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Facilitating industrial symbiosis to achieve circular economy using value-added by design: A case study in transforming the automobile industry sheet metal waste-flow into Voronoi facade systems

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ABSTRACT

Today, a significant portion of steel production worldwide is coming from recycling practices. It is inevitable that the smelting process during steel recycling operations is expensive and consumes a tremendous amount of energy. Therefore, hypothetically, direct reuse of steel materials without smelting can be environmentally and economically advantageous over recycling. In this article, an innovative recovering path for size-specific sheet metal scrap from the automobile industry is being proposed. The idea is to directly use the sizable sheet metal scrap generated from the car-body manufacturing process in the automobile industry to design and fabricate new metal facade systems for buildings' exteriors. An empirical case study was conducted, which is being presented to illustrate the benefits of reusing steel scrap over recycling with the same material using quantitative analysis. The required capital cost and energy consumption of generating a building metal facade system were evaluated. The results showed that reusing the sheet metal scrap over conventional recycling of the same material would lead to a cost reduction of approximately 40% (400 $/ton) and savings of approximately 67% (10 MJ/kg) of energy consumption. The tested concept promotes an innovative industrial symbiosis between the auto industry and the building and construction industry through creating a secondary closed supply-chain loop to achieve both circular economy and energy savings through adding value by design.

1. Introduction

1.1. Establishing a distinction between reuse and recycling

The work presented in this study practically and further explains and illustrates the distinction between reuse and recycling that is expected to structure the proposed paradigm shift in the architectural products design process. Recycling involves the processing of material-waste and by-products in making new materials. This waste is considered to be part of the ingredients of making new materials that include recycled contents, and by allowing it to be part of the ingredients, two benefits might be achieved; firstly, the diversion of waste from the solid waste streams, and secondly, the reduction in demand for virgin resources. By virtue of recycling, the final product contains a percentage of what used to be called waste, and the physical characteristics of the recycled material are known to the product designer a priori. This information and data are widely accessible and ready to be specified for new architectural products similar to any other conventional materials. From the regulatory point of view, there are four methods of legislation for recycling: minimum recycled content mandates, utilization rates, procurement policies and recycled product labeling. As a result, manufacturers have to provide all pertinent data of these materials in a manner that is similar to the non-recycled materials. Recycled material can be cataloged for which a standard set of data is available, just like any standard building product (Ali, 2017).

In contrast, reused materials require unique and special data and information that are customized for the source, quantity and the destination of the material. These data and information are highly dynamic and constantly changing. Currently, the management of

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the supply-chain process for reused material does not easily support the acquisition of this information, which inhibits the implementation of material reuse integration and adoption at a larger scale. The fact that there has been no legislation on resources reuse similar to those on recycle adds to the complexity of the issue. It is the intent of this study to showcase the benefits of reuse over conventional recycling processes in a material that is globally considered as one of the most recycled.

1.2. Current status of steel recycling and reuse

Today, a significant portion of steel production comes from recycling activities. Approximately 35% of the world's steel is currently made from scrap sources and the other part is from newly mined ore (Allwood et al., 2010; IEA, 2010). When it comes to energy consumption, generating liquid steel from scraps requires about 1/3 of the primary energy of making steel from virgin ore and emits less than 1/4 of total CO_2 emissions (Ayres, 2006; L. McDonald, Ellis & Moore Consulting Engineers, 2003). That significant amount implies the necessity for finding alternative solutions over recycling metal scrap. Furthermore, recycling steel can only save approximately 50% of the energy required and CO_2 emissions over making new steel from virgin materials (Dunant et al., 2018; Norgare, 2007). However, the process of steel recycling is still energetically expensive, which can include, but not limited to, processes such as sorting, de-galvanizing and smelting with a minimum melting temperature around 1500 °C. It is anticipated that reusing metal scrap with minimum alteration and without melting will lead to significant energy and CO_2 emission savings and therefore should get more attention from research scientists, government entities, and the private sector. Experience shows that re-fabricated steel components from the process of reuse can be as good as new steel (L. McDonald, Ellis & Moore Consulting Engineers, 2003) and re-fabrication can be easily achieved by conventional fabricators (Geyer and Jackson, 2004).

Considering the environmental and economic benefits of reusing scrap, the idea of incorporating metal scrap reuse within a circular economy approach has already been initiated and tested particularly in Europe and China (Dunant et al., 2018; Densley Tingley et al., 2017; Liu et al., 2018; Tilwankar et al., 2008; Pongiglione and Calderini, 2014; Gorgolewski et al., 2006). Although steel recycling is a common practice in the United States, the country is lagging behind in terms of implementing the concept of circular economy, especially the reuse of steel scrap materials (L. McDonald, Ellis & Moore Consulting Engineers, 2003; Fenton, 2001; Yellishetty et al., 2011; Sibley and Butterman, 1995). The authors argue that it is critical for the U.S. to stop promoting the typical throw-away practices and start paying more attention to circular economy strategies and regulations that can save energy and reduce CO_2 emissions over the long term.

During the year of 2017, raw steel production was about 82 million tons in the United States (Pacelli et al., 2015). Therefore, recycled steel scrap is a vital processed material for the production of new steel products with the potential of replacing more than 30% of virgin material (Ali, 2017; Densley Tingley et al., 2017). The primary source for steel scrap includes approximately 58% post-consumer (old, obsolete) scrap, 24% prompt scrap (produced in steel-product manufacturing plants), and 18% home scrap (recirculating scrap from current operations) (Fenton, 2018). Among the 24% prompt scraps, recent studies on metal scraps showed that stamping operations, particularly in the automobile industry, generate a large amount of steel and aluminum scraps (Ali et al., 2018; Koros et al., 1995; Ali and Kio, 2018). Furthermore, there currently exists a relatively mature recycling loop and supply-chain for steel production from recycled steel scraps in the United States. However, similar concepts and systems are lacking in steel scraps reuse, even though reusing steel scraps can be identified as a promising opportunity that can result in significant energy reduction, CO_2 and capital savings. For those reasons, this study focused on the by-products steel scraps generated from the manufacturing process in the automobile industry.

1.3. Standard sheet metal scrap flow

According to a recent report published by the Grand View Research group, the world's largest and most trusted market research database, the market size of global metal stamping (a manufacturing term for forming sheet metal) was estimated at 204.6 billion dollars in 2016 and is expected to reach 299.6 billion dollars by 2025. The increasing use of sheet metal particularly in the automobile and consumer electronics industries is expected to drive the demand for stamping processes due to their use in the fabrication of the automobile chassis, transmission components, and interior & exterior structural components of electronics. Technological innovations in the form of improved stamping processes have seen commercial usage in the recent past. In addition, regulatory policies aimed at improving working conditions and safety standards, waste disposal, and materials used are imperative for shaping growth and sustainability strategies of the stamping companies over the forecast period. The sheet metal scrap discussed in this paper is limited to the category of bulky ferrous metals consistently generated from the automobile industry, known as “offal.” Offal is a surplus material generated by blanking operations as seen in Fig. 1. The by-product is a resilient material comprising of light-gauge steel sheet with a layer of zinc coating on both sides (approximately 60 μm); which it has been galvanized by either hot-dipped galvanization or electro-galvanization processes.

1.4. Sizable galvanized steel scrap from General Motors Company

According to Koros et al. (1995), 1.6 million tons of steel scrap per year were generated at General Motors Company (GM) in 1995. Today, the same blanking and stamping processes of sheet metal still generate an enormous volume of galvanized steel scrap. This waste-flow is generated as consistently sized; high-quality irregular shaped sheets that are produced when windows and other car components are stamped out of body panels on the assembly lines. Because of their predicted volume and consistent size, shape, and quality, these pieces are assumed to be valuable for much more than the traditional scrap market value. Offal pieces are usually sized between 0.5 mm and 3.2 mm thick, have various coatings thicknesses (mostly zinc), and totalled at 1500 metric tons per year. Promising cost-benefits are available through the reuse of these materials. One plant in Flint, Michigan for example, generates approximately 40,000 pieces per month in about 11 different shapes and sizes (Fig. 1). In 2014, General Motors (GM) claimed that it generated nearly one billion dollars in annual revenue through reusing and recycling its by-products and avoided releasing over 10 million tons of CO_2-equivalent emissions into the atmosphere.

The steel scrap discussed herein is generated and provided for research by GM. The sizable scrap from the blanking operations corresponds to the different car designs and models made by GM, as shown in Fig. 1. It is primarily generated when blanking out the car windows, openings, and doors parts. The American Society for Testing and Materials (ASTM) has guidelines for treatment of manufacturing metal scrap stated in ASTM E702. Moreover, this study is limited to standards governing galvanized sheet metal for the automobile industry. With the example of reusing waste steel scraps from GM, the analysis and methodology used in this study can be scaled up to all companies in the automobile industry

Fig. 1. Sizable Sheet metal scrap from General Motors (GM) in 11 different sizes and shapes.

around the world, which could yield a large amount of energy and CO_2 emission savings.

1.5. Issues of scrap metal de-galvanization

The recent trade conflicts between the U.S. government and other nations that started when the Trump administration imposed tariffs on imported steel and aluminum is causing a lot of concerns in many circles. Aside from the politics regarding steel and aluminum imports, to justify reusing galvanized sheet metal over de-galvanizing and recycling it, one must first understand the recycling process within the scope of energy consumption. Scrap drives were first embarked on during the war days. Packard Motor Car Company started the first scrap-collection drive program among its dealers. GM followed a month later with a similar campaign. Since then, de-galvanization techniques have been developed; however, the technical and economic feasibility of available de-zincing technologies pales in comparison to the practicality of material reuse. In fact, the cost of de-galvanizing steel is overwhelmingly high. For that purpose, this study focuses on the size-predicted scrap accrued during the production of stamped sheet metal in making automobile body parts. It is worth noting that the auto industry generates a high-quality uniformed scrap, which makes it a favorite to the many steel mills that purchased the material for recycling (Lawrence, 2016). Galvanized sheet metal used in the automobile body typically consists of a carbon steel sheet coated with zinc on both sides during the continuous hot-dip process. The process results in a tightly adhered layer of zinc on each side of the steel sheet through diffusion-driven bonding of molten zinc. By reusing galvanized steel, the energy necessary for de-zincing during recycling can be saved. Furthermore, galvanized sheet metal requires no maintenance during the first 60-year life due to its durability and resilience; therefore, the scrap metal can be reused in building applications as well.

It is worth noting that de-galvanization is beneficial in the recycling of galvanized steel to avoid the problems associated with re-melting of large amounts of galvanized steel scrap (Dudek and Daniels, 1993). During de-galvanization, steel and zinc are separated and recovered effectively. Even though recycling and de-galvanizing steel scrap can save energy and minimize zinc imports, if the galvanized steel can be reused directly without de-galvanization, cost and energy can be saved considerably.

1.6. Metal cladding for building facade systems

Metal has been used for assemblies and ornaments in buildings for more than 9000 years. In the 19th century, the use of metal grew substantially, and metal was used for exterior applications including cornices and storefronts (Dudek and Daniels, 1993). The interest in sheet metal as a cladding material grew substantially with the technological advancement in galvanizing techniques. Metal cladding made from galvanized steel was adopted because painting alone was not sufficient to protect metals from corrosion effects over an extended period of time. Exterior cladding was perceived as lightweight, non-load bearing (acting as a skin in buildings), and able to be used as a breathing barrier in buildings, allowing air and daylight to pass through. The introduction of galvanized sheet metal cladding accelerated construction time and enabled designers to introduce more significant building spans and more complex shapes (Howell, 1988; Ferretti et al., 1976). For example, the Alcoa Company in Pittsburgh had a keen interest in the use of sheet metal for exterior walls, which eventually led to its use in the company's headquarter high-rise building (Yeomans, 1998). In the last decade, metal fabricators in the United States such as Zahner have shifted their focus to architectural metal surfaces and have assisted well-known architects in the realization of their work. Even though development of sheet metal cladding systems has benefitted from digital fabrication processes, reliance on sheet metal production methods and the typical open-loop supply chains has remained unchanged.

1.7. Problem statement

In this study, an innovative method for developing building metal facade by reusing sizable galvanized sheet metal scrap from the automobile industry is proposed and analyzed, which can be adopted by architects, product designers, and industry engineers. The method provides new technological and commercial opportunities for efficient materials transfer between two different industries, by enabling the consistent waste-to-raw material flow from the automobile industry to the building construction industry. Industrial Symbiosis is defined as a form of brokering to bring companies together in innovative collaborations, finding ways to use the waste from one as raw material for the other. Therefore, the proposed method in this study would contribute to the development of Industrial Symbiosis between the automobile industry and the building construction industry. Under the framework of circular economy, which is an alternative to a traditional linear economy (fabrication, use, disposal) resources are kept in use for as long as possible by extracting their maximum value while in use. Then, materials are recovered and used to generate products and materials at the end of each service life. The method proposed in this study can be used to identify a key area of potential Circular Economy development between the auto and the building industries by recovering and regenerating building construction products, while creating maximum value for the steel scrap materials used in the automobile industry.

In summary, this study focuses on the following:

- In addition to the well-established definition and goals of circular economy proposed by Ellen MacArthur Foundation, which include material reduction, recycling and reuse, this study specifically addresses the reuse of galvanized steel through a value-added approach in a practical case.
- Promotes the reuse of steel scrap wastes from the automobile industry to generate innovative products for the building construction industry
- Facilitate Industrial Symbiosis between the automobile industry and the building industry
- Enables the creation of a by-pass supply-chain loop for scrapped galvanized steel, thus minimizing the need for recycling

In summary, the study is based on the principles of circular economy, in which segments of the material flow loops are strengthened by improving the reusability of processed materials. The proposed approach does bring about effective cost and energy savings by improving a segment in the circular economy loop of galvanized steel while preserving its material properties.

2. Material and methods

2.1. New recovering path for by-products steel scrap generated from the automobile industry

In this study, a viable approach for reusing sizable steel scrap from the manufacturing process in the automobile industry for environmental and economic advantages is presented. Fig. 2 shows the current recycling loop status for steel scrap and rejects from the automobile industry. Metal scrap is collected and smelted to make new raw steel material. Also, the steel material flow related to the automobile industry has been quantified as shown in Fig. 2 based on the concept of material flow analysis. According to (Ali, 2017; Ali et al., 2018; Ali and Kio, 2018; Densley Tingley et al., 2017; Fenton, 2018; Koros et al., 1995), approximately 9.8 million tons of steel materials will be consumed by the automobile industry per year in the United States and 5.7 million tons of steel scrap prompts will be generated per year during the manufacturing process in the automobile industry. The 5.7 million tons of steel scrap materials can then be recycled and reused to produce new raw steel materials.

As previously discussed, reusing the waste steel scrap could be more beneficial in certain industrial applications. Therefore, an innovative and alternative recovering path is proposed by reusing, instead of recycling, the same steel scrap wastes from the automobile industry to make building metal facade product, as shown in Fig. 3. The reusing path for the by-products metal scrap is highlighted in red color. Same as it is demonstrated in Fig. 2, quantitative material flow is presented in Fig. 3, based on (Koros et al., 1995), 1.6 out of 5.7 million tons per year of steel scrap materials from the automobile industry are assumedly reused in designing and producing building metal facade exteriors. Accordingly, in the proposed approach, architects and engineers work together and design conceptual metal facade products made by reusing waste steel scrap from the automobile industry. In such a creative way of reuse, not only the value of waste steel scrap is preserved but also added new value is generated with the design and fabrication of new industrial products. For this study, products were designed, fabricated and later evaluated in terms of required cost and energy consumption to showcase the tangible benefits of the approach. With the design and fabrication of metal building facades, the potential and feasibility of designing new industrial products by reusing materials can be showcased, when a reusing operation is economically and environmentally valuable. Furthermore, collaboration between industrial designers and engineers is imperative but sometimes challenging to achieve when designing new products (Fenton, 2018; Rio et al., 2012). Therefore, this study also provides guidance for industrial designers and engineers to work together efficiently.

Starting with the original galvanized sheet metal scrap shown in Fig. 1, architects created conceptual metal building facades by maximally and efficiently reusing the sizable sheet metal scrap. For the same building metal facade product, the required energy and capital cost for making the product by reusing or recycling waste steel scrap from GM was compared as shown later, which demonstrates that reusing steel scrap material is more environmentally and economically efficient than recycling. Furthermore, the manufacturing feasibility, fabrication cost, and energy consumption of each building metal facade design were investigated by mechanical engineers, who provided design feedback during the iterative design process. In fact, several design iterations were collaboratively conducted between the architects and engineers during the design phase. As a result, reduced fabrication cost and lower energy consumption for making each product were achieved.

2.2. Methodology to evaluate the building metal facade product made by reusing steel material

To quantitatively compare the cost and energy consumption for practically creating an identical metal building facade product by reusing and recycling the waste steel scrap from GM, mathematical models based on energy consumption and fabrication cost were developed.

The required capital cost for making a new metal building facade product by recycling of the waste steel scrap from GM can be estimated by the following equation, as postulated by (Dunant et al., 2018),

$$C_{recycling} = C_I + C_{th} + C_S + C_1 + C_F \quad (1)$$

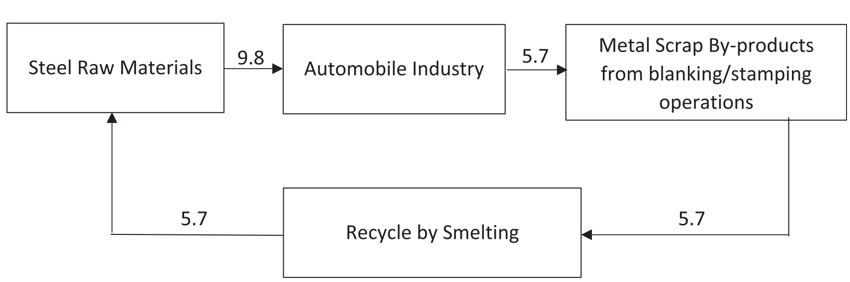

Fig. 2. Current recycling loop with material flow analysis for the automobile industry metal scrap in United States (million tons/year).

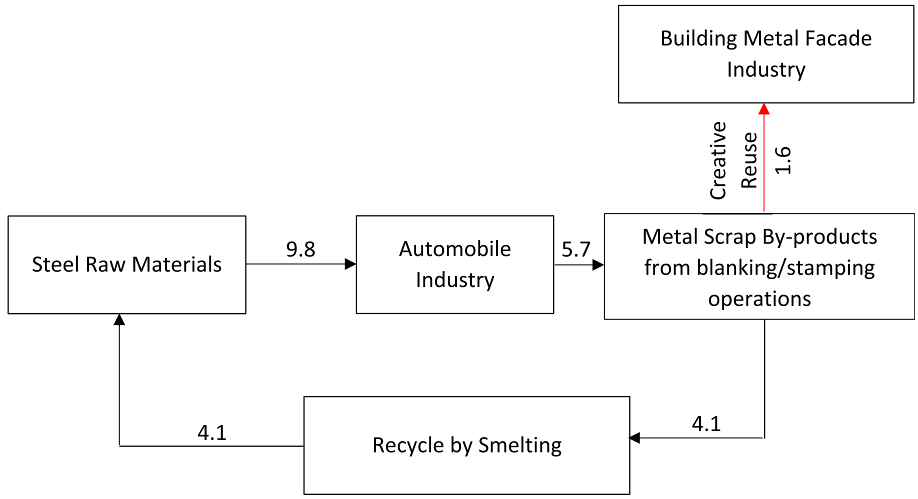

Fig. 3. An alternative path with material-flow analysis for recovering the automobile manufacturing scrap metal in United States (million tons/year).

Where C_I is the market price GM sales their waste steel scrap material, C_{th} is the price for transportation and handling, C_S is the smelting cost, C_1 is the price for reconditioning and processing, C_F is the price for fabrication, as shown in Fig. 4.

The required capital cost for making the identical building metal facade product by directly reusing waste steel scrap material provided by GM can be estimated by the following equation, which was also postulated by (Dunant et al., 2018),

$$C_{reusing} = C_I + C_{th} + C_F \quad (2)$$

Where C_I is the market price GM sales their waste steel scrap material, C_{th} is the price for transportation and handling, C_F is the price for fabrication, as shown in Fig. 5.

Therefore, for making the identical metal building facade product, the potential capital cost savings by reusing waste steel scrap from GM can be expressed as follows:

$$\Delta C = C_S + C_1 \quad (3)$$

As Equation (2) shows, there is no smelting cost C_S if the waste steel scrap is reused instead of recycling it. Also, by directly reusing the waste steel scrap from GM, the reconditioning and processing cost C_1 can be avoided. The transportation and handling cost C_{th} was assumed to be the same for comparison purposes. Numerical results based on the equations are presented later in the case study section.

The required energy consumption for fabricating a building metal facade product by recycling GM waste steel scrap can be estimated using the following equation based on (Gao et al., 2001):

$$E_{recycling} = E_M + E_{th} + E_1 + E_F \quad (4)$$

Where E_M is the required energy for smelting the recycled waste steel scrap, E_{th} is the required energy for transportation and handling, E_1 is the energy consumption of re-conditioning and testing, E_F is the energy consumption of fabrication, as shown in Fig. 6.

The required energy consumption for fabricating the identical metal building facade product by reusing waste steel scrap from GM can be estimated using the following equation based on (Gao et al., 2001):

$$E_{reusing} = E_{th} + E_F \quad (5)$$

Where E_{th} is the required energy for transportation and handling, E_F is the energy consumption of fabrication, as shown in Fig. 7.

Therefore, to fabricate the identical metal building facade product, the energy consumption savings by the proposed reuse methodology when compared with recycling can be expressed as follows:

$$\Delta E = E_M + E_1 \quad (6)$$

Since there is no smelting process in the reuse process, E_M will be saved. The galvanized steel scrap provided by GM can be directly used in the metal building facade design without re-conditioning and testing so that E_1 can be saved as well. The energy consumption for transportation and handling can be assumed to be the same for the recycling and reusing cases. More detailed information is presented in the case study section.

3. Bio-inspired (Voronoi) metal facade system case study

3.1. Creatively design a building metal facade product by reusing the waste steel scrap from GM

To maximally and efficiently reuse the waste steel scrap material from GM as shown in Fig. 1 and create a new path for recovering the value of waste steel scrap material, conceptual metal building

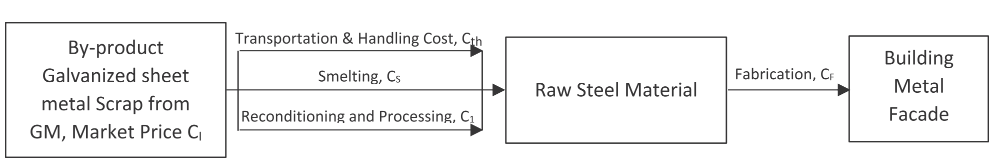

Fig. 4. Capital cost flowchart for making a building metal facade product by recycling steel scrap material.

Fig. 5. Capital cost flowchart for making a building metal facade product by reusing steel scrap material.

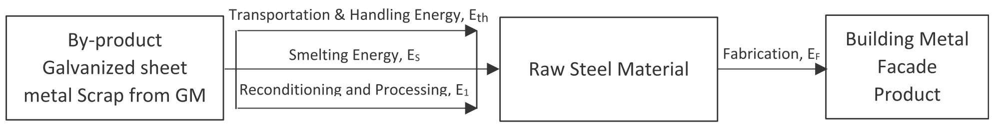

Fig. 6. Energy consumption flowchart for making a building metal facade product by recycling steel scrap material.

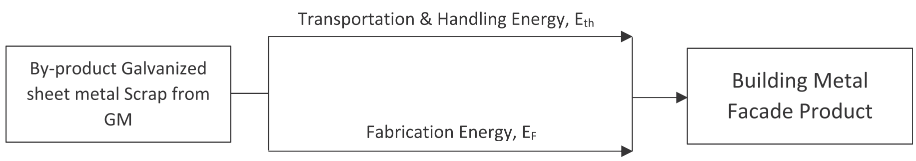

Fig. 7. Energy consumption flowchart for making a building metal facade product by reusing steel scrap material.

facade design was conducted through cooperation between architects and mechanical engineers. A bio-inspired building metal facade design was selected for the case study to illustrate the benefits of reusing waste steel scrap to make metal building facade products. Several design iterations were carried out by architects and engineers working together, to reduce the cost and energy consumption for making a building metal facade product.

In many instances, architects and designers are often inspired by nature and its mode of operation in their design process. For example, a "Voronoi" mathematical patterns are prevalent in animal skins and other natural phenomena, which were the basis for the winning entry for the redevelopment of The Arts Centre Gold Coast in Sydney, Australia. A "Voronoi" diagram, known as Voronoi tessellation, is a partitioning of a plane into regions based on distance to points in a specific subset of the plane. That set of points (called seeds, sites, or generators) is specified beforehand, and for each seed there is a corresponding region consisting of all points closer to the seed than to any other. Fig. 8 shows some intriguing natural patterns, which can be referred to the "Voronoi" diagram.

There are also many contemporary architecture works inspired by the "Voronoi" pattern. The Fry building sunscreen facade in the School of Mathematics building at the University of Bristol, United Kingdom, shown in Fig. 9 is a good example of a Voronoi-inspired design. Similarly, a conceptual building metal facade design was considered for this study, as shown in Fig. 10, to maximally and efficiently reuse the area of sizable sheet metal scrap (Offal) generated by GM while preserving the decent Voronoi building metal facade appearance and functionality. The sizable galvanized sheet metal scrap was directly re-fabricated (cut, punched, and bent) and assembled as a Voronoi patterned metal facade unit. During the fabrication process, the sheet metal scrap was formed into proper shapes. The material was edge folded and holes punched in order to connect the Voronoi cladding panels together before completely generating the metal facade product. Fig. 11 shows the fabrication design scenarios of the "Voronoi" patterned building metal facade. Each Offal from the 11 different shapes and sizes provided by GM was mathematically optimized and maximized to generate a Voronoi polygon. Folding the Offal 90° allowed for the panels to be assembled (connected), to form a larger façade wall. The red lines show the edges for folding while the blue lines show the cutting path. Also, there are punched holes along the profile of the metal piece necessary for jointing.

3.2. Quantitatively evaluate the metal facade design and compare making the identical product by reusing and recycling waste steel scrap material from GM

To understand and demonstrate the value of making building metal facade using reused instead of recycled galvanized sheet metal from automobile industry, the required total cost and energy

Fig. 8. Inspiring Voronoi patterns found in nature.

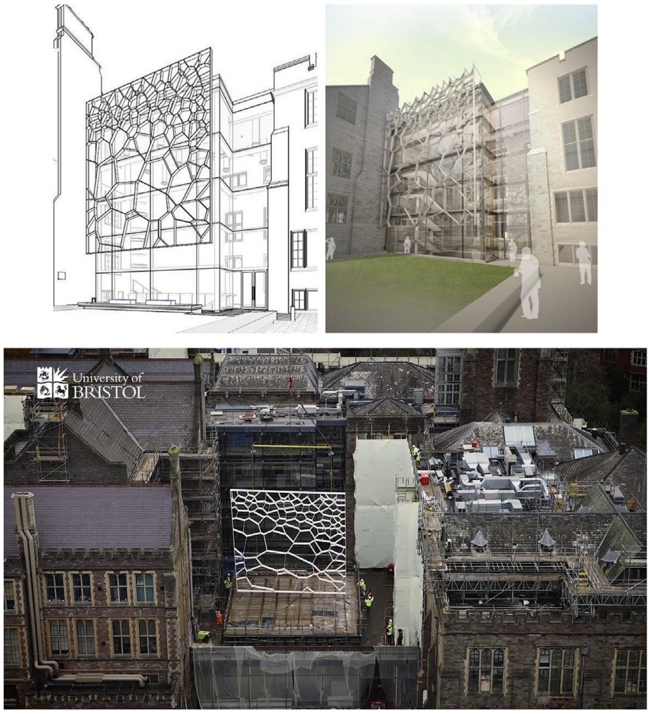

Fig. 9. Voronoi pattern in architecture: Fry building sunscreen facade, School of Mathematics, University of Bristol, United Kingdom.

consumption of producing the Voronoi cladding system was quantitatively estimated.

The required total capital cost for a designed metal facade product can be estimated using Equations (1) and (2) for the case of using reused steel scraps from GM and recycled steel materials from the market, respectively. In Equations (1) and (2), the average market value for GM steel scraps was set at 0.18 $/kg ($C_I$). The transportation, handling costs, re-conditioning and processing costs (C_{th} and C_{RT}) were approximated based on Table 1 of (Dunant et al., 2018). In this study, an average transportation cost value was applied, but the transportation cost does depend on a variety of factors such as the type of transportation carrier, the location of destination and the transportation distance. The estimated average transportation distance was assumed to be 100 km for comparison purposes. A typical value of 300 $/ton was used for the steel smelting cost (C_M) if the GM steel scrap was recycled.

The required fabrication cost (C_F) in Equations (1) and (2) was evaluated individually based on different types of fabrication processes. For cutting, a Computer Numerically Controlled (CNC) waterjet cutting machine from OMAX Corporation (OMAX Maxiem 1530) was used. The total cutting cost including both machine and labor costs for a certain metal facade product can be calculated based on the actual machine operating data as shown in Table 1. The data were acquired directly from the software that controls the waterjet cutting machine while cutting a sample of galvanized steel scrap provided by GM. An example of the data generated by the machine and software is shown in Fig. 12. The waterjet cutting machine data shown in Table 1 takes into account the type of

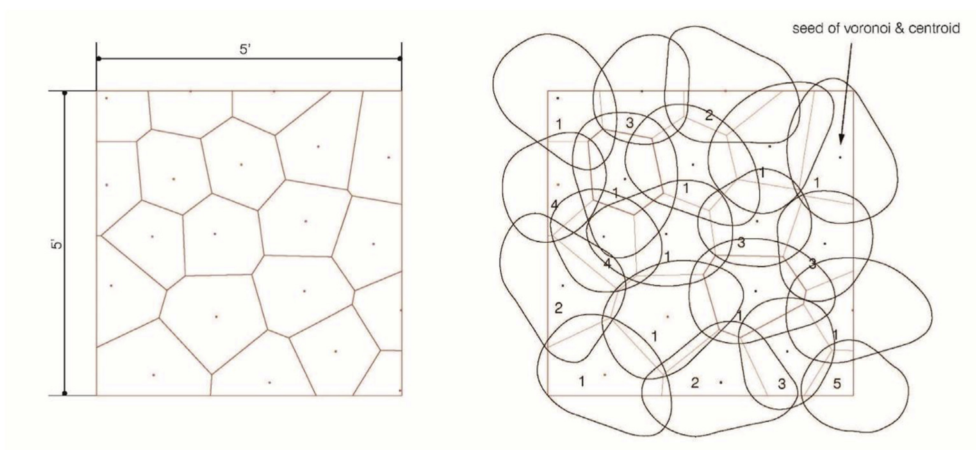

Fig. 10. Schematic drawings of a Voronoi building metal facade design unit (figured provided by Kawagashira).

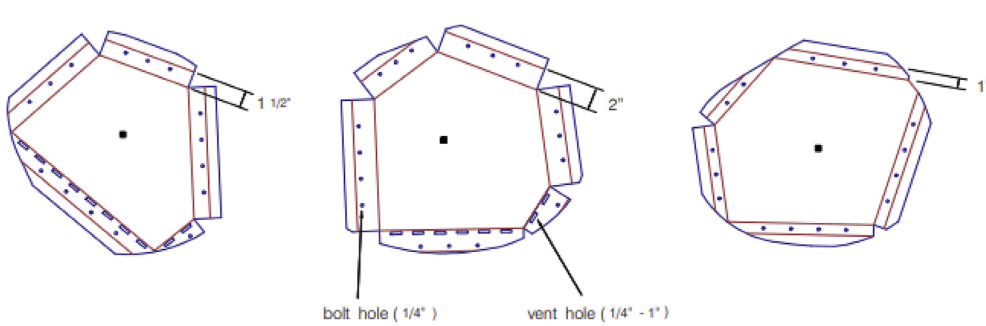

Fig. 11. Voronoi metal facade fabrication design drawing (1st design iteration) (figure provided by Kawagashira).

Table 1
Real Maxiem 1530 waterjet data for cutting galvanized sheet metal scrap.

Material	Galvanized sheet metal	High Pressure Setting	310.3 MPa
Thickness	0.1 cm	Abrasive Flow Rate	0.3 kg/min
Estimated Time for Path	27.26 min	Average Speed When Cutting	68.9 cm/min
Estimated Cost for Path	US $68.16	Length of Tool Path	1862.4 cm

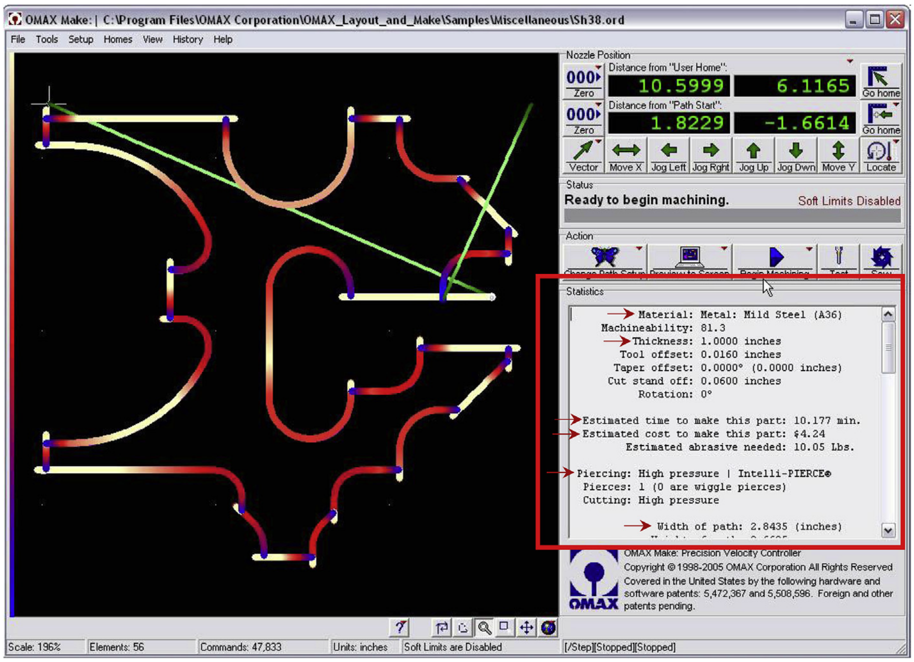

Fig. 12. Omax Maxiem 1530 water cutting machine operation settings display screen.

material being cut and the thickness of the sheet metal. The waterjet cutting machine and the approach of data acquisition can be applied to other sheet metals by specifying materials and process variables in the software. In general, the thicker the sheet is, the longer it will take for the machine to cut the material.

A manual pan & box brake was used for bending operations of the metal facade system prototype. It is anticipated that a die with an automated bending operation will be used for mass production of the system. The corresponding bending cost can be estimated as the sum of machine and labor costs, which can be calculated based on the required bending force, power and time for each bending in each metal facade unit, as presented in following equations:

$$F = \frac{K \cdot TS \cdot w \cdot t^2}{D} \tag{7}$$

$$P = F \cdot V \tag{8}$$

$$T = BD/V \tag{9}$$

where *F*, *K*, *TS*, *w*, *t*, *P*, *V*, *T*, *BD* are required bending force per bend, bending coefficient (1.33 for V-bending, 0.33 for edge bending), tensile strength of the galvanized sheet metal, part width in direction of bend axis, thickness of the sheet metal, required bending power per bend, the operational speed of the bending machine, the required time for each bend and the bend dimension, respectively (Kalpakjian, 2003; Groover, 1996; Chang, 2006). A minimum machine operating time was used in the calculations and therefore, the estimated total bending cost and energy consumption were considered to be a relatively conservative values. The total energy, and total cost for bending is the sum of the costs of all the Voronoi metal facade units, which can be obtained based on the number of bends and the number of units in a metal facade product.

An automated punching machine was assumed to be used for punching holes on the sheet metal scraps for connecting and jointing the integrated building metal facade product. The cost of hole punching is the sum of machine and labor costs, which can be calculated based on the required power and time, as shown in following equations:

$$F = \pi \cdot d \cdot t \cdot s \tag{10}$$

$$P = F \cdot V \tag{11}$$

$$T = t/V \tag{12}$$

where *F*, *d*, *s*, *t*, *P*, *V*, *T* are required punching force per punch, diameter of the punching hole, shear strength of the steel scrap sheet, thickness of the steel scrap sheet, required punching power per punch, the operational speed of the punching machine and the required time for each punch, respectively (Kalpakjian, 2003; Groover, 1996; Chang, 2006). Similar to the analysis of the bending operation, a minimum machine operating time was applied in the calculation of hole punching and therefore the estimated total punching cost and energy consumption are considered to be a relatively conservative value. The total energy, and total capital cost for punching operations is the sum of the costs of all metal facade units, which can be obtained based on the number of punches and the number of units in a metal facade product.

Fig. 13 shows a prototype unit of the Voronoi metal facade design after all the fabrication operations including cutting, bending and hole punching. It is the realization of the proposed schematic design shown in Figs. 10 and 11.

4. Results and discussion

4.1. Comparison of capital cost between reusing and recycling by-products galvanized sheet metal scrap from GM to make identical building metal facade product

The total cost for achieving the Voronoi metal facade product by reusing and recycling GM sheet metal scrap was compared, as shown in Fig. 14.

As illustrated in Fig. 14, the cost for making the same metal facade product was lower for reusing galvanized sheet metal scrap from GM than recycling the same scrap. The savings are approximately about $400/ton. According to the steel scrap material flow analysis shown in Figs. 2 and 3, and assuming that 1.6 million tons per year of steel scraps will be reused for producing building metal facades rather than recycling it, the direct savings will be approximately 640 million US dollars per year. Another important observation is that the fabrication cost accounts for a significant percentage of the total cost of the product, even though the fabrication costs were the same for both the reusing and recycling cases. However, generally speaking, the fabrication cost of a product highly depends on the design; for example, the length of all the cuts and number of holes/punches in each design plays a decisive role in the overall cost calculation.

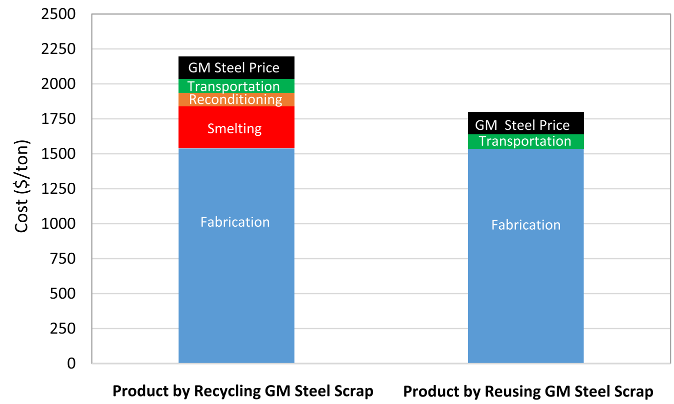

Fig. 14. Required cost of making the Voronoi metal facade by reusing or recycling the same GM steel scrap.

4.2. Comparison of required energy consumption between reusing and recycling GM sheet metal scrap to make identical building metal facade product

Besides investigating the total cost required to fabricate a metal facade product, it is also important to estimate the required total energy consumption, which has a significant impact on energy resources and CO_2 emissions on the environment. The required energy consumption for making the above Voronoi metal facade system by reusing GM steel scrap or recycling the same scrap can be evaluated by using Equations (4) and (5), respectively. In Equations (4) and (5), the energy consumption to process the recycled sheet metal scrap into new material ($E_M + E_1$) was approximately 11 MJ/

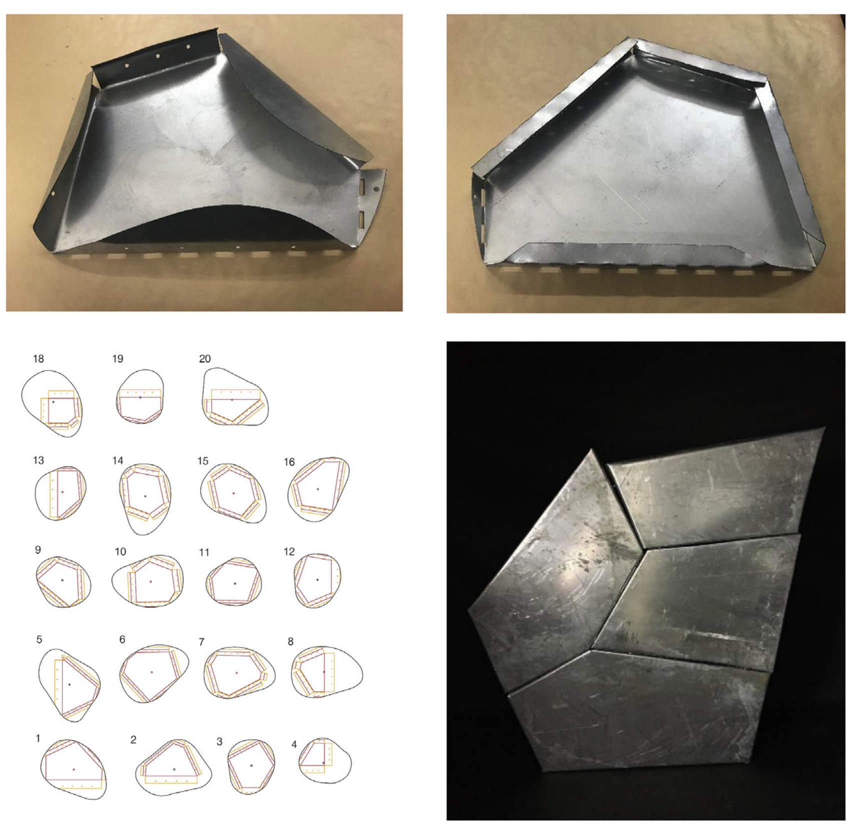

Fig. 13. A prototype of Voronoi patterned metal facade unit (figures provided by Kawagashira).

kg based on Table 3 of (Gao et al., 2001). The transportation and handling energy consumption (E_{th}) was estimated using equation (2) in (Gao et al., 2001). The fabrication energy consumption was obtained based on Equations (7)-(12) and the real CNC waterjet cutting machine data as shown in Table 1.

The total required energy consumption for fabricating the Voronoi metal facade system by reusing and recycling GM galvanized sheet metal scrap was compared and shown in Fig. 15.

As illustrated in Fig. 15, the total energy consumption for making identical metal facade product was lower when the sheet metal scraps from GM were reused. The difference between the two cases is approximately about 10000 MJ/ton. Based on the steel scrap material flow analysis shown in Figs. 2 and 3, and assuming 1.6 million tons per year of steel scraps will be reused for producing building metal facades rather than recycling it, the energy savings will be approximately 16000 MJ per year in the United States alone by following this innovative and alternative steel scrap recovering method. It can also be seen that the fabrication and transportation energy consumptions are the same for both cases and only account for a relatively small portion of the total energy consumption. The main reason for the energy consumption difference is due to steel smelting, which is quite large and can be saved if the GM steel scrap is reused and not recycled.

4.3. *Further reduction of required cost and energy consumption for Voronoi metal facade with additional product design iteration*

As illustrated in both Figs. 14 and 15, the fabrication process accounts for a significant portion of the total cost and energy consumption of the metal facade system no matter if the GM steel scrap is recycled or reused. Furthermore, the fabrication energy consumption is relatively small compared with the smelting energy consumption when GM steel scrap is recycled, but the amount of fabrication energy still is significant in the reusing case. Therefore, it is wise to revise the design to reduce the fabrication time and energy in order to reduce the total cost and energy consumption of the metal facade product. Accordingly, several design iterations were undertaken to improve the Voronoi metal cladding system design.

The schematic drawings of the first and second design iterations for the Voronoi metal facade are shown in Fig. 16 (a) and (b), respectively. As it can be observed in the second design iteration, the length and number of cuts in the unit were reduced. Also, fewer holes were required in the unit after the second design iteration.

The cost and energy consumption of the same product before and after design iterations were estimated using Equations (7)-(12)

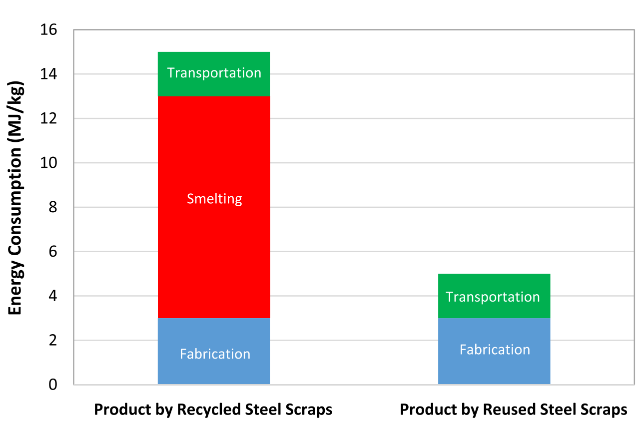

Fig. 15. Energy consumption of making the Voronoi metal facade by reusing or recycling identical GM steel scrap.

and the real CNC waterjet cutting machine data shown in Table 1. Figs. 17 and 18 show the revised cost and energy consumption of the unit after the design iteration. It can be observed that with certain design improvements, such as decreasing the length and number of cuts, and changing the type of assembly, approximately more than 30% of cost (18 $/ton) and energy consumption (600 MJ/ton) can be saved for fabricating identical metal facade product by reusing GM galvanized sheet metal scrap. According to the steel scrap material flow analysis shown in Figs. 2 and 3, 1.6 million tons per year of steel scraps could be reused for producing building metal facades. Conservatively assuming 18$/ton and 600 MJ/ton for average cost and energy reductions by improving the building façade design shown in Fig. 16, the total cost and energy savings could be as high as 29 million dollars in saved material cost and 960 MJ per year, respectively. More importantly, most of the fabrication costs and energy consumptions in this study were based on single manual operations, which did not consider the possibility of mass production. Therefore, if mass production of the metal facade system is considered, the total cost and energy consumption for making the identical product will be significantly reduced.

5. Conclusions

This study introduces a novel approach in structuring an industrial symbiosis and synergistic circular economy between non-hazardous automobile by-products and the building industry. Particularly, the approach is suitable for creating a bio-inspired building facade system (Voronoi) from galvanized sheet metal waste-flow generated from the automotive industry.

To justify the reuse over recycling of galvanized sheet metal, this study has also shown promising energy and cost savings associated with material reuse. The results of the investigation revealed that the design based on the reuse of galvanized sheet metal has a direct effect on the overall fabrication cost. In the future, sizable scrap management can include more designs and fabrication processes centered on reuse. Eventually, an industrial symbiosis influenced by circular economy will be further established with the potential elimination of this particular type of industrial waste.

In this article, a case study for designing and making a systematic building metal facade by reusing galvanized sheet metal scrap from the automobile industry has been presented. The study demonstrates an innovative and alternative recovering path for sizable metal scrap from the automobile industry, which has the potential for growth and development. Analytical results quantitatively showed that the capital cost and energy consumption were 40% (400 $/ton) and 67% (10000 MJ/ton) less, respectively, for producing an identical building metal facade system by simply reusing sheet metal scrap from General Motors Company, rather than recycling it. Also, the cost and energy consumption of the metal facade product can be further reduced by approximately 30% (18 $/ton and 600 MJ/ton) by simply redesigning minimal aspects of the original building façade.

Therefore, this study raises the awareness among product designers, engineers, and architects when considering material reuse as a viable alternative to just mere recycling of by-products steel scrap from the automobile industry. This in turn would save natural resources and create new jobs while promoting environmental quality and circular economy. More importantly, since the engineering methods and mathematical equations used in the study are well-established, they could be used by architects and engineers as general guidelines and analysis tools for similar industrial applications. This is particularly applicable in the reuse of sheet-type waste materials such as cardboards and rubber sheets, which could be used to produce new products through mechanical operations such as cutting, bending, and folding.

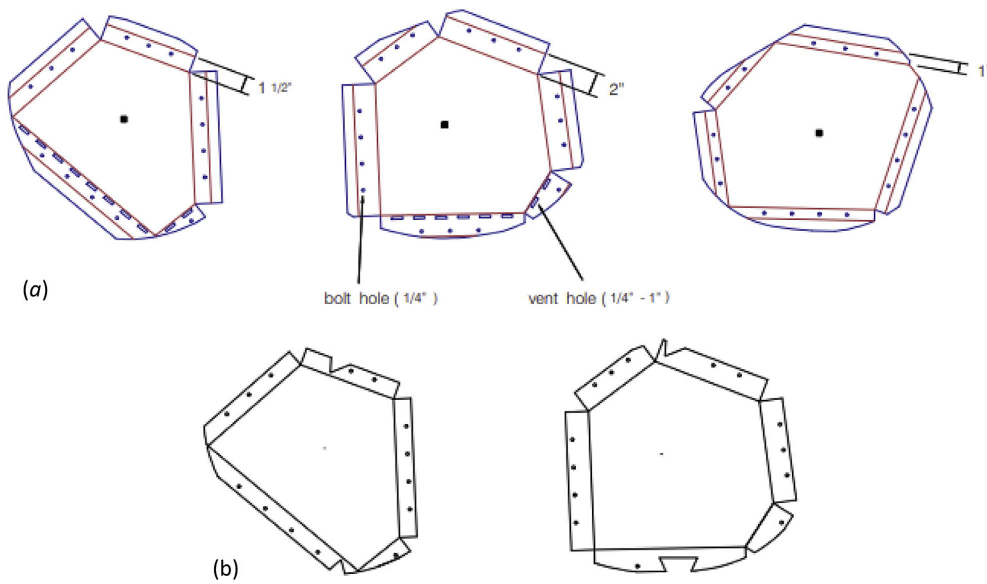

Fig. 16. Voronoi patterned metal facade fabrication design drawing: (a) first design iteration (b) second design iteration (figures provided by Kawagashira).

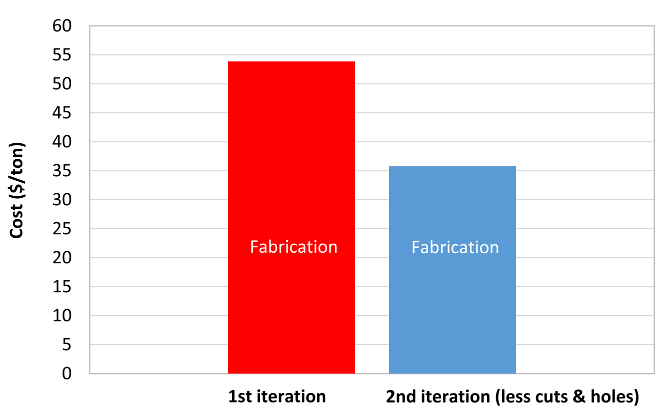

Fig. 17. Comparative required cost for metal facade product before and after design improvements.

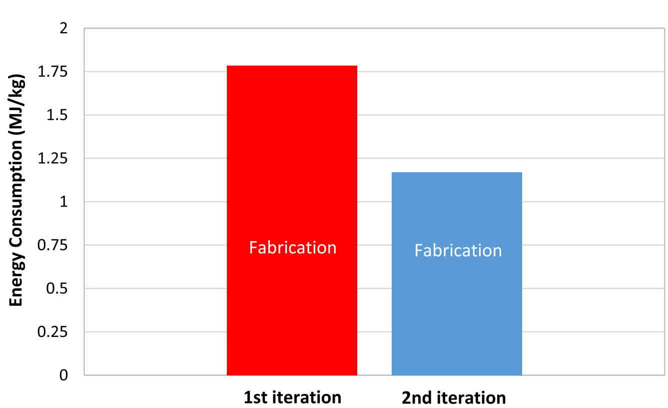

Fig. 18. Comparative required energy consumption for metal facade product before and after design improvements.

In summary, it is through such a systematic approach, that a true closed-loop supply chain of materials can be activated between two different industries, even after applying maximum optimization standards. Further investigations and studies will be conducted to scale-up the presented ideas to different manufacturers and industries.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.202.

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