

Sustainable mechanical design and manufacturing of pressure relief valves

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Abstract: This paper aims to provide an argument to take a closer look at the development and application of technology in relation to sustainability. Environmental awareness is driving industries across all sectors to re-evaluate their practices to reduce their impact on the environment. Therefore, integrating sustainability into the mechanical design and manufacturing of products and systems has become mandatory. An often-overlooked aspect of industrial processes is the role of valves; however, only a few studies have addressed their environmental sustainability. To address this research gap, this study aims to integrate mechanical engineering design with sustainable environmental engineering of industrial valves. The redesign concept has been applied to pressure relief valves and has been achieved by proposing the use of alternative materials other than metals, such as polytetrafluoroethylene (PTFE) and perfluoro alkoxy polymer (PFA). This study used some relevant tools to evaluate the suitability of such proposed materials, including energy consumption and CO₂ emissions. A modified design that met the properties and specifications of the proposed polymer type was implemented, resulting in a simpler valve design, fewer valve parts, easier assembly, less weight, and lower cost. The implications of the trade-offs between metallic and polymeric valves for sustainable manufacturing fall within the theoretical framework of 6R, where all its concepts play an important role in promoting sustainable and environmentally conscious manufacturing. All to reduce emissions, energy consumption, and waste.

Keywords: sustainable development; sustainable design; sustainable manufacturing; PTFE; valves; pressure relief valves

1. Introduction

Nowadays, environmental awareness has become the center of global discussion and debate, prompting industries in all fields to re-evaluate their practices to reduce their impact on the environment. The machinery manufacturing industry is considered a major factor in environmental pollution and resource consumption due to the production of much mechanical equipment. The traditional concept of mechanical design is more concerned with a product's functional features, such as cost, quality, and operating cycle, with less emphasis on environmental aspects. According to the traditional concept, the product would generate waste and pollute the environment at the end of its lifecycle [1]. Thus, sustainable or green design and manufacturing strategies are needed to address the current resource, energy, and environmental issues posed by the manufacturing industry [2]. The main difference between green mechanical design and traditional mechanical design is that green design considers the environmental aspects of mechanical products, such as consumption, remanufacturing, recycling, and other environmental protection aspects [1]. The

central argument about sustainable development is whether to adopt a weak or a strong concept of sustainability. It is a contested perception that is usually described as the intersection between the sustainability pillars: environment, economy, and society, which are viewed as distinct but interconnected entities, as shown in **Figure 1**. This view of sustainability, referred to as weak sustainability, is commonly presented as a three-ring sector view of sustainable development and is seen by Bob Giddings and others [3] to have significant weaknesses and limitations. However, a stronger concept of sustainability can be achieved by studying the relationship between the three pillars of sustainability, where both the economy and society pillars are constrained by environmental limits. They are seen as fully interdependent, where, in other words, the economy is dependent on society, and both are dependent on the environment.

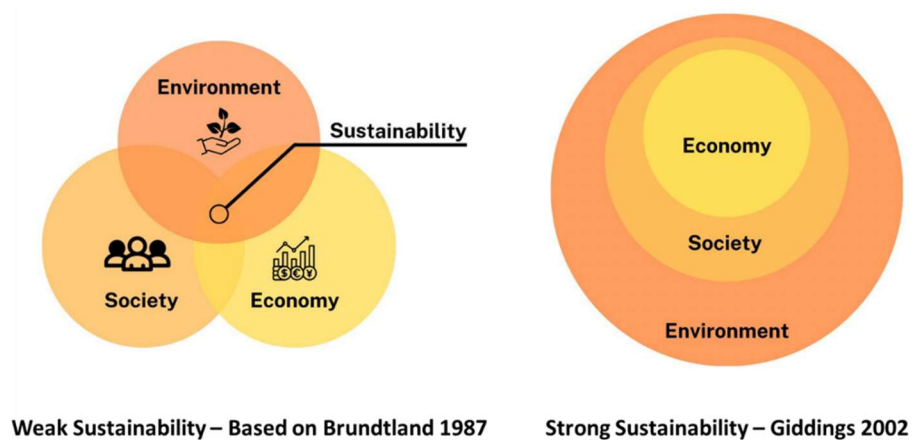


Figure 1. Difference between weak and strong sustainability.

The machinery manufacturing industry is mainly concerned with the production of equipment for various industries, and it is also a critical source of energy conservation and emission reduction, which results in environmental pollution control. According to statistics, energy consumption in the machinery industry accounts for a large proportion of total industrial energy consumption, and some high-energy-consuming equipment emits many pollutants during the production process. Their energy demands are so high that green design and manufacturing techniques must be implemented. It is not only vital to apply these principles to all mechanical engineering equipment but also to guarantee that the equipment’s operating cycle is developed with these environmentally conscious concepts in mind [2].

An often-overlooked aspect of industrial processes is the role of valves and their impact on the environment. Although valves are critical components in a variety of industrial and process systems, they can contribute significantly to environmental degradation. When examining valves from a sustainability perspective, there are three main areas to consider: emissions, internal tightness, and life cycle. Looking at these three cases, it is worth noting that industry standards and regulations are crucial in driving development and maintaining the environmental performance of industrial processes [4]. One of the largest sources of fugitive emissions in a plant is valve-related, with most emissions coming from valve stems and fittings (joints); therefore, many government regulations have been targeting these areas, and, in recent years, the allowable leakage rates have been reduced. For example, the Clean Air Act

Amendments enacted by the U.S. Environmental Protection Agency reduced the permissible leak rate limit from 500 ppm to 100 ppm and, in some cases, to 50 ppm [5]. **Figure 2** shows an example of the percentage of fugitive emissions from valves in a plant [5].

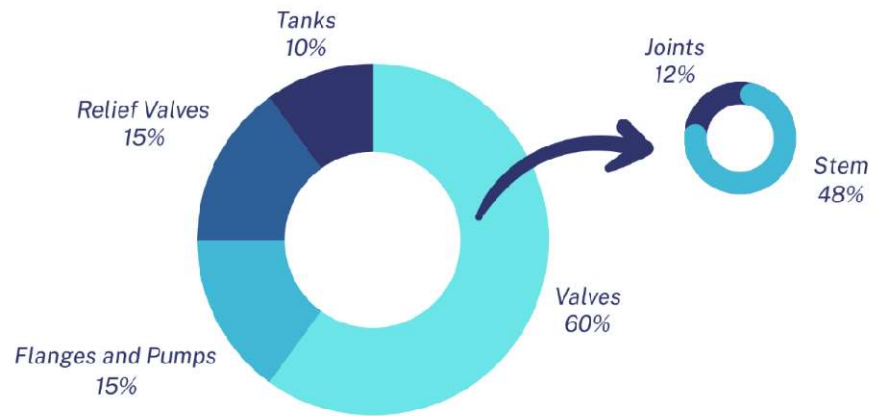


Figure 2. Percentage of fugitive emissions from valves in a plant, where valve stems and joints account for a large portion of the emissions.

When discussing the sustainability of valves in the process industries, emissions are often the first thing that comes to mind. By preventing fugitive emissions from entering the atmosphere, local health and safety risks are reduced while minimizing the broader environmental impact on the climate. While regulations from governing bodies continue to impose strict standards, there has been a significant shift in customer expectations for valves used in industrial processes. This shift in emphasis has been from Factory Acceptance Testing (FAT) towards type testing, where valves are subjected to extensive testing—sometimes up to a hundred thousand cycles under simulated conditions. This shift reflects a more lifecycle-focused approach to sustainability, where valves must not only pass pressure tests prior to installation but also demonstrate long-term performance of design and manufacturing quality. Emissions standards have obviously been around for many years, and there have been few fundamental changes in standardization over time, but there have been many incremental developments. For example, an important development in the United States is the bundling of valve design standards with emission type testing (API 608 for ball valves now also requires API 641 standardization). These growing sustainability considerations are influencing the design and manufacture of valves. Thus, industries need to take all of this into account when developing and designing valve products [4].

Moreover, the need for more sustainable design and manufacturing of valves has led to the exploration of advances in polymer-based materials, which have a dramatic impact on design, sustainability, performance, and cost. With recent innovations in polymer technology and thermoplastics, it has become possible to design valves in a way that allows them to be used in a variety of different applications. In terms of the development of polymer-based materials, high-performance polymers have replaced standard conventional polymers and are now designed to withstand harsh conditions such as chemical exposure, severe temperatures, and mechanical contact stresses.

High-performance polymers can withstand intense weathering, harsh environments, and mechanical damage while still maintaining their functionality and desired properties [6]. For example, polymers can be improved by adding additives, such as heat stabilizers, to prevent them from degrading during manufacturing and in high-temperature applications. The addition of filler materials such as fibers, flakes, calcium carbonate, silica, glass fibers, and carbon is a widely used technique to reinforce and increase the stiffness of polymer materials. Also, nano-additives improve barrier properties while maintaining toughness, and antioxidants reduce oxidation during processing and end-use [7].

2. Materials and methods

The 6R concept (redesign, reduce, recover, reuse, recycle, and remanufacture) promotes environmentally conscious methods and sustainability of production. In the 6R method, the goal of redesign is to use recycled and recovered components, materials, and resources to create future products. Reduce refers to using fewer materials, energy, and other resources, as well as lowering emissions and waste output. Meanwhile, “recover” refers to collecting products at the end of their use stage so that they can be used in future years of the product’s life cycle, and “reuse” is the reusing of end-of-life items, components, and products in a later life cycle. Recycling is the process of converting waste into new materials, and finally, remanufacturing focuses on reprocessing previously used products to return them to their original state while reusing as many parts as possible. Implementing the 6R principles allows for the recycling of waste products, resulting in a closed loop, a whole lifecycle-based resource/material flow, and more sustainable manufacturing [8,9]. Additionally, redesigning goods and products to be sustainable requires a broad strategy that considers the entire life cycle of a product, from raw material sourcing to final disposal. A fundamental idea guiding this approach is the concept of circular design, the practice of making products that can be reused, repaired, or recycled at the end of their useful life. Moving from a linear “take-make-dispose” approach to a circular one reduces waste while increasing resource efficiencies [10].

2.1. Manufacturing of valves

An often-overlooked aspect of industrial processes is the role of valves and their impact on the environment, and emissions are often the first thing that comes to mind when discussing sustainability in the process industries. Casting is one of the most common processes used in the manufacturing of valves, and many valve manufacturers choose this technique as it allows for the creation of complicated shapes and designs. As shown in **Figure 3**, the method consists of a series of steps: mold preparation, which includes melting of the metal, pouring of molten metal into the mold, solidification of the metal, release of the cast part from the mold, and finally finishing and polishing of the part [11].

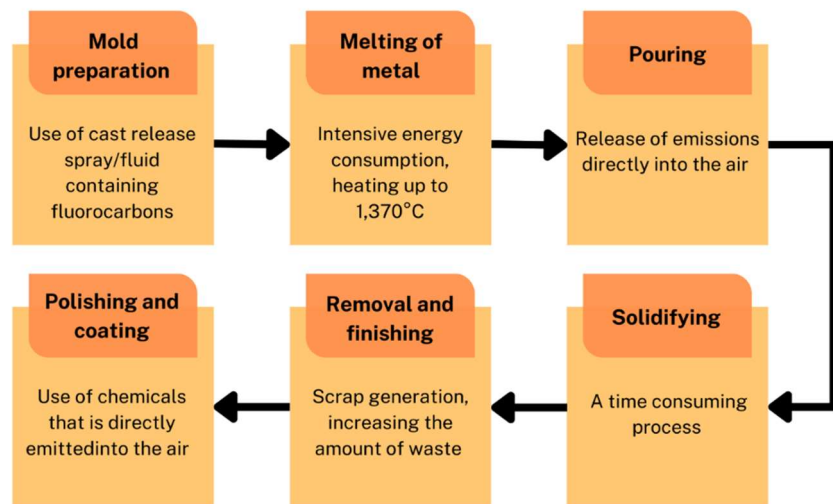


Figure 3. Process flowchart of valve casting and its environmental impact.

2.2. Raw materials and extraction processes

The first phase in the valve manufacturing process is the extraction of raw materials, and most valves are made of metals such as steel, brass, and bronze, which require mining and processing. This step is especially challenging because of the high energy usage, water consumption, and high waste generation volume [12]. Mining, the extraction of metals such as copper, iron, and tin, necessitates considerable mining activities, which can result in soil erosion, habitat damage, and contamination of water supplies [13]. The extraction of these minerals necessitates considerable amounts of energy, which is frequently generated by fossil fuels, resulting in greenhouse gas (GHG) emissions as well as contributing to climate change that harms local air quality and human health. Not only that, the extraction and processing of raw materials also require large amounts of water, which can deplete local water sources and harm neighboring ecosystems [12].

2.3. Manufacturing process and waste generation

Once the raw materials have been obtained, they are processed and converted into valve parts. This phase was also fraught with environmental issues. Like the extraction process, the manufacturing process requires a lot of energy and results in high GHG emissions while generating a variety of wastes, including packaging materials, substandard components, and manufacturing by-products. If not handled appropriately, these wastes can contaminate the soil, water, and air. Additionally, chemicals are often used at this stage, especially during the polishing and coating steps, which can have adverse effects on the environment if not properly disposed of [12]. The impact of valve manufacturing on the environment is far-reaching, affecting not only the local ecosystem but also global climate change. Metal production accounts for 40% of all industrial emissions of GHGs, 10% of world energy consumption, 3.2 billion metric tons of metals mined, and a few billion metric tons of by-products produced annually [14]. Furthermore, the total amount of waste generated by the previously mentioned processes is approximately 15–20 times the amount of metal produced [14].

2.4. Sustainable manufacturing of valves

The main difference between the sustainable mechanical design concept and the traditional mechanical design concept is the consideration of the environmental aspects of mechanical products, including recycling, remanufacturing, and consumption [1]. The sustainable mechanical design and manufacturing of valves proposed in this paper revolves around the concepts of redesign, remanufacturing, reducing waste and energy consumption, and recycling waste, as shown in **Figure 4**. Redesigning valves for sustainability requires a comprehensive approach that considers the entire lifecycle of the valve, from raw material sourcing to end-of-life disposal. One of the key principles in driving sustainable development is to choose alternative materials with minimal environmental impact to reduce dependence on finite resources. This is because traditional valve materials, such as cast iron and carbon steel, often rely on resource-intensive mining and manufacturing processes, resulting in higher carbon emissions. Therefore, exploring the use of alternative materials, such as polymers, can reduce emissions and thus pollution [1,15].

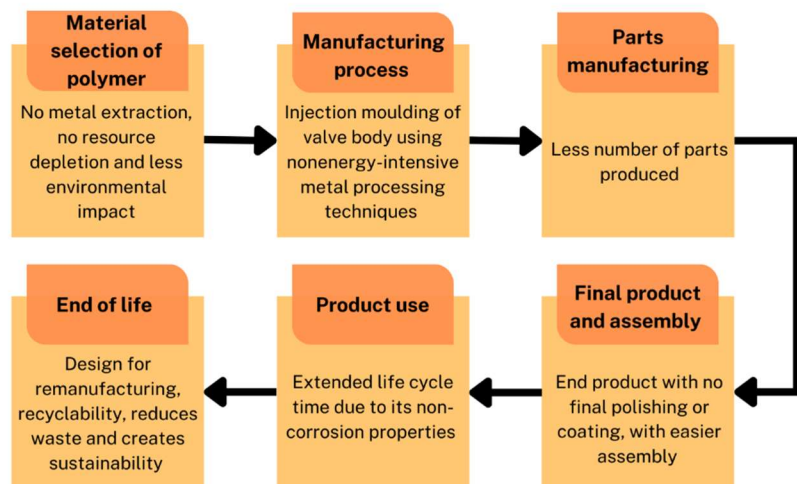


Figure 4. Sustainable mechanical design and manufacturing flowchart.

Furthermore, injection molding is considered one of the most cost-effective processing techniques for building both functional valve prototypes and end-use products, and with the use of polymers, there is no need for the use of energy-intensive processing of metals, resulting in less manufacturing cost and energy consumption. Not only that, but with the idea of redesigning valves using polymers, a simpler design can be achieved with the manufacturing of a smaller number of valve parts. The main advantage of using injection molding is that the end-use valve can be preserved without the need for additional processing techniques such as final polishing and coating. Another important advantage of manufacturing polymer valves is the ease of assembly of the valve body and its components. A wide range of polymers are known for their corrosion-resistance properties, which in many applications can contribute to the valve's life cycle that protects it from the harsh environment of chemicals, in contrast to metals, which can easily corrode and pit. In the traditional mechanical design concept, used products will eventually become scrap metal; thus, sustainable design should consider the design of recycling and remanufacturing while achieving

reuse at the lowest cost.

The manufacturing of valve raw materials (metals) requires energy-intensive processes, which means that the carbon dioxide (CO₂) emissions from the manufacturing process are greatly influenced by the different energy sources used, referred to as the energy mix, which includes nuclear energy, renewable energy, and fossil energy such as natural gas, crude oil, and coal. Therefore, it is important to apply Life Cycle Assessment (LCA), which is an environmental assessment method that evaluates the environmental impact of a product from its beginning to the end of its use [2]. As part of LCA data collection, the Life Cycle Inventory (LCI) database provides a variety of energy mix options, and the choice of one mix has a significant impact on the result of CO₂ emissions [16]. According to a report on the climate impact of metal casting submitted by Swerea SWECAST AB in 2016, the energy mix of the raw material has a greater impact on the material’s carbon footprint than the material being melted itself [17,18].

Furthermore, the carbon footprint of valves demonstrates its Global Warming Potential (GWP), and it is reported in terms of carbon dioxide equivalent (CO₂-eq) used to analyze the emissions of various GHGs by converting their amounts to the equivalent amount of CO₂ with the same GWP. The higher the GWP of a gas, the greater its contribution to global warming over a 100-year period [19]. The carbon footprint of valve materials is usually expressed as kilograms of carbon dioxide equivalent (kg CO₂e) or kilograms of carbon dioxide equivalent (kg CO₂e/kg) produced per kilogram of material. According to the LCA carried out by Haque and Norgate [20], the estimated GHG emissions from the mining and processing of 1 tonne of iron ore were 11.9 kg CO₂e, and the embodied energy values were 153 MJ per tonne of iron ore. Their findings show that loading and transportation contribute the most to GHG emissions from mining and processing of iron ore, accounting for about 50 percent. Based on Haider Saied, the Supply Chain Specialist from Broen, the carbon footprint of some of the common metals used in the manufacturing of their typical valves is 5.58 kg CO₂e for stainless steel, 2.40 kg CO₂e for structural steel, and 3.61 kg CO₂e for brass [18]. These values represent the average carbon footprint of the raw material used in Broen valves per kilogram of finished product [18]. **Figure 5** elaborates the LCA modules on which the environmental assessment of a product is carried out [21].

Product Stage			Construction Stage		Use Stage							End of Life Stage				Net Benefits and Loads
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 5. Life Cycle Assessment (LCA) modules.

Carbon emissions from the use of valves (B1–B7) in closed-loop systems mainly come from pressure and heat losses. All fittings in a heating, ventilation, and air conditioning (HVAC) system cause a drop in pressure, or pressure loss, which is an unwanted phenomenon. Each valve has its own specific K_v value, which is the flow coefficient of the valve. The K_v value is defined as the flow rate of water in cubic meters per hour [m^3/h] at a pressure drop of 1 bar across the valve. If the flow coefficient and flow rate are known, the pressure loss across the valve can be calculated using the formula

$$K_v = q_v \sqrt{\frac{\rho}{\Delta p}}$$

where q_v is the flow rate of water in m^3/h , ρ is the density of water ($=1 \text{ kg}/\text{dm}^3$), and Δp is the pressure drop across the valve in bars [18].

Because the pipes of a heating system are hotter than the surrounding air, heat loss from the system occurs. While this heat loss is not inherently wasted, it is still unnecessary in locations such as a building's basement, where radiators may not have thermostats to maintain a constant temperature. For example, in Finland, pipes in heating systems are often insulated to prevent or reduce heat loss, while valves are rarely insulated. Each valve construction material has a specific thermal resistance or resistivity, R , which is measured in Kelvin meters per watt (Km/W). For uninsulated pipes, three thermal resistivities must be calculated: the inside surface, the pipe material, and the outside surface [18]. The thermal resistivity of the inner surface is calculated with the formula

$$R_i = \frac{1}{\alpha \pi d_i}$$

where R_i is the thermal resistivity of the inner surface in Km/W , α is the heat transfer coefficient for the inner surface in $\text{W}/\text{m}^2\text{K}$, and d_i is the inner diameter of the pipe in m [18]. The pipe material has its own specific thermal conductivity, which determines how much heat flows through the pipe. When the inner and outer diameters of the pipe and the thermal conductivity of the material are known, the thermal resistivity of the pipe can be calculated using the formula

$$R_i = \frac{1}{2\pi\lambda_p} \times \ln \frac{d_o}{d_i}$$

where R_i is the thermal resistivity of the pipe in Km/W , λ_p is the thermal conductivity of the pipe in W/Km , d_i is the inner diameter of the pipe in m, and d_o is the outer diameter of the pipe in m [18].

3. Case study

There is a wide variety of different valve types, each with a different purpose. Valves are divided into two main categories: manual valves and automatic valves. Manual valves are used to stop, start, control, and divert flow for manual operations, and they are divided into four main groups according to the way the closing member slides on the valve seat. These are rotary valves (such as plug valves), slide valves

(such as gate valves), flex-body valves, where the valve body is flexed by the closure member (such as diaphragm valves), and closing-down valves with a stopper-like closure member (such as ball valves). Each valve group is made up of several different types of valves, each of which is manufactured in a variety of ways. Automatic valves, on the other hand, are valves that actuate automatically to prevent the backflow of fluids and relieve pressure. These valves are divided into two types: check valves and pressure relief valves. Check valves prevent backflow and are classified into four groups also based on how the closing member slides on the valve seat, such as lift check valves, tilt check valves, swing check valves, and diaphragm check valves [22]. Additionally, pressure relief valves are important safety devices that protect equipment and pipelines from the potentially catastrophic effects of an overpressure event. Pressure relief valves work on the concept of mechanical spring tension or fluid pressure. They keep shut until the pressure in the system exceeds a specific set point, at which point they open to let off excess pressure, preventing equipment damage and ensuring the safety of both the system and the environment around them [23]. There are two groups of pressure relief valves: direct-acting, which is actuated by system fluid pressure, and pilot-operated, which is controlled by a pilot and opens and closes the main valve based on system pressure. Furthermore, auxiliary actuators can be used with direct-acting pressure to help lift the valve during the opening process and provide an additional closing force when re-seating; lift assist prevents valve chatter, while supplemental valve load reduces valve flicker. The auxiliary actuators are powered by an external power supply, and if the external power fails, the valve acts as a direct pressure relief valve [22]. **Figure 6** illustrates a typical pressure relief valve, and **Table 1** displays its components and the material from which they are typically made.

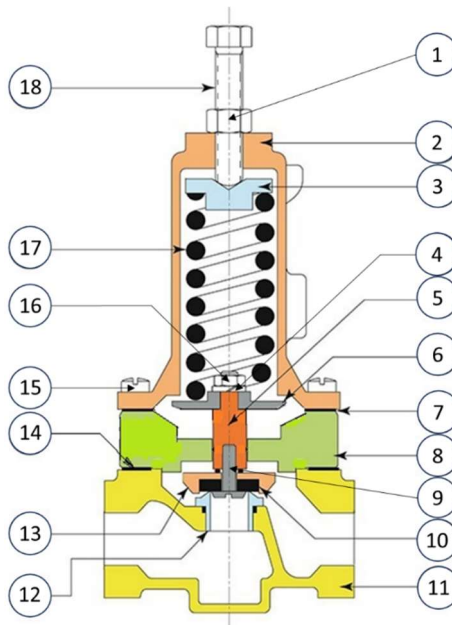


Figure 6. Typical pressure relief valve.

Table 1. Technical data of the original valve design.

No.	Part	Material
1	Nut	Carbon steel
2	Pilot cover	Bronze
3	Top spring guide	Bronze
4	Spring washer	Carbon steel
5	Stem/obturator	Brass
6	Top diaphragm washer	Brass nickel-plated
7	Gasket	NBR
8	Spacer	Brass nickel-plated
9	Bolt	Carbon steel
10	Seat gasket	NBR
11	Body	Bronze
12	Seat	AISI 316
13	Seat retainer	Brass
14	Gasket	NBR
15	Screw	Carbon steel
16	Nut	Carbon steel
17	Spring	AISI 302
18	Setting screw	AISI 303

NBR, nitrile butadiene rubber.

3.1. Modified valve design

This paper aims to develop a case study around the concept of sustainable design and manufacturing of mechanical equipment, considering all necessary and important environmental aspects. As a preliminary case, the concept of sustainable design and manufacturing has been applied to pressure relief valves. However, the sustainable design and manufacturing procedures presented in this article can also be applied to other mechanical systems, considering any additional requirements that the selected system may require. As for the chosen system in this paper, the concept of sustainable redesign is achieved by proposing the use of alternative materials other than metals to manufacture valves, such as polymers, and modifying its design into a simpler one, with the features and specifications that comply with the type of polymer proposed. **Figure 7** shows the new modified design of the previously proposed pressure relief valve, and **Table 2** shows its components and the materials from which they can be manufactured, which are discussed further below. As illustrated in **Figure 7**, nuts and bolts are removed in the new design due to merging the body of the valve to be only one part instead of three as in the original design (the spacer is removed), the material of the valve is now 100% polymer instead of metal, and the diaphragm is removed as well as the top and bottom diaphragm washers.

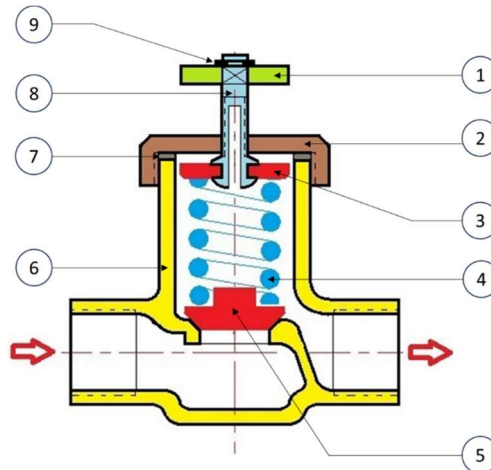


Figure 7. Modified design of pressure relief valve.

Table 2. Technical data of the modified valve design.

No.	Part	Material
1	Handle	PVC
2	Valve cover	PTFE/PFA
3	Upper seat	PFA
4	Spring	FRP
5	Lower seat	PFA
6	Body	PTFE/PFA
7	Gasket	NBR
8	Stem	PFA
9	Retaining ring	PTFE

PVC, polyvinyl chloride; PTFE, polytetrafluoroethylene; PFA, perfluoro alkoxy; FRP, fiber reinforced polymer; NBR, nitride butadiene rubber.

To successfully lower the weight of a helical spring, the material characteristics can be optimized, or alternative innovative materials can be used in place of traditional engineering materials. Springs are usually made of steel and are used to dampen vibrations in mechanical systems [24]. A composite material called fiber reinforced polymer (FRP) can reduce the weight of coil springs while maintaining load-bearing capacity. Replacing traditional steel springs with springs made from FRP composites can provide numerous improvements, such as improved strength-to-weight ratio, increased stiffness, increased impact energy absorption, and reduced stress [25].

3.2. New design analysis

One of the main factors that contribute to the environmental impact of industrial valves is the choice of materials. Not only that, but they can also significantly influence the design of fluid control systems. Some materials are suitable for high temperatures, while others can withstand corrosive chemicals. Some are cost-effective; others have environmental advantages. Several factors are usually involved in advanced, complex applications; thus, it is beneficial to have a wide selection of materials in mind during design. Metals have always been used in the manufacturing of valves; nowadays, most valves are made of some kind of metal, ranging from low-priced die-cast aluminum,

brass, and stainless-steel valves to high-performance high-nickel alloys [26]. However, with the ongoing development in the mechanical manufacturing industry, alternative non-metallic materials, such as polymers, have been considered and are being studied for their feasibility in the manufacturing of valves. Polymers are being widely used as a material for the manufacturing of seals and certain valve parts, including covers, caps, handles, gaskets, etc., yet the main material used in the production of the key elements of valves is steel.

Table 3. A comprehensive comparison of PTFE, FEP, PFA, and PVC [27–29].

PTFE	PFA	FEP	PVC
Chemical Corrosion Resistance			
PTFE is the most chemically resistant polymer and is inert to most chemicals, including acids, bases, and solvents. However, some fluorinating agents, such as chlorine trifluoride and oxygen difluoride, gaseous fluorine, and molten alkali metals at high pressures and temperatures, can damage PTFE.	Likewise, PFA and FEP are extremely chemically resistant and inert to chemicals, including acids, bases, and organic and inorganic solvents. The chemical resistance of the polymer is enhanced by increasing the fluorine content.		PVC has good chemical resistance, but it is affected by strong solvents, ketones, and aromatic hydrocarbons. It is ideal for applications with moderate chemical exposure.
Mechanical Properties			
PTFE has high tensile strength and a high degree of flexibility. It is wear-resistant and has low friction and has a tensile strength at break and RT of 5000%.	It has a tensile strength at break and RT of 4500%.	FEP has lower mechanical properties at elevated temperatures and a tensile strength at break and RT of 3000%.	PVC offers good tensile strength and toughness.
Temperature Resistance			
PTFE can withstand temperatures from $-200\text{ }^{\circ}\text{C}$ to $+260\text{ }^{\circ}\text{C}$ ($-328\text{ }^{\circ}\text{F}$ to $+500\text{ }^{\circ}\text{F}$). Thus, it is well suited for high-temperature applications.	PFA has the same continuous use temperature range of $-200\text{ }^{\circ}\text{C}$ to $+260\text{ }^{\circ}\text{C}$ as PTFE.	FEP has a lower continuous use temperature range of $-200\text{ }^{\circ}\text{C}$ to $+200\text{ }^{\circ}\text{C}$.	PVC has low temperature resistance, generally ranging from $-15\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$ ($5\text{ }^{\circ}\text{F}$ to $140\text{ }^{\circ}\text{F}$), making it suitable for electrical insulation and residential plumbing.
Electrical Performance			
PTFE has high electrical insulator that maintains its dielectric properties over a wide range of temperature and frequency, making it well suited for high temperature and high frequency electrical applications.	Likewise, PFA and FEP have high-frequency dielectric properties that depends on the fluorine content in the molecule.		PVC has high electrical insulator, but its effectiveness decreases as temperature increases, limiting its use in harsh environments.
Injection Moulding			
PTFE does not flow, which is a basic requirement in melt-processing technologies. Thus, it cannot be injection moulded easily like other polymers.	PFA is a melt-processable fluoropolymer that can be injection moulded without the need for expensive secondary operations.	FEP is a melt-processable fluoropolymer that can be injection moulded.	PVC is a thermoplastic polymer that can be easily liquified and injection moulded.
Recyclability			
Primary, secondary, and tertiary recycling techniques.	Most melt-processable fluoropolymers can be reprocessed in a manner similar to other thermoplastics.		PVC can be reused, regrind, melted, and extruded numerous times. It can be easily melted down and reprocessed, thus it can be easily recycled.

RT, room temperature; PTFE, polytetrafluoroethylene; PFA, perfluoro alkoxy polymer; FEP, fluorinated ethylene propylene; PVC, polyvinyl chlorides.

It is important to select the right material in industrial applications to ensure

performance, durability, and safety. Polytetrafluoroethylene (PTFE) and polyvinyl chloride (PVC) are two commonly used valve polymer materials. PTFE, also known as Teflon, is a high-performance synthetic fluoropolymer that offers high chemical and heat resistance as well as non-stick and low-friction properties. PVC, on the other hand, is a thermoplastic polymer that is commonly used in healthcare, construction, and several other industries. Due to its high chemical and mechanical properties, it has become one of the most prominent plastics worldwide [27]. However, since the processing technology proposed for polymer valve manufacturing in this article is injection molding, it is worth noting that not all types of fluoropolymers are suitable for this application. This is because fluoropolymers are divided into two main categories: melt-processable and non-melt-processable. Melt-processable fluoropolymers are those that can be processed and manufactured into products by injection molding and other types of molding technologies; these are known as thermoplastics. On the other hand, non-melt-processable fluoropolymers cannot be molded by heating them into a molten state and can only be machined or compression molded. Since PTFE is a non-melt-processable fluoropolymer that cannot be injection molded due to its extremely high melt viscosity, other high-performance melt-processable fluoropolymers that can be used to make valves are fluorinated ethylene propylene (FEP) and perfluoro alkoxy (PFA) [28]. **Table 3** provides a comprehensive comparison of PTFE, FEP, PFA, and PVC.

The primary recycling of PTFE involves collecting, sorting, and grinding sintered PTFE scrap into a powder, which allows the material to be reused, although its physical properties are different from virgin PTFE. Reprocessed PTFE, for instance, usually shows decreased elongation and tensile strength. However, it remains suitable for specific applications, such as ram extrusion processes where both temperature and pressure are applied simultaneously. This technique minimizes the impact on the environment and eliminates the demand for additional raw materials by allowing the repurposing of PTFE waste [29]. Companies like Shamrock Technologies are at the forefront of primary PTFE recycling [30].

In contrast to primary recycling, secondary recycling involves the degradation of high molecular PTFE into micro powder. Industries achieve this process using high-energy radiation, such as beta or gamma radiation, or thermomechanical deterioration. They supplement the irradiation process with grinding to achieve the desired particle size. However, this process drastically reduces the molecular chain length to around 1% of its original length. As a result, the degraded PTFE's characteristics drastically change, rendering it inappropriate for common PTFE uses. Instead, the micro powder produced through secondary recycling is used as an additive in various other applications [29].

Tertiary recycling, also known as upcycling, involves the pyrolysis of PTFE under an inert atmosphere to recover valuable monomers such as hexafluoropropylene (HFP) and tetrafluoroethylene (TFE). These recovered monomers can be purified and reused in polymerization reactions to produce new fluoropolymer products. One of the advantages of this process is that it can process not only homogeneous PTFE but also fully fluorinated thermoplastics such as PFA and FEP. However, upcycling requires specialized infrastructure and equipment, limiting its accessibility to certain companies [29].

Tables 4 and **5** list the typical melting points, processing temperatures, and continuous use of the above-discussed fluoropolymers and the effect of increasing the fluorine content on the polymers' properties, respectively [28].

Table 4. Typical melting points, processing, and continuous use temperatures of fluoropolymers.

Polymer	Typical melting point (°C)	Typical processing temperature (°C)	Typical maximum continuous use temperature (°C)
PTFE	340	380	260
PFA	265–310	360–380	225–260
FEP	250–270	360	205

PTFE, polytetrafluoroethylene; PFA, perfluoro alkoxy polymer; FEP, fluorinated ethylene propylene.

Table 5. Effect of increasing fluorine content on fluoropolymer properties.

Property	Effect
Chemical resistance	Increases
Mechanical properties	Decreases
Thermal stability	Increases
Dielectric content	Decreases
Melting point	Increases
Coefficient of friction	Decreases
Flame resistance	Increases
Coefficient of friction	Decreases
Volume and surface resistivity	Increases
Dissipation factor	Decreases
Resistance to weathering	Increases

4. Results and discussion

4.1. Material properties comparison

A preliminary proposal of using PTFE as the valve material is taken (as shown in **Table 2**); however, other materials are compared and proposed in **Table 3**, depending on the application that best suits the material's properties. This is because PTFE is an extremely durable material that can withstand any type of corrosion, whether acidic or alkaline, due to its high chemical resistance and inertness. Its inelasticity makes it suitable for valve applications, and its hard, non-rubbery nature prevents it from stretching or bending, making it resistant to wear and tear, thereby preventing damage to the valve closing mechanism. Its non-stick property prevents the jamming and disabling of its moving parts due to any debris that can be formed by adhesion or abrasion, especially those caused by large particles. A more easily processable fluoropolymer that can be used as an alternative to PTFE is FEP, which can be melted in an extruder and used in injection molding. However, the main drawback of using FEP instead of PTFE is that it has lower mechanical properties at elevated temperatures, and thus, it has a lower maximum continuous use temperature of 200 °C. A better alternative to FEP is PFA, which has both melt processability and the same maximum continuous use temperature as PTFE (260 °C). Furthermore, there are other methods of molding or extruding PTFE, such as compression molding. In

this method, PTFE resin is filled into a mold cavity (usually with a simple shape, e.g., inner and outer diameters, basic profile, length, and width), and the powder is then compressed using a hydraulic press. The pressure ranges from 300 to 400 kg/cm². Owing to the high bulk density of PTFE, the resin is compressed in the mold to one-third of its volume. Therefore, for a product of height 100 mm, the mold will need to be filled to a height of 300 mm. After being compressed, the PTFE is allowed to sit for a few hours to a day, depending on its size, before being placed in a sintering oven, where the heat eventually approaches the PTFE's melting temperature, and the particles melt, creating the final product.

In any case, if the temperature of the fluoropolymer is within its continuous use range of -200 °C to +260 °C and does not exceed the operating temperature of 450 °C, the polymer will not degrade. According to Ebnesajjad [28], this is because fluoropolymers degrade in the presence of oxygen at temperatures above 450 °C to the oxidation products carbonyl fluoride and hydrofluoric acid and become toxic. Overall, the comprehensive comparison of the proposed polymer valve materials shown in **Table 3** shows that polymer valves are not as susceptible to rust, corrosion, or pitting as metal valves. Their chemical and corrosion resistance properties allow them to have a longer service life expectancy, which contributes to lower maintenance costs. Not only that, but they have a smooth interior lining and abrasion resistance, thus creating a higher flow coefficient and providing even flow rates over time. They are also lightweight, which in turn eases installation by reducing material handling, freight, labor, and installation costs. In addition, as shown in **Figure 7**, the improvement of the valve reduces the number of parts, which also extends the service life of the valve, reduces the maintenance workload, and improves the reliability of the valve and the ease of assembly. The replacement of traditional steel springs with springs made from FRP composites contributes to the valves lighter weight advantage, improving the valves strength-to-weight ratio, as well as increasing stiffness and impact energy absorption and reducing stress, in line with Kara's study [25].

However, as one might expect, metal valves are better suited for heavy-duty applications, such as industrial processes involving high-pressure and high-temperature systems. Plastic valves, on the other hand, are often used in applications where chemical compatibility or metal corrosion is an issue. This has led to widespread acceptance of plastic valves in commercial and industrial applications such as water supply, water and wastewater treatment, irrigation systems, metal and chemical processing, food and pharmaceuticals, and low-pressure systems. In conclusion, metal valves are typically more durable compared to plastic valves; however, the decision between metal and plastic valves should be determined based on the application's specific requirements, considering chemical compatibility, pressure, temperature, and budget limits. While PTFE has many advantages due to its unique properties, it also has some limitations that need to be considered. For example, compared to metals, PTFE has a relatively low load-bearing capacity; in other words, the maximum load that the material can support without excessive deformation is lower. This limits its use in applications that require high load-bearing capabilities or mechanical strength. Despite these limitations, PTFE remains a beneficial material in many applications that need its unique qualities; therefore, it is critical to carefully examine these issues before selecting PTFE for a particular application. **Table 6**

displays a summary of the trade-off between some common metal alloys used as valve material and PTFE in terms of the material’s properties. To improve the stability of the valve during use, it is of great significance to consider the medium of the application and choose the appropriate valve material. The durability and performance of valves are based on the properties of the chosen manufacturing material and the application’s environment, which, for instance, can be quantified by chemical exposure testing, salt spray testing, routine mechanical testing, and fatigue testing.

The implications of the trade-offs between metallic and polymeric valves for sustainable manufacturing fall within the theoretical framework of 6R, where all its concepts play an important role in promoting sustainable and environmentally conscious manufacturing. The redesign concept was applied by creating a new valve model with a reduced number of parts and the use of alternative materials, which in turn played a role in the reduction concept. This will reduce consumption, energy, emissions, and waste output from the mining of metal ores. Also, choosing polymer as an alternative material contributes to the valve’s product life by extending its life cycle due to its non-corrosive properties, which can be recovered, recycled, and reused as per the 6R framework.

Table 6. Trade-off between metallic and polymeric valves in terms of material properties [28,31–36].

Property	Metallic valve			PTFE valve
	Stainless Steel	Brass	Bronze	
Chemical resistance	AISI 304 is highly resistant to organic acids, such as sulphuric, nitric and phosphoric acids.	Good corrosion resistance—can be harmed by high salt and chlorine levels.	Bronze has a higher corrosion resistance than brass—ideal for seawater applications.	Most chemically resistant polymer—inert to acids, bases, and solvents.
Melting point	The melting point varies depending on the ratio of the alloy components. AISI 316: 1375–1400 °C AISI 303: 1400–1420 °C	Brass has an average value of 927 °C	Bronze has an average value of 958 °C	340 °C
Continuous service temperature	AISI 316 and AISI 302: 925 °C	Brass service temperature can range from 200 to 250 °C.	ASTM B61: 287 °C ASTM B62: 232 °C	260 °C
Tensile strength	Stainless steel has an average value of 935 MPa	Alloy 360 brass: 338–469 MPa Alloy 464 brass: 379–607 MPa	ASTM B62: 205 MPa	It has an average value of 20.7 to 34.5 MPa
Wear resistance	Higher content of carbon increases the wear resistance of stainless steel.	Brass has a poor wear resistance compared to bronze.	Bronze has a higher tin content than brass, making it more resistant to wear and tear.	PTFE has low friction coefficient, resulting in high wear resistance.
Weight per Volume (kg/m ³)	AISI 316: 8000 AISI 302: 7860 AISI 303: 8027	It varies depending on the composition. (typically, between 8400 to 8700)	Aluminium bronze C95400: 7450	2200 (Lightest weight)

4.2. FRP spring substitution

Fatigue performance in safety valve standards, such as those from ASME, API, and ISO, is crucial for ensuring the valve’s reliability and longevity, especially under cyclic operating conditions. These standards incorporate requirements for material selection, design criteria, and testing procedures to mitigate the risk of fatigue failure, which can lead to leakage, malfunction, or even catastrophic failure. Industry standards such as API 526 and ISO 4126-1:2013 specify requirements for safety valve design, including material selection and performance criteria, with a focus on fatigue

resistance. The materials used in safety valve components, especially the springs, play a significant role in their fatigue life. Factors like high temperatures, corrosive substances, and improper repairs can also contribute to fatigue failure, emphasizing the need for regular maintenance and inspection.

Choi and Choi investigated the static spring stiffness of coil springs made of carbon fiber reinforced epoxy (thermosetting resin) composites, known as CFRP. According to their study, the shear modulus of the composite material with a 45° ply angle was found to be approximately 16.8% of that of steel. Based on the data obtained from their study, the estimated shear modulus was in good agreement with the experimental results. Furthermore, their research showed that coil springs made of CFRP can reduce weight by about 55% compared to steel springs [37].

Sequeira et al. conducted a numerical study of some mechanical behaviors of carbon and Kevlar composite coil springs and steel coil springs using ANSYS software. Their research shows that the specific modulus (Young's modulus (E) on mass density of the material (ρ)) of the CFRP composite spring is the highest. However, the load and deflection characteristics of steel springs have been found to be superior to composite springs. Also, the weight of the CFRP helical spring has been determined to be very low compared to the steel one, and it is very beneficial to use a carbon spring instead of a steel spring to reduce the weight of the related mechanical systems [38].

In most cases, FRP composite springs show better mechanical behavior than conventional steel ones. However, composite springs need a special design process, especially dimensional optimization, which plays a crucial role in the mechanical behavior. Mechanical properties of such springs can be established by a micromechanics approach (analytically). For the analysis purpose, ANSYS software is recommended, as it gives adequate results. Investigation shows that CFRP achieves the best mechanical behavior for FRP helical spring design [25].

In summary, while some FRPs have good fatigue and creep resistance, their suitability for safety valve applications must be carefully evaluated based on the specific design, loading conditions, and applicable standards. Furthermore, the manufacturing of the composite coil spring is very important to its final mechanical properties [25]. According to all research, the best manufacturing process, which is effective positively, can be proposed as a combination of filament winding technique (FWT) and resin transfer molding (RTM) [25].

4.3. Energy consumption and CO₂ emissions comparison

Carbon dioxide emissions are by far the most destructive and dangerous greenhouse gas, making metal production the leading cause of global warming. Therefore, exploring alternative metal materials (such as polymers) for valve production opens the door to optimizing CO₂ emissions. For example, the use of polymers eliminates the idea of metal ore mining, which is one of the largest sources of CO₂ emissions. The average carbon footprint of the raw material used in Broen valves per kilogram of finished product is 5.58 kg CO₂e for stainless steel [18]. On the contrary, the CO₂ emissions from the manufacturing of PVC, for example, are 7.83 kg CO₂e [39]. Although the production process of a product contributes significantly to

its carbon footprint, the overall carbon footprint of any of the mentioned materials, whether a metal or a polymer, should be determined not only based on its production (A1-3) but also based on all its LCA modules, as elaborated by **Figure 5** [21]. Furthermore, Shamrock Technologies estimated the CO₂ emissions from PTFE production by conducting a polymerization plant model study; the model was based on a U.S. fluorochemicals site that produces PTFE. Based on this model, they were able to estimate the total energy consumption of PTFE production and, from this, convert the required amounts of electricity and natural gas into CO₂-equivalent emissions [39]. According to their analysis, the carbon footprint of PTFE polymer is approximately 9.6 kg CO₂e/kg PTFE, and the estimated total energy consumption for PTFE production includes 5400 kWh/MT (19,440 MJ/MT) using electric energy and 680 Therm/MT (\approx 72,000 MJ/MT) using natural gas. This math excludes the energy consumed in mining calcium fluoride as well as the production of chloroform and sulfuric acid, all of which contribute to total energy consumption. They also found that using one kilogram of recycled PTFE in place of virgin PTFE could reduce CO₂ emissions by at least ten kilograms [30].

According to the LCA carried out by Haque and Norgate [20], the embodied energy values from the mining and processing of 1 ton of iron ore were 153 MJ. Furthermore, as mentioned by Ahmed and Enemuoh [40], the energy embodied in the primary production of stainless steel is 77,000–85,000 MJ/MT, while that embodied from recycling is about 22,000–25,000 MJ/MT. Correspondingly, according to stainless steel manufacturer Double Stone Steel, it takes about 15,000–25,000 MJ of energy to produce 1 tonne of stainless steel [41]. However, the choice of valve production material depends on a variety of factors, all of which must be considered to make an optimized decision.

5. Conclusion

Despite the widespread use of valves in several industrial sectors, little attention has been paid to the environmental impact of their design and production. The redesign concept has been applied to pressure relief valves by suggesting the use of alternative materials such as PTFE instead of metal. The study evaluated the appropriateness of the suggested materials using a variety of relevant tools, such as carbon dioxide emissions and energy use. The modified sustainable design resulted in fewer valve parts, easier assembly, less weight, and lower cost, and the valve is made entirely of polymer rather than metal, which reduced the total carbon emissions from the valve's production. Furthermore, the foundations of this article can be applied to the design and manufacturing of any other mechanical or electromechanical system.

However, as one might expect, metal valves are better suited for heavy-duty applications, such as industrial processes involving high-pressure and high-temperature systems. Plastic valves, on the other hand, are often used in applications where chemical compatibility or metal corrosion is an issue. In conclusion, metal valves are typically more durable compared to plastic valves; however, the decision between metal and plastic valves should be determined based on the application's specific requirements, considering chemical compatibility, pressure, temperature, and budget limits.

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Abbreviations

FAT	Factory Acceptance Testing
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
GWP	Global Warming Potential
NBR	Nitrile Butadiene Rubber
ASIS 316	Stainless, austenitic chromium-nickel-molybdenum steels
AISI 302	Stainless steel 302
AISI 303	Austenitic stainless steel
PTFE	Polytetrafluoroethylene
PFA	Perfluoro Alkoxy
FEP	Fluorinated Ethylene Propylene
PVC	Polyvinyl Chloride
FRP	Fiber Reinforced Polymer
HFP	Hexafluoropropylene
TFE	Tetrafluoroethylene
AISI 304	Austenitic chromium-nickel stainless steel
ASTM B61	Copper Alloy UNS No. C83600
ASTM B62	Copper Alloy UNS No. C83600
CFRP	Carbon Fibre Reinforced Polymer
FWT	Filament Winding Technique
RTM	Resin Transfer Moulding

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