

Finding Perfection in Imperfection: A Case Study of Adding Value by Design in Circular Economy

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ABSTRACT: The United States' manufacturing industry generates approximately 7.6 billion tons of non-hazardous solid waste each year, a significant portion of which is either recyclable or reusable. Emerging ecosystem concepts such as cradle-to-cradle, design for disassembly, sustainable manufacturing, and most recently circular economy, are promoting the reusing or recycling of non-hazardous industrial waste. Empirical evidence suggests that there are significant economic, environmental, and social benefits to reusing industrial waste rather than recycling it. This paper presents, discusses and synthesis five speculative case studies in designing exterior building skins using standard automobile stamping by-products. The goal of the design experiment was to transform the linear approach in making building components, particularly, exterior metal skins and cladding systems, to a closed-loop approach, which ensures multi-dimensional economic, social, and environmental benefits. The results of the study are expected to aid in the reduction of energy used for extracting new materials and change the focus of the current waste management practices in the manufacturing industry from conventional recycling to creative reuse. The imperfection of the manufacturing industrial waste despite optimization measures, and the aging of zinc (patina) can both be transformed into novel unconventional architectural products.

KEYWORDS: Automobile solid waste, Circular economy design, Metal building skins, Galvanized sheet metal

INTRODUCTION

Imperfection is a quality that is fundamentally inseparable from any human effort, particularly in the act of building. Imperfection in architecture carries aesthetics worth in itself that should be accepted and celebrated. The work of Louis Kahn profoundly elevated materials and construction imperfections to a poetic notion of perfection. This refinement, for example, was elaborated in his cast-in-place concrete work at both the Salk Institute and the Kimbell Art Museum by preserving the marks of the construction process, which profoundly revealed how elements were constructed. While Kahn's concrete work exposed the imprints of its formwork and the pour joints became a tectonic expression, contemporary work of architecture has heavily invested in shiny complex surfaces that are often cladded in a variety of sheet metal from zinc to titanium. Metal fabricators in the United States such as Zahner have shifted their focus, in the last decade, to architectural metal surfaces and have assisted well-known architects in the realization of their work. Development of sheet metal cladding systems has undoubtedly benefitted from digital fabrication processes; however, reliance on sheet metal production methods and the open-loop supply chains has remained the same. This study aims to provide alternative methods in designing exterior metal skins using sheet metal by-products from the car industry that can be populated and extended directly by architects.

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 even being used for cornices and storefronts. Literature suggests that the Alcoa Company in Pittsburgh had a keen interest in construction with sheet metal exterior walls, which was reflected in the design of their headquarters (Yeomans 1998). The interest in sheet metal as a cladding material grew substantially with the technological advancement in galvanizing techniques. Galvanization using a process called "hot-dipping" was first introduced in the 1840s, and it made iron more suitable for exterior applications. Over the years, experiments carried out resulted in the mass production of metal thereby reducing its cost and making it available for construction purposes. Metal cladding made from galvanized steel was adopted because painting only was unable to protect the metal from rust over an extended period of time. Exterior cladding was perceived as lightweight, non-load bearing (skin), and able to be used as a membrane for the building, allowing air and daylight to pass through to occupants. The trade catalog was the chief marketing tool for sheet metal and created the link between manufacturers and consumers. Contractors collected brochures from building journals, to show potential customers the possibilities of metal cladding. As the uses of metal in interior and exterior cladding began in the late 19th century, sheet metals were not coated but painted on site with bitumen. 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). In particular, the coatings based on zinc were widely used to protect steel structures against atmospheric corrosion (Ferretti, Traverso, and Ventura 1976). It is in the nature of architecture that the appearance of new building materials would be accompanied by experimental explorations of its possibilities, and therefore aging of zinc was introduced (Yeomans 1998). Natural aging of zinc coating comes with a variety of change in the appearance of zinc coated galvanized sheet due to aging known as patina. This study highlights the relationship between design and application of by-products sheet metal cladding and its aging.

1.0 STATEMENT OF THE PROBLEM

The rise in sheet metal market size comes with an inevitable increase in scrap and by-products waste, even with maximum optimization measures in place. Existing literature on scrap management of sheet metals shows that stamping operations, particularly in the automobile industry, generates an enormous volume of scraps. For example, almost two decades ago at the General Motors Company, 1.6 million tons of scrap metal per year was generated (Koros, Hellickson, and Dudek 1995). Scrap management of sheet metal (particularly steel and aluminum) consists mostly of recycling, which introduces problems such as enormous energy consumption for sorting, smelting, and de-galvanizing. As the current practice of blanking and stamping sheet metal continue to generate a substantial volume of galvanized scrap, the creative reuse of scrap as suggested in this study, offers the most logical solution over recycling processes. The problem of recycling galvanized steel has its roots in the chemistry of steel making. Steel mills require specific raw material "recipes" to produce steel products with the properties needed by the builders and manufacturers who will ultimately use the steel. These recipes contain narrow margins of error. Scrap shipments to mills that have too much zinc, the material present in galvanized auto bodies, create problems and reduce the quality of steel during the melting stages.

1.1. Sheet metal scrap

According to a recent report published by the GVR 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 due to its use in manufacturing automotive 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 & safety standards, waste disposal, and materials used are imperative for shaping growth and sustainability strategies of the stamping companies over the forecast period (Grand View Research 2017). The scraps discussed in this paper, are limited to the category of bulky ferrous metals consistently generated from the automobile industry, known as "offal". 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 scraps stated in ASTM E702. This study is limited to standards governing galvanized sheet metal for the automobile industry.

1.2. Automobile stamping offal

General Motors (GM) sheet metal offal is a surplus material generated by its blanking operations as seen in Figure 1. The GM offal is a resilient material comprising of light gauge steel sheet (24-22), and zinc coating on both sides (approximately 60 microns); it is galvanized to preserve the steel in a process known as hot-dipped galvanization or electro-galvanization. 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 traditional scrap market value. Offal pieces are usually sized between 0.5mm to 3.2mm thick, have various coatings thicknesses (mostly zinc), and total at 1,500 metric tons per year. Promising cost-benefits are available through the reuse of these materials for GM and future users of the reclaimed steel. One plant in Flint, Michigan for example, generates approximately 40,000 pieces per month in about 11 different shapes and sizes (Figure 1). In 2014, 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 CO₂-equivalent emissions into the atmosphere.

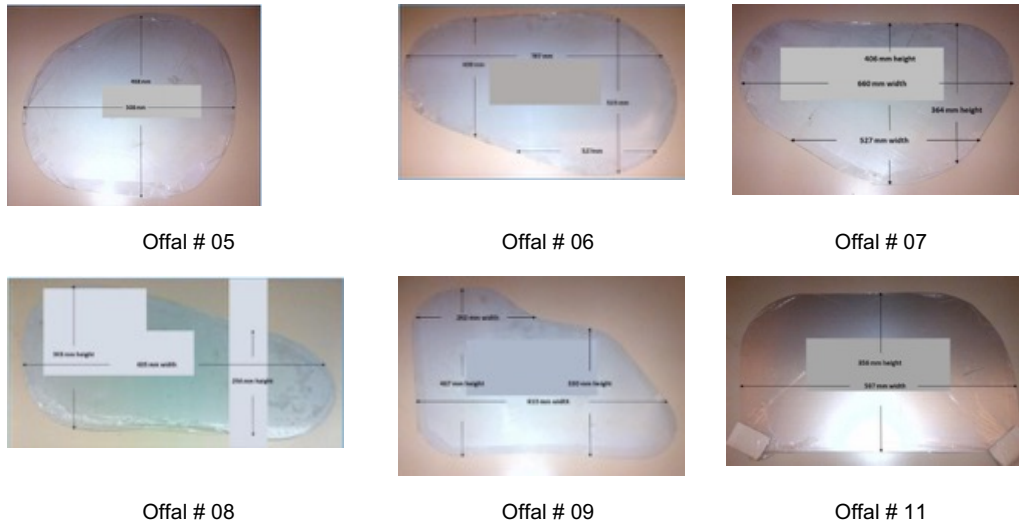


Figure 1: Six different sizes of Offal available as scrap materials from General Motors Source: (GM, 2016)

1.3. Imperfection in stamping/blanking processes and zinc patination

Although the car industry has pushed stamping and blanking operations to the maximum optimization measures, it is yet unable to achieve zero waste strategies. It is inevitable that the car industry will continue to generate a sizable amount of sheet metal by-products as long as the stamping operations are the dominant manufacturing process in the making of the car. On the other hand, architectural zinc has had a long history of application on buildings for almost three centuries and has been increasing in popularity in North America since the early 1990s (Kweton 2017). Zinc is a resilient material and is used for many purposes in the environment. According to the American Zinc Association, the average vehicle now contains 37 pounds of zinc (17 pounds in the form of corrosion-protection coatings and another 20 pounds in the form of zinc die cast parts) such as door handles and locks. Imperfection in zinc is often related to its aging patina. Zinc cannot be specified without an appreciation for the patina and aging process. The material is long-lasting, lends itself to unique detailing, and is versatile, but an understanding of the maturation process manages client expectations and allows a specification to leave a legacy long after the project is complete. Zinc, if specified properly can last for 100 years (Kweton 2017).

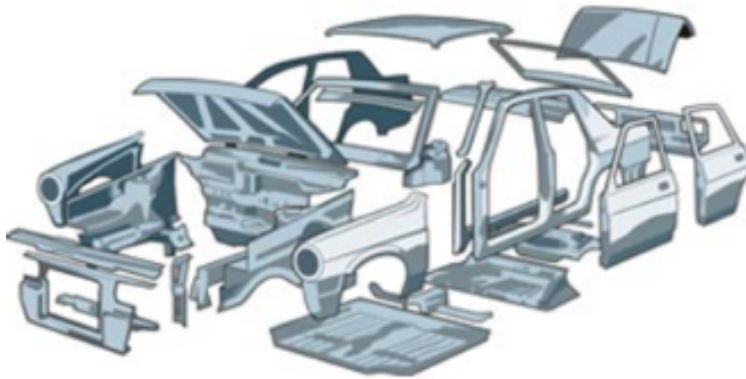


Figure 2: Car Stamping Diagram Source: (USA 2009)

2.0. RESEARCH METHODOLOGY

In this study, the authors utilize a quantitative approach limiting variables to one single material (galvanized sheet metal) in one single thickness (1mm) investigating its possibilities. The study was conducted in two phases. First an ideation phase, and second, an assessment phase. Five designs proposed by the authors' affiliated Resource-Based Design Research Lab (RBDR) were designed, illustrated and modeled, then were quantified based on the feasibilities of manufacturing processes and the comparison cost of the raw versus

the upcycled materials used. The design and engineering team worked in an interdisciplinary model which involved feedback and feedforward process in an academic collaborative setting. The focus was limited to the process of production implied by each design solution and the cost of obtaining material for each design. The cost of production of each design proposal was compared to show the effect of the use of new material for building skins against the use of a consistent waste-flow material. In the following sections, a description of each design followed by illustrations is presented. Then a comparison in manufacturability and cost savings are discussed.

3.0. PROPOSED DESIGN SOLUTIONS FOR METAL BUILDING SKIN

It is common for individual industries to develop its processes without involving other industries' sustainability goals. And too often in manufacturing, engineers may not have the time or the opportunity to work closely with designers. Some of the specific properties of the metal offal included their lack of stiffness, the vulnerability of their edges, their tendency to be shaped or dented by powerful forces, along with the noise that would be generated when they came in contact with another force, for example, heavy rain/hail. All these factors had an impact on the design process. To develop a synergy between the car industry and the building industry, the following proposals are primarily focused on exterior building skin applications that ranged from metal cladding to sun-shading screens. Each design solution utilized a different offal shape and size to match the unit geometry closely and to minimize materials waste. See Table 1 and 2 for design proposals analysis.

3.1. Design #1: Passive cooling perforated skin

The proposed triangulated skin allows fresh air to flow from a positively pressured exterior into a negatively pressured cavity space and then the air would be captured as potential cooling by an in-ground passive cooling system. While minimal waste is still being produced through the maximized geometry of the offal, the function of the skin and the passive cooling system allows for more significant energy waste reduction over time. Offal #6 has an estimated monthly production of 1,000 pieces. Using 80 percent of the offal, with an area of about 592 square inches, yields two pieces per offal. Upon folding and perforating, the offal is transformed to a standard panelling system which contains 60 pieces per panel.

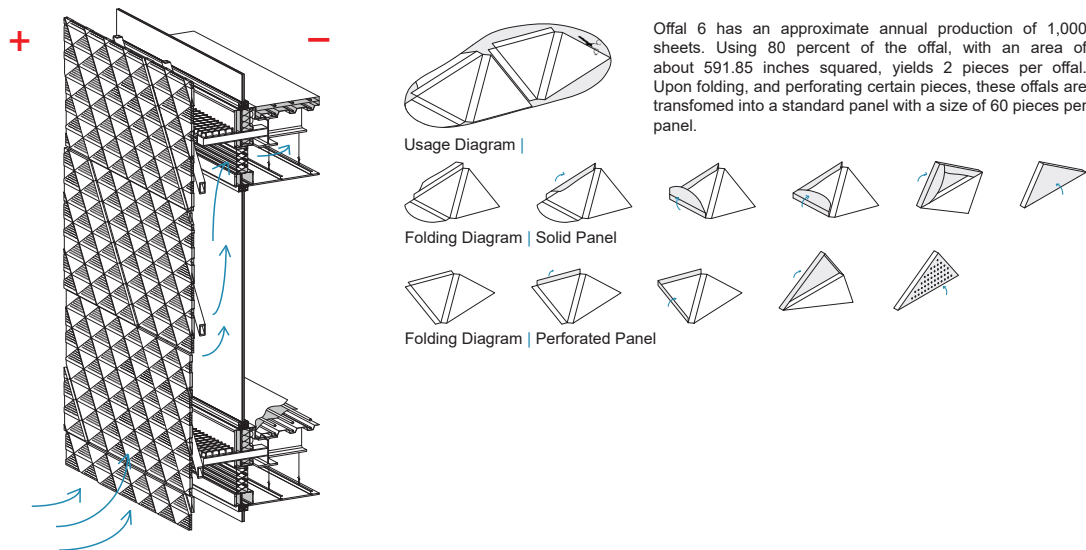


Figure 3: Passive cooling skin made from offal #6. Source: (Buckley, 2017)

3.2. Design #2: Breathable Skin

The design allows air and light to penetrate the building exterior skin. By altering the geometry of # 8 offal, four different degrees of bending were created. The pieces were bent at varying degrees at the center of the panel, bringing the two-dimensional flat offal into a three-dimensional object. When assembled, these components can create an opening of varying sizes in the building envelope, allowing the building to breathe. The "breathing" of the envelope encourages the circulation of fresh air against the facade of the overall structure, thereby reducing the need for cooling systems within the interior spaces. Additionally, by strategically placing the openings in front of the subsequent fenestrations, the envelope can bring natural light into the building.

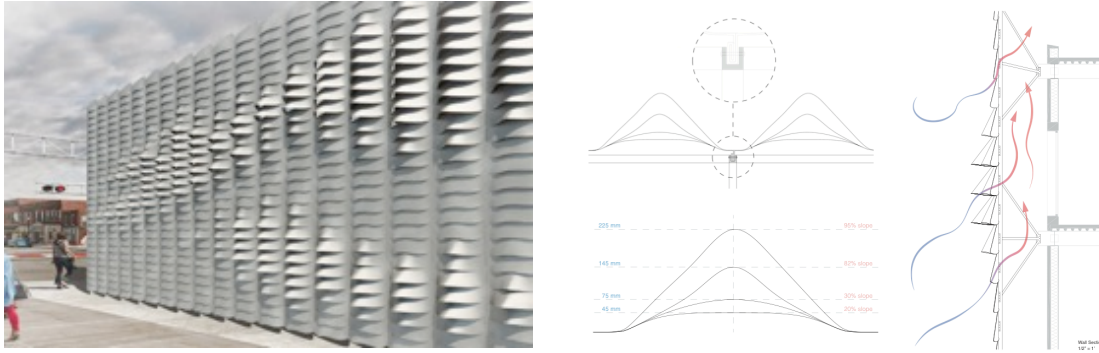


Figure 4: Breathable Skin made from offal #8. Source: (Lopez, 2017)

3.3. Design #3: Faceted Complex Curvature Skin

The design introduced a triangulated modular system for building skins. By folding offal #5, which has the closest geometry to a circle, a triangular pyramid emerged. Placing the pyramids in groups of six created hexagons, which were assembled to form a complexly curved surface building skin.

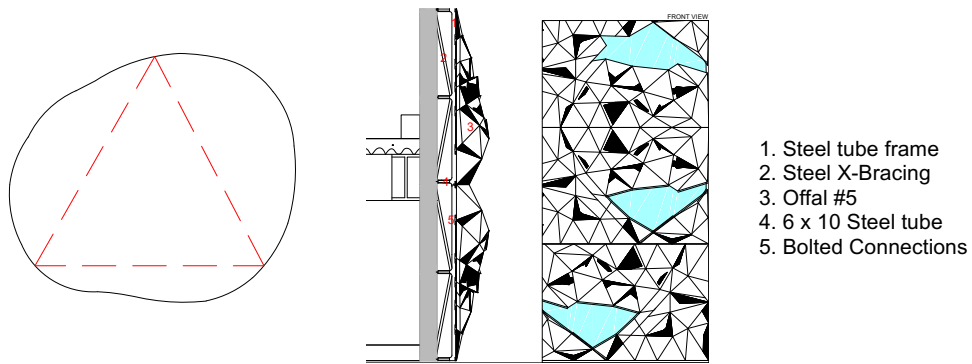


Figure 5: Faceted complex curvature skin made from offal #5. Source: (Escalente, 2017)

3.4. Design #4: Metal Brick Façade System

This metal-masonry system is made from offal #11, which is the closest to a rectangular shape and would create minimum waste while shaping a volumetric module. Four pieces of the offal were folded to form a rectangular box module measured at 500mm x 285mm x 140mm in size. Utilizing this offal module as a veneer façade element creates a building envelope visually similar to an exposed masonry façade. A dry sealant is used as an adhesive for units to prevent water penetration.

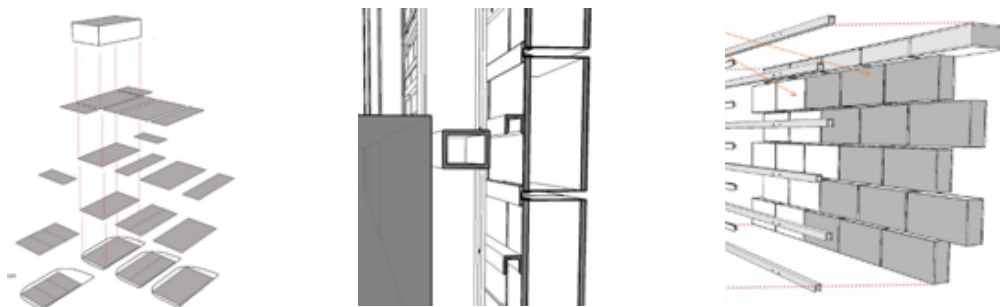


Figure 6: Metal brick insulated units envelope made from offal #11. Source: (Mathews, 2017)

3.5. Design #5: Trapezoid Zigzag Sunscreen

The skin system is made from offal #9 and maximizes the surface to create a triangular box. Two triangles were made into one object to form a box; holes were drilled for connections. The two-triangle units make trapezoids, which are arranged in a zigzag pattern as a shading screen for the building exterior.

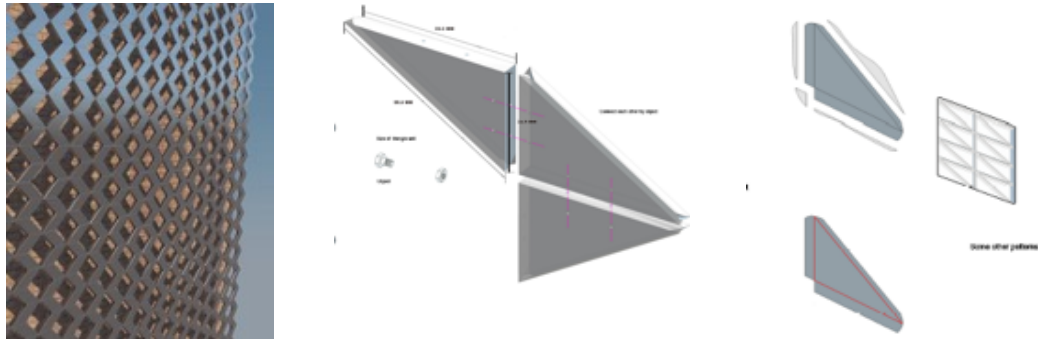


Figure 7: Trapezoid zigzag sunscreen made from offal #9. Source: (Lang, 2017)

4.0 COST COMPARISON BETWEEN RAW AND SCRAP GALVANIZED SHEET METAL

The current cost of raw galvanized sheet metal was obtained by comparing prices from different companies, see table 2. Alibaba, an online retailer, sells coils of sheet metal ranging from \$0.25/lb to \$0.5/lb (Alibaba 1999), the cheapest of which places a minimum on the quantity of the order. The cost of scrap metal was obtained from recycling companies such as Montgomery Scrap Corp. at \$0.07/lb. (Scrap 1949), Rockaway Recycling Company rate is at \$0.06/lb - \$0.1/lb. (Recycling 1977) and Scrap Monster at \$0.11/lb. (Monster 2009). The cost for raw galvanized sheet metal is averaged at \$0.45/lb., and for Offal as scrap, it is at \$0.08/lb.

4.1. Manufacturability analysis

To understand the cost of the automated manufacturing processes performed on the five proposals, a basic quantitative assessment was performed. This process revealed the influence of design on the manufacturability of the materials for use. Assessments of manufacturability specify a choice of cutting done by a waterjet cutter to calculate cutting energy; for the purpose of this study, design proposals were analysed based only on the number of folds and cuts. The proposed designs were analysed according to the number of units of offal used in the system, the number of cuts per unit, the size of cuts, the number of folds per unit, the size and degree of folding, the number of joints in the system and the types of joints as shown in Table 1 and 2. Further precise analysis regarding the cost of manufacturability will be presented in future publications.

Table 1: Manufacturability of the design proposals. Source: (Authors 2018)

Design Solution	# of Units in the System	# of Cutting per Unit	Size of Cutting	# of Folding per Unit	Size/Degree of Folding	# of Joints	Type of Joints
1	15 units / m ²	3-4 (irregular)	60 cm	6	30 cm/90°	60 bolts / m ²	Bolts
2	5 units / m ²	0	0	1	0	30 bolts / m ²	Bolts
3	10 units / m ²	3	40-50 cm	0	0	60 bolts / m ²	Bolts
4	5 units / m ²	15-20	30-60 cm	0	0	50 bolts / m ²	Bolts
5	2 units / m ²	16-20	30-60 cm	6	30-60 cm/90°	20 bolts / m ²	Bolts

Table 2: Analysis of five design proposals. Source: (Authors 2018)

Design Solution	# of Units in the System	Type of Offal	# of Cuttings per Unit	Mass of Offal per square meter	Cost of raw material @\$0.45/lb.	Cost of scrap@ \$0.08/lb.

1	15 units / m ²	Offal #6	3-4 (irregular)	2340.95 x 15 = 35,114.25g (77.4lbs)	\$34.83	\$6.2
2	5 units / m ²	Offal #8	0	1116.98g x 5 = 5584.9g (12.3lbs)	\$5.54	\$1
3	10 units / m ²	Offal #5	3	1087.53 x 10 = 10,875.3g (23.98lbs)	\$10.79	\$1.9
4	5 units / m ²	Offal #11	15-20	1068.63 x 5 = 5343.15g (11.78lbs)	\$5.3	\$0.9
5	2 units / m ²	Offal #9	16-20	1244.862 x 2 = 2489.724g (5.49lbs)	\$2.47	\$0.4

While each design proposal is unique and different in its building application, the design proposal with the lowest cost is #5 as shown in Table 2. Figure 8 illustrates a comparison of cost when manufacturing the proposed solutions using offal versus raw materials. From this comparison, one observes that designers who were presented with the same materials provided unique solutions for building skins. After an analysis of optimized use and material flow, results show that design plays a significant role in the final cost of using the waste-flow material. Further studies will be conducted to emphasize the need for manufacturability and embodied energy analysis at the early stages of design to save both cost and energy.

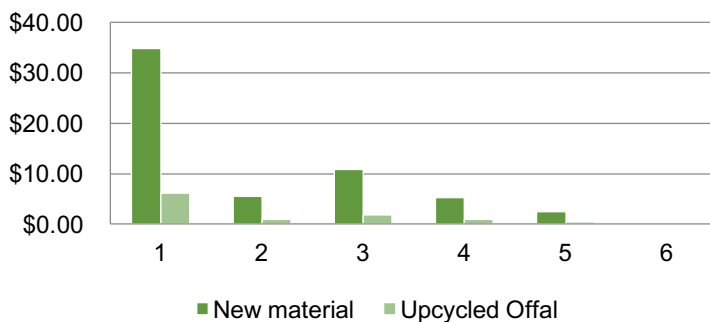


Figure 8: Cost comparison between raw and offal sheet metal Source: (Authors, 2018)

CONCLUSION

This paper introduced a novel approach in designing a symbiosis between non-hazardous automotive waste and the building industry. Particularly, creating building skin systems from by-product galvanized sheet metal from the automotive industry. A similar resource reuse revolution is making way for a new architectural paradigm shift, which is emerging through the integration of creative reuse, synergistic business processes, and a circular economy. To establish a market for reusing galvanized metal scraps, the design should be considered as a value-adding factor of which both the building industry and the car industry could benefit from. Factors responsible for the total cost of production of the design proposals are design, materials, and manufacturing. Using the sizable scrap metal encourages a return of materials at the end of the life of a project. When there is a strategy to use returned materials for building skins, the cost is reduced, and the supply chain of the automobile industry is closed. The fraction of GM offal produced yearly, 1.6 million tons compared to 7.6 billion tons of total waste is minimal. This study has also shown the cost savings for the reuse of and appreciation for the imperfection of the materials aging and its process. The results of the investigation reveal that design of galvanized sheet metal for reuse influences the cost of production. There is no fixed formula to determine the savings of one particular design proposal, but by a unified triangular approach, perfection, in a sense of mitigating wasteflow production, can be sought. In the future, scrap management can include more processes centered on reuse. Improved scrap management will ensure that there is an established chain of supply for scrap metal, which will increase opportunities for job creation. The environment will improve as it will reduce the demand for raw materials. This will, in turn, reduce the carbon footprint of products that involve the use of metals. A circular economy will be further established, and there will be an elimination of waste and established perfection in the imperfect waste.

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