed by the criteria and basis of selection of the final EOL products for reuse.

Selected Material: Steel Wire Rope

After the second phase of material scanning, steel wire ropes were selected for reuse in the new construction as it was available in substantial quantity with minimum degradation level as shown in figure 10. Since it is made of steel, the estimated residual life is higher than other products under consideration. Products like the wooden and metal support, although potential candidates for reuse, they cannot be applied since they are available in relatively smaller quantities whereas the rubber tires were initially considered for repurpose but later rejected due to high degradation visible on the surface such that it surpasses the discard criteria.

Category	Item	Storage	
Accessory	Steel Wire Ropes	20 ft DV container	
	Rubber Wheel	20 ft DV container	
	Fender	20 ft DV container	
Vessel Parts	Wooden Support	20 ft DV container	
	Metal Panel	20 ft DV container	

TABLE 3: Product from Second – Stage Scan



Figure 10: EOL Steel Wire Ropes

Functionality

Having identified the products for reuse from available inventory, two possible applications of the wire ropes are brainstormed as mentioned below

Extrinsic functionality- The intrinsic use of the wire ropes was that of taking tension forces for rigging purposes. In the new office construction, one proposal is to use these wire ropes again for taking tension forces except for the fact that the performance levels are not identical. Now, it would support a mezzanine floor instead. Since, it is a structural application, testing is imperative in this case and will greatly determine the reuse feasibility.

Repurpose- here the function of the wire rope is no longer the same. Instead it is now used as a façade element. Different configurations are designed to test the reuse feasibility. The repurposing greatly reduces the assessment cost as it is a case of over-dimensioning which will be explained later in the report.

4.5.2. Preliminary Investigation

- a) **Product Portfolio-** Wire ropes have various application in maritime vessels such as ships, drilling vessels, etc. Hoisting, towing, anchoring, mooring, rigging and handling heavy lifts are amongst the most common applications of these wire ropes in the shipping industry. There are broadly two types of wire ropes: stainless steel wire ropes and hot-dip galvanized steel wire ropes. Unlike stainless steel wire ropes, the steel wire ropes are not inherently corrosion proof and are therefore treated beforehand. The available EOL wire ropes are hot-dip galvanized steel wire ropes. Coating is done at temperature of about 4500^o-4600^o C, steel wire is dipped in zinc bath and then cooled down forming zinc coating on the surface which is very durable and resistant to corrosion. The basic information available about the product is listed in table-----.

Type of product	Steel wire rope slings
Physical dimensions	Diameter = 44 mm, Length= 11.5 m
Technical capacity	Safe working load (SWL) = 4.25 Tonnes Minimum Breaking Load (MBL) = 137.6 tonnes
Former Use	Rigging the sailing vessel
EOL Scenarios	Scraped with other steel profiles

b. Is it a standardized product?

First step in analyzing the extent of product standardization is to research the IS specifications pertinent to the steel wire rope as listed below

- (1) **For general requirements:** EN 12385-1: 2002+A1: 2008 Steel wire ropes - Safety - Part 1: General requirements
- (2) **For Classification:** EN 12385-2: 2002+A1: 2008 Steel wire ropes - Safety - Part 2: Terms, designation and classification
- (3) **For maintenance:** EN 12385-3: 2004+A1: 2008 Steel wire ropes - Safety - Part 3: Information for use and maintenance
- (4) **For structural application:** EN 12385-10: 2003+A1: 2008 Steel wire ropes - Safety - Part 10: Spiral ropes for general structural applications
- (5) EN10264-1: 2012-3 Steel wire and wire products - Steel wire for ropes - Part 1: General requirements

Market Research Wire rope slings are extremely strong and an excellent choice for heavy duty jobs. Wire rope slings are manufactured in a variety of configurations, with 6*19 and 6*36, being two of the most common ones. One way to identify the category of wire rope is to know how many wires make up a strand and how many strands are wrapped around a core. For example, a 6*37 wire rope is 6 strands of 37 wires. Variations in these numbers determine a wire ropes' resistance to abrasion and flexibility. As a rule of thumb, more wires increase flexibility and resistance to kinks, but also makes it more prone to abrasion wear. Fewer wires will make the wire rope larger in diameter, with a higher abrasion resistance, but instead reduce the slings' lifting flexibility (USCC, 2019).

Another way to classify the wire ropes is by the type of end connections attached to the rope. As shown in figure 11, there are various types end connections such as single leg, 2-leg, 3-leg, 4-leg and domestic wire rope.



Figure 11: Types of Wire Rope End Connections (Source)

The wire ropes available for reuse in this case are 6 *19 type with single leg also called eye & eye slings. The eyes are formed using a Flemish eye splice in which the rope is separated into two parts. These two rope parts are then re-laid back into the opposite direction, forming an eye and secured with a carbon steel sleeve.

c. Estimate Remaining service life

There is no information available on the age of wire ropes available in the yard since they have been used in different vessels for different duration of use without proper data keeping. As a result, it is not feasible to apply them for extrinsic application i.e. to support the mezzanine floor without having done destructive testing to assess the durability and strength. Hence, now only the repurpose vs recycling option will be assessed in this report.

d. Degradation level

i) **Types of damages-** Following are the common types of damages observed in steel wire ropes (Alioto, 2019)

- A. Broken wires in the rope-
- B. Kinked Wire
- C. Abraded/worn Wire
- D. Popped Core Wire
- E. Corrosion
- F. Heat Damage
- G. Bird Caging
- H. Damaged Fittings

These are the most common degradation mechanisms for wire ropes and each of these have different treatment method, for example, the broken ends can damage other strands in the rope.

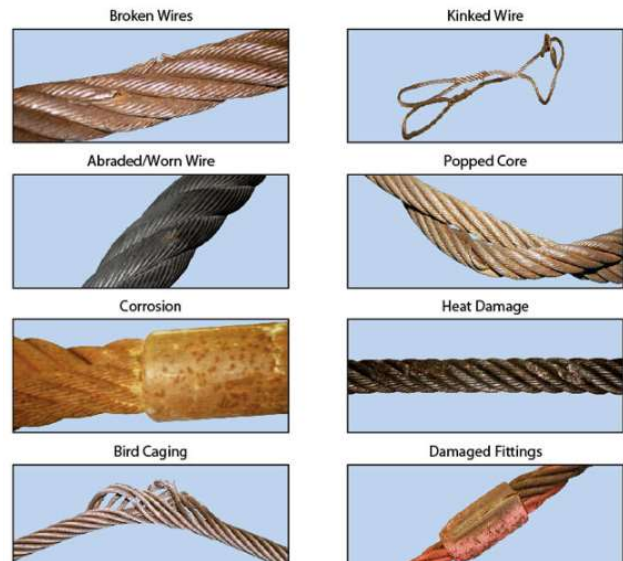


Figure 12: Degradation Mechanism Wire Ropes (Alioto, 2019)

These should not be pinched off with a pair of nippers but instead be broken deep in the valley between two outer strands (CASAR, 2018). However, for practical limitations, it was not possible to open all each container and inspect each segment for these defects. But a market research is done to be aware of the defects that can be sighted once the decision is made to reuse the ropes.

- ii) **Discard Criteria-** it is the criteria which demines if the degradation level of the product is acceptable or so intensive that the product/part needs to be discarded.
 - a. **Broken Wire Ropes:** For the wire ropes, broken wires is one major discard criteria. There is a permissible limit of the number of broken wires that can be tolerated in a wire rope without affecting its functionality. As per ISO 4309:2011, the rope must be discarded whenever the number of broken wires counted, in 6d or 30d, is equal to, or greater than, those listed in the standards. The length of the rope depends on the diameter of the rope as 6d or 30d (“d” = nominal rope diameter).
 - b. **Broken Strand:** a rope is immediately discarded in case of a broken strand. However, in case of repurpose application, one can consider to reuse a part of the rope with intact strands.
 - c. **Reduction in Diameter:** It is a measure of internal wear of the rope. A reduction of about 15% in the diameter is a general discard criterion due to internal wear whereas a reduction of 10% due to surface abrasion also leads to discard from reuse. However, it is too conservative for repurpose.

To detect possible damage, you should perform a visual inspection of the entire sling and also feel along its entire length, as some damage may be felt more than seen. One should also look and feel for any of the types of conditions listed in the discard criteria above.

- iii) **Assessment-** Based on the findings of the preliminary investigation, it is decided to proceed with the repurpose functionality application and not for extrinsic application. This is because, in some of the lots as shown in figure 10, there are visible signs of degradation and the information on remaining service life is also not available. Therefore as per table 2, detail and expert testing becomes imperative in case of extrinsic reuse. However, the company does not want to invest in testing each of these ropes due to the uncertainty of the results and associated cost. Hence, extrinsic reuse is not possible in this case. Since, repurpose is still a possibility, its feasibility will be explored in the coming sections.

Design ideas- Wire Ropes as Façade Elements

There are many inspirations available for the use of wire ropes as a façade element as listed below:

- 1. Wire ropes as vertical supports for secondary elements-** Here the term secondary elements refers to sun-shading, wind and glare control devices. The wire ropes are suspended vertically and support the secondary elements in the horizontal direction. An ideal example is the Windwave façade which is fully supported by wire rope structures and additionally controls wind and glare with hanging metal pieces (BuildingandInteriors, 2019). The principle is depicted in figure 11.



Figure 11: Wire Rope in Façade, Source (BuildingandInteriors, 2019)

- 2. Wire ropes as horizontal base**

This concept is quite similar to the previous one except that the orientation of the wire ropes which is supporting the secondary elements is horizontal. This alternative, however, is not suitable for application in the given case since the weight of the wire ropes demands for horizontal anchoring transferring the load to the main façade body wherein in case of vertical suspension, these are freely suspended under gravity with both ends fixed



Figure 12: Horizontal Base, source: Wikiimages

- 3. Woven mesh**

In this variant, the wire ropes spread along both the horizontal and vertical directions and are woven to form a mesh profile as depicted in figure 13. It is also not a feasible application for the given case since it requires weaving of the existing ropes which is difficult for the given diameter of the ropes.



Figure 13: Woven Mesh, source: Wikiimages

Design

The selected design is inspired by the concept of the windwave façade. The wire ropes are used in vertical orientation and are locked at both the ends. Since over-dimensioned ropes are used, aluminum panel plates are used to support these ropes which transfer the loads to the floor. The ends of the ropes are tied in a magnetic screw cap as shown below. The horizontal blind headrail is embedded in the aluminum support panel which is regulated by the building management system (BMS).

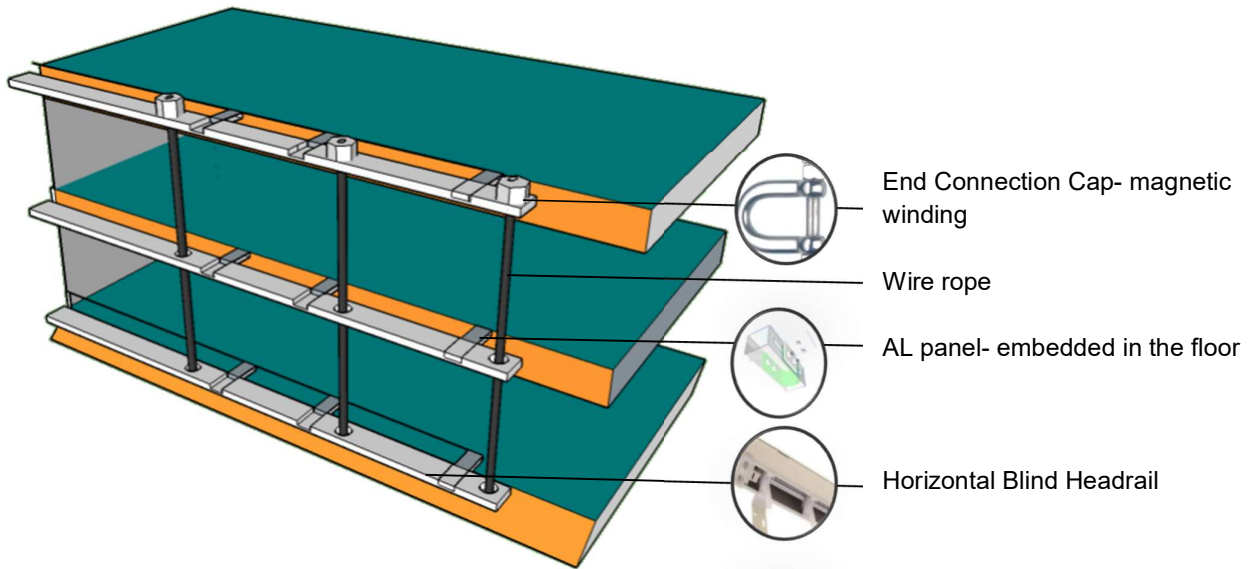


Figure 14: Wire Rope Integration in the Façade

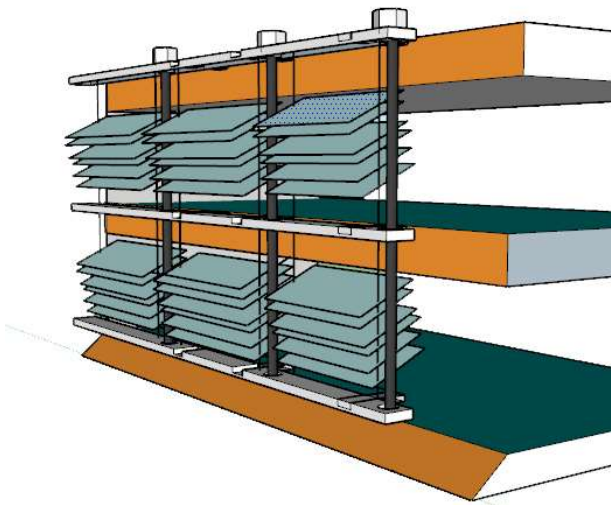


Figure 15: Wire Rope Façade with Sunshade Onn

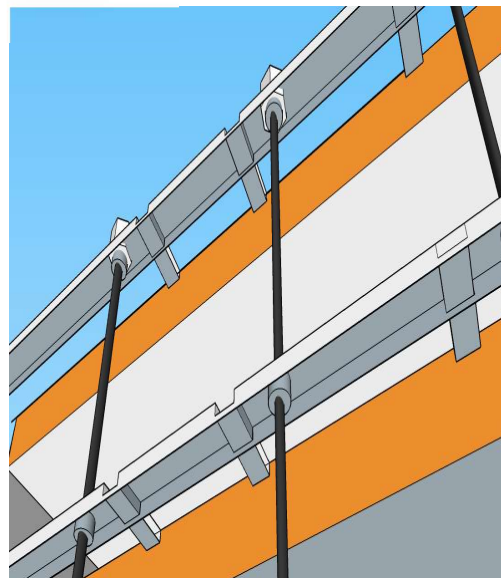


Figure 16: Connection Assembly Underneath

4.5.3. Decision to Reuse or Recycle

The reuse feasibility is quantitatively assessed by equation 1 as well as equation 2 as shown below.

$$LCI_A - V_{scrap} + LCI_{scrap} > LCI_B + C_{TB} \dots\dots\dots \text{(in case of OLR),(1)}$$

$$LCI_A - LCI_{scrap} - V_{scrap} > LCI_B + C_{TB} \dots\dots\dots (2)$$

Where

- $LCI_A - V_{scrap} + LCI_{scrap}$ = Cost of recycling in OLR system
- $LCI_A - LCI_{scrap} - V_{scrap}$ = net value of recycling in CLR system
- $LCI_B + C_{TB}$ = Cost of Reuse
- LCI_A = Environmental Impact of Virgin Material
- LCI_B = Environmental Impact of Reused Material
- LCI_{scrap} = Environmental impact of recycling scrap
- V_{scrap} = Value (economic) of scrap
- C_{TB} = Additional cost of re-conditioning secondary material for reuse

a. Value of LCI_A , LCI_{scrap}

For the LCI_A of the virgin material comparisons will be made based on existing data since performing an LCA analysis is out of the scope of this study. In such cases, the data can be availed from sources such as international organizations, national databases and published literature. For realistic analysis, the source of data should be same.

Source : World Steel Association

There are various frameworks available for assessing the net value of reuse vs recycling. Depending on the material under investigation suitable framework should be selected. In this case study, to compare the results, the framework of the World Steel Association, “Life Cycle Inventory Methodology Report for Steel Products” which is itself based on ISO 14040: 2006 and ISO 14044: 2006 is used as source 1. The methodology is internationally agreed and universally applicable to steel products (World Steel Association, 2017). The obtained LCA values are then converted to LCI.

Functional Unit Used: LCI of 1 kg of steel product at the factory gate (Cradle to Gate) including recycling. Recycling is accounted as the upstream burdens of the scrap used in the steel making process and the credit from the EOL recycling scarp.

System Boundaries: It is a cradle to gate LCI study, including all production steps from raw materials in the earth (i.e. the cradle) to the finished product (in this case the wire rod) with EOL recycling. The recycling credits are accounted by subtracting any input scrap used in the manufacturing from the EOL scarp sent for recycling.

Net scrap = Amount of steel recycled at end-of-life – Scrap input

Product Category under study: The LCA is carried out on the wire rods used for making the riggings under the long product classification

Product category	Manufacturing route	List of products
Long products	Basic oxygen furnace route and Electric arc furnace route	Sections Rebar Wire rod Engineering steels

Figure 17: Source - (World Steel Association, Life Cycle Inventory Study, 2018)

Method used by World Steel Association

LCI for 1 kg of steel product including recycling =

$$X - (RR-S) Y (X_{pr} - X_{re}) \dots\dots\dots(\text{World Steel Association, 2017})$$

Where

- X = cradle to gate LCI of steel product
- RR-S = net amount of scrap produced from system
- RR = EOL recycling rate of steel product
- S= scrap input to the steelmaking process
- Y(X_{pr}- X_{re}) = LCI value of steel scrap
- Y = process yield of the EAF (more than 1 kg scrap is required to produce 1 kg steel)
- X_{pr} = LCI for 100% primary metal production
- X_{re} = LCI for 100% secondary metal production

Results from inventory (World Steel Association, Life Cycle Inventory Study, 2018)

The impact of recycling 1kg steel scrap

Impact category	LCIA for 1kg steel scrap
Primary energy demand, MJ	13.8
Global warming potential (100 years) kg CO ₂ -e	1.67
Acidification potential, kg SO ₂ -e	0.0032
Eutrophication potential, kg Phosphate-e	2.23E-04
Photochemical ozone creation potential, kg Ethene -e	0.00078

TABLE 4: Primary Energy Demand for 1 kg Steel Scrap (Association, Life Cycle Inventory Study, 2018)

LCA results of various products studied by Worldsteel are shown below. It should be noted that the wire rod under consideration is prepared under Hot- dip galvanized steel category, produced in the EAF and BOF route, though typically with a higher proportion of BOF route so the amount of net scrap consumption is generally a lot lower, around 0.06 tonnes per tonne of hot-dip galvanized steel (World Steel Association, Life Cycle Inventory Study, 2018)

		PED MJ	GWP kg CO ₂ -e	AP kg SO ₂ -e	EP kg Phosphate-e	POCP kg ethene-e
Sections, 1kg	Cradle-to-gate	18.3	1.5	0.0037	0.00033	0.00068
	Net recycling benefit	-2.8	-0.3	-0.0007	-0.00005	-0.00016
	Cradle-to-gate including recycling	15.4	1.2	0.0031	0.00029	0.00052
Hot rolled coil, 1kg	Cradle-to-gate	23.2	2.3	0.0056	0.00044	0.00092
	Net recycling benefit	-10.0	-1.2	-0.0023	-0.00016	-0.00056
	Cradle-to-gate including recycling	13.2	1.1	0.0033	0.00028	0.00036
Hot-dip galvanized steel, 1kg	Cradle-to-gate	29.9	2.8	0.0064	0.00055	0.00100
	Net recycling benefit	-10.9	-1.3	-0.0025	-0.00018	-0.00061
	Cradle-to-gate including recycling	19.0	1.3	0.0025	0.00018	0.00061

TABLE 5: Life Cycle Impact Assessment of Steel Products, (Association, Life Cycle Inventory Study, 2018)

Translation to Reuse Feasibility Method

Reuse is feasible if

$$LCI_A - V_{scrap} + LCI_{scrap} > LCI_B + C_{TB} \dots \dots \dots \text{(in case of OLR), (1)}$$

$$LCI_A - LCI_{scrap} - V_{scrap} > LCI_B + C_{TB} \dots \dots \dots \text{(in case of CLR), (2)}$$

The values here are economic, therefore the above data needs conversion to shadow costs. The following economic cost indicators are used

Impact category	Unit	Weighting Factor (€/ unit)
Global warming	kg CO2-eq	0,05 €
Ozone depletion	kg CFC-11-eq	30,00 €
Acidification of soil and water	kg SO2-eq	4,00 €
Eutrophication	kg PO4.3--eq	9,00 €
Depletion of abiotic resources – elements	kg Sb-eq	0,16 €
Depletion of abiotic resources – fossil fuels	kg Sb-eq	0,16 €
Human toxicity	kg 1,4 DB-eq	0,09 €
Freshwater ecotoxicity	kg 1,4 DB-eq	0,03 €
Marine water ecotoxicity	kg 1,4 DB-eq	0,00001 €
Terrestrial ecotoxicity	1,4-DCB-eq	0,06 €
Photochemical oxidant creation (Smog)	kg C2H4	2,00 €

TABLE 6: Economic Cost Indicators, (Ecochain, 2019)

Hot- dip galvanized steel, 1kg				
Impact Category	GWP (kg CO2)	AP (kg SO2)	EP Kg Phosphate	POCP kg ethene
Monetary Value (€)	0.05	4	9	2
Cradle-to- gate	2.8	0.0064	0.00055	0.001
Cradle- to- gate including recycling	1.3	0.0025	0.00018	0.00061
Net recycling benefit	-1.3	-0.0025	-0.00018	-0.00061
LCI (Cradle to Gate)	0.14	0.0256	0.00495	0.002
LCI (Cradle to Gate including recycling)	0.065	0.01	0.00162	0.00122

TABLE 7: Calculated LCI of Steel

LCI_A (cradle to gate) = 0.173 euros/kg

LCI_A (Crdle to gate incl. recycling) = 0.077 euros/kg

Steel Scrap, 1Kg				
Impact Category	GWP (kg CO2)	AP (kg SO2)	EP Kg Phosphate	POCP kg ethene
Monetary Value (€)	0.05	4	9	2
	1.67	0.0032	0.000223	0.00078
LCI	0.0835	0.0128	0.002007	0.00156
Total LCI per kg scrap	0.10 €/kg			

TABLE 8: Calculated LCI of Steel Scrap

Putting the values in eq 1 and 2

For OLR

$$LCI_A - V_{scrap} + LCI_{scrap} > LCI_B + C_{TB} \dots\dots\dots \text{(in case of OLR),(1)}$$

$$LCI_A = 0.173 \text{ euros/kg}$$

$$LCI_B = 0, \text{ euros/kg}$$

$$LCI_{scrap} = 0.10 \text{ euros/kg}$$

Putting in eq 1

$$0.173 - V_{scrap} + 0.10 > 0 + C_{TB}$$

$$0.273 - V_{scrap} > C_{TB} \dots\dots\dots 1.1$$

For CLR

$$LCI_A - LCI_{scrap} - V_{scrap} > LCI_B + C_{TB} \dots\dots\dots (2)$$

Putting in eqn 2

$$LCI_A - LCI_{scrap} = 0.077 \text{ euros/kg}$$

$$LCI_B = 0$$

$$0.077 - V_{scrap} > 0 + C_{TB} \dots\dots\dots 1.2$$

b. Value of V_{scrap}

The EOL wire ropes are sold in scrap steel along with other steel profiles. Data from scrap dealers is studied to analyse the upper and lower bound of V_{scrap} . Dealers such as Krommenhoek, Rotterdam buys steel scrap at 0.12 euros/kg (KH Metals, 2019), HKS metals, Amsterdam at 0.08 euros/kg (HKS, 2019). The value is more or less the same with other dealers as well. However, to analyze worst case for reuse, a higher value of scrap is taken to be 0.12 euros/kg as V_{scrap} .

c. Value of C_{TB}

For OLR

$$0.273 - V_{scrap} > C_{TB} \dots\dots\dots 1.1$$

Substituting V_{scrap} .

$$C_{TB} < 0.273 - 0.12 = 0.153$$

$$C_{TB} < 0.153 \text{ euros/kg}$$

For CLR

$$0.077 - V_{scrap} > 0 + C_{TB} \dots\dots\dots 1.2$$

$$0.077 - 0.12 > C_{TB}$$

$$C_{TB} < -0.043 \text{ euros/kg}$$

As evident from the results above, in case of OLR the reuse is feasible only if the reconditioning cost is less than 0.153 euros/kg which is nearly the price of scrap material as well. Hence, instead of selling the EOL in scarp it can be a successful reuse case with the re-conditioning is capped within these bounds. Therefore, repurpose is the most feasible application here as it only requires repainting and cutting the wire ropes in desired lengths. However, one can also note that in case of CLR, the reconditioning cost is negative, i.e, the benefits of selling the scrap in closed loop recycling system already overcome the reuse cost. Hence, in this case there is no buffer cost available for reconditioning making it economically unfeasible to reuse but it is not possible to estimate the aesthetic benefits of this repurpose for the company making it a debatable decision. It is therefore left to the discretion of the firm to decide if the added aesthetic and emotional value gained from this reuse of wire ropes in the façade is feasible for them.

4.5.4. HEALTH ASSESSMENT

The typical detailed tests, also called the proof tests performed on wire ropes are done in the factory where the wire rope is pull tested to 2x the vertical rating. (USCC, 2019). This method is of course not selected since it is a destructive method and renders the specimen unfit for further use.

Analyzing the results of previous section, the allowable C_{TB} is practically too low to carry out any detail and expert testing. Hence in consultation with the involved shareholders (Prof. Arie Bergsma), it is decided to not opt for the proposed extrinsic functionality reuse which mandates detailed testing in order to use wire ropes for structural purposes and thereby leaving repurpose only as the viable option.

Analyzing the C_{TB} by components

$C_{TB} < 0.153$ euros/kg

$$C_{TB} = C_p + C_t + C_a + C_r$$

In case of the proposed repurpose,

C_p = Cost of procurement= virtually 0 euros/kg (in-house inventory)

C_t = Cost of transportation= 0 euros/kg since the EOL product is available in- situ

C_a = Cost of assessing the quality and health= nearly 0, no expert and detailed testing is carried out since it a case of repurpose. To ensure safe reuse, the principle of over-dimensioning is used wherein the diameter of the wire ropes is about three times of that of ropes usually deployed as façade element.

C_r = Cost of Re-conditioning, estimated during preliminary investigation

It includes costs of repairs or refurbishment needed before applying the secondary material. These costs depend upon the condition of the product. However, they must be within the permissible limits not overriding the reuse savings.

Hence,

$$C_{TB} = C_r < 0.153 \text{ euros/kg}$$

5. Conclusion

It can be observed from the given case study that the developed framework is unbiased and gives practical figures and methods to determine reuse feasibility. It is evident from the case study application that there are times when reuse is not a feasible option when compared to recycling. However, in the end it is up to the discretion of the owner/ cost bearer to go for the aesthetic and emotional value of reuse which is hard to quantify. For instance, in the given case study, reuse in the form of repurpose in CLR is not feasible as per the established framework however it has aesthetic value attached to it which is non-quantifiable.

6. Limitations

A major limitation is the sequential application of the framework, i.e., every consecutive step is built upon the results of its predecessor. In such a case its application is somewhat restricted to new projects and not on-going ones. Furthermore, it does not define who is an "expert" to judge the degradation level and how reliable is his judgement? Is it equivalent to a certification? Lastly, the cost and time invested in researching the information on secondary material is not accounted for in the reuse feasibility equation assuming it to be equivalent to that of virgin material, which is not always the case in practical situations.

7. Recommendations

- a. **Framework to quantify aesthetic value-** it is needed to develop a framework which can further quantify the aesthetic value addition parameter in the reuse feasibility equation which for now is an intangible entity. Such a quantification will strengthen the results of reuse feasibility making it a more practical option. Percentage capping can be one of the methods to quantify aesthetic value addition wherein the cost bearer defines what percentage of virgin material cost can he bear as a trade of to added value of reuse.
- b. **Digital Material Passport-** permanent product marking systems and digital data keeping should be followed religiously as this will eliminate or atleast reduce the need for expert testing and re-certification of the reclaimed products before reuse making reuse a profitable business case.
- c. **Aim for futuristic design-** A futuristic design serves the present requirements with solutions for future reuse after EOL material. One should design keeping EOL scenarios in mind. Effective futuristic reuse can be achieved by designing modular components which are standardized, demountable and allow for effective reuse possibilities.
- d. **Support from government-** with the prevailing reuse barriers, government and policy support is a must to promote reuse since in most of the cases it is difficult to reach the reuse feasibility equilibrium as the virgin material costs cheaper than EOL product reuse. Therefore subsidizing the process and promoting it in the policies is a major way forward.

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