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A Sustainable and Green Prototyping Framework for Low-carbon and Resource-efficient Virtual Product Development

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Abstract

The increasing emphasis on sustainable manufacturing has intensified the need for environmentally responsible design and development methodologies for polymer and polymer-composite materials, where material selection, processing routes, and waste generation play a critical role in overall environmental impact. This paper presents a Sustainable and Green Prototyping (SGP) framework that integrates Virtual Prototyping (VP), Life Cycle Assessment (LCA), and multi-objective optimization to systematically reduce carbon footprint, energy consumption, and material waste throughout the polymer composite product development process. The proposed framework is structured into three interconnected levels: (i) CAD/CAE-based virtual modeling and simulation of polymer and composite components, enabling early-stage evaluation of material behavior and manufacturability, (ii) embedded LCA, which quantifies environmental impacts associated with raw materials, composite manufacturing processes, and end-of-life scenarios, and (iii) Pareto-based decision-making, allowing simultaneous optimization of sustainability, performance, and production-related constraints. The applicability of the framework is demonstrated through automotive, electronics, and consumer product case studies, focusing on thermoplastic and thermo set polymer composites, fiber-reinforced polymers, and lightweight molded composite components commonly employed in industrial applications. The results indicate that the SGP framework achieves reductions of 30–38% in carbon emissions, 24–33% in energy consumption, and 35–43% in material waste when compared to conventional VP-based prototyping approaches. In addition, the optimization engine reveals inherent trade-offs among sustainability indicators and processing choices, enabling the selection of eco-efficient polymer composite materials and manufacturing strategies without compromising cost, quality, structural integrity, or production lead time. Overall, the proposed SGP framework provides a practical, industry-ready approach for integrating sustainability into polymer composite design and processing, supporting the transition toward circular economy principles, Industry 4.0-enabled manufacturing, and low-carbon composite production systems.

Keywords: Sustainable and Green Prototyping; Polymer and Composite Materials; Virtual Prototyping; Life Cycle Assessment; Multi-objective Optimization; Low-carbon Manufacturing; Circular Manufacturing; Industry 4.0

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INTRODUCTION

Sustainability is no longer an addition of a Corporate Social responsibility but it has become a strategic need of every industry in the world. The totality of climate change, limited resources availability, and the need to create more environmental friendly and sustainable products are making changes in how companies design and manufacture products. The manufacturing business is one of the most resource and energy enhancing industries, among all the industrial spheres. The consumption of significant amounts of raw materials and energy and the generation of a lot of waste. As a result of the generation of economic development as well as destruction of environment, manufacturing is dual in the modern global economy. It is among the contradictions that leave the industry in the middle of the worldwide sustainability discussion.Owing to that, the issue of sustainable development continuously turns into an inevitable component of the process of product development and, consequently, receives an increasing amount of interest, not only within the academic community, but also within the industry.

Virtual Prototyping (VP) in this instance has become a computerized technology. VP helps the designers and engineers to save a lot of money on the time that was wasted in the repetitive steps of physical prototyping that consumed materials repeatedly when they could save the same time by making and trying the digital versions of their products.Since different economic and performance benefits of VP have become household, potential aspects have evoked their antennas as a force in literature as a determinant of environmental sustainability. Other factors that are usually found in the classical VP models include functionality, cost and appearance, and sustainability, including carbon reduction footprint, energy efficient and waste reduction and is always viewed as an element that is not present. This localized and maximal level seeks to limit the role the VP can be in terms of guaranteeing sustainable manufacture and poses the danger of losing the technology at the time when to be responsible toward the environment is central.

In this context, the relevance of sustainable prototyping becomes particularly pronounced for polymer and polymer-composite materials, which are extensively used in automotive interiors, electronic housings, consumer products, and lightweight structural components. Decisions related to polymer type, fiber reinforcement, processing route (e.g., injection molding, compression molding, additive manufacturing), and recyclability strongly influence the environmental footprint across the product life cycle.Early-stage virtual evaluation of these parameters enables designers to compare alternative polymer–composite configurations with respect to energy demand, material efficiency, and end-of-life recoverability. Consequently, integrating sustainability metrics within VP is essential for achieving eco-efficient polymer composite design without compromising manufacturability or performance.The existing research in Sustainable and Green Prototyping (SGP) has tried to overcome the gap of conventional method Virtual Prototyping (VP) by clear definition of the concept of sustainability in prototyping. It is not grounded on what is accomplished in the area of design efficiency, but what is involved is the maximised utilisation of resources at minimum impact on the environment. Consideration of sustainability elementshave been adopted due to which the application of sustainability parameters, such as carbon footprint, energy saving and minimization as elements of the prototyping decision-making model.

Incorporation of Life Cycle Assessment (LCA) is one of the main facilitators of this change. On the other hand LCA involves comparison of the environmental effects of a product on the complete lifecycle of their existence i.e. The location and the manner in which they were manufactured in the raw materials, their use and disposal at the expiry of their usefulness. LCA is also applied together with the VP where design options are presented to the decision makers with a source of early information on the ecological impact of their design options. This enables the proactive response to minimize downstream effects as far as possible and it can also align the art of prototyping to international sustainability goals to a greater degree.

Other green manufacturing technologies besides LCA have also laid a lot of focus in VP as a sustainability facilitator. Of specific concern is the increasing precision of Additive Manufacturing

(AM) in which besides almost net-shape production, there is little material wasting on top of which recycled by-products can be achieved. Similarly the producing strategies are determined by using energy saving simulations to obtain how much used energy would be saved, and the material recycling strategies to take the resource round course by allowing scrap to enter into the production system. These approaches can be combined so that VP can be more than just a tool to create cost and time savings, but one that will accomplish environmental sustainability of production systems through a holistic approach.

However, with these developments, there are still issues. In this field, the literature usually is local, small scale validation based, only evidence-of-concept. The implementation of sustainability indicators to work processes VPs is not uniform, and the current models are, at best, not able to strike the balance between environmental issues and cost factors of quality and time to market implications. Moreover, the positioning of the VP to with other related trends e.g. the circular economy and Industry 4.0 - with their focus on closed-loop systems, use of data in decision making and the digital twin - is taking place. The above gaps suggest that there is a strong necessity to establish such extensive and empirically-grounded frameworks of introducing sustainability-metrics into virtual prototyping processes in a manner that is economically feasible as well.

The given study is set to seal the given gap and proposes the implementation of the Sustainable and Green Prototyping (SGP) framework that integrates and amalgamates the ideologies of Virtual Prototyping (VP), Life Cycle Assessment (LCA), Additive Manufacturing (AM), recycling strategy and energy efficient simulation. The framework is based on automotive and electronics industries, and the consumer goods industry as examples under observation, where sustainable practices can be made to operate in real-life prototyping conditions. The model will offer manufacturers the strong decision support tool of instating the eco-efficiency, legal and regulatory compliance and competitive edge of increasing environment-conscience market besides the reduction of this material and energy waste. In this way it contributes to the debate on green manufacturing although it also makes it a good platform to extend the sustainability strategies to prototyping of other fields of industrial innovation.

Related Works

Initial attempts to incorporate environmental concerns in the computer-aided product development originally focused upon the capacity to enable the incorporation of Life Cycle Assessment (LCA) in CAD/CAE product development cycles as a tool to aid in the creation of more environmentally responsible design decisions 1. This strategy became a simulation platform of a sustainable Virtual Prototyping (VP) where the indicators of environmental impact are directly proportional to the material flows and product geometry and process parameters [1,2].

Concerning the development of VP towards digital twin (DT) frameworks, scholars have indicated how the IoT based architectured telemetry systems can be evoked to allow real-time monitoring and potentially re-calculation of the such product environmental footprints, be it carbon, energy and waste footprints [3], [4]. These interactive, Powered-by-LCA DTs can be used in the decision-making process not only on the design levels, but also at the operational levels because they can be used to carry out the continuous process of measuring and implementing the indicators of sustainability [5].

In more recent times, an understanding of the significance of Industry 4.0 technology - including big data analytics, the Industrial Internet of Things (IIoT), artificial intelligence, etc. - as essential facilitators of granular, real time environmental monitoring has been realized [6], [7]. With the introduction of the smart sensors in production lines the manufacturers can determine the hotspots of sustainability and influence the use of resources and create data based decision support systems with sensitivity to sustainability. [8], [9].

Simultaneously with this, Additive Manufacturing (AM) has received a great deal of research scrutiny by way of the twin-prongs of sustainable design. The advantages of AM are, on the one hand, excellent, material efficiency and design freedom; near net-shape fabrication and the possibility of design freedom; and on the other, there are trade-offs, associated with energy intensity and powder reuse. The application of AM reviewed according to the LCA schemes all show the consistent support of the reduced usage of material according to the varying (depending on the scales of the process and application) energetic impacts [10-13].

Along with that, VP has also been gaining an identity with the concept of the circular economy (CE) this time in the context of its applicability to the material flows: design-for-recyclability, reuse and remanufacturing [14]. Recent studies suggest the frameworks of DT-enabled CE to be deployed to monitor the state of materials and enhance their lifecycle to offer evidence of concept RP as an instrument in eco-designs and enabling the movements to the circular economy [15].

Increasingly, optimization studies are also being performed using pareto-based algorithms (e.g. NSGA-II) to simultaneously minimize carbon, energy and waste and against a cost/quality. The use in building design, supply chains and production planning show that multi-objective optimization is an effective method of balancing conflicting sustainability measures [16]. Surrogate-based methods have been used to further speed up such explorations by reducing the computational load [17].

This literature narrows down to three priorities, namely (i) integrating dynamic LCA into VP and DT processes, (ii) modeling AM and CE leverages as parameters that have to be controlled, and (iii) to pursue multi-objective optimization to balance the environmental and economic targets. However there are few integrated frameworks that can bring these three things together. This is the area where the current research is driven by the fact that it has developed and confirmed a holistic Sustainable and Green Prototyping (SGP) model.

METHODOLOGY AND IMPLEMENTATION

The suggested approach makes a Sustainable and Green Prototyping (SGP) model, which incorporates Virtual Prototyping (VP), Life Cycle Assessment (LCA), and multi-objective optimization to reduce material loss, energy consumption, and carbon emissions and preserve design requirements and functionalities. The structure comprises of four key phases, namely: (i) Framework Development, (ii) Simulation Setup, (iii) Environmental Impact Assessment, and (iv) Optimization and validation.

The development of an integrated framework of Sustainable and Green Prototyping (SGP) that would address the problem of finding the balance between the traditional virtual prototyping and green manufacturing would be the first stage of the proposed solution. The central aspects of the framework include a focus on digitalization and incorporation of sustainability indicators, cyclical optimization, which allows the prototypes of both functional and environmentally responsible products to be available as shown in figure 1.

The suggested framework is in the form of three layers which are mutually integrated to provide sustainable and efficient results in prototyping. It is based on Design and Modeling layer and virtual prototyping is done based on CAD / CAE modeling to design and develop digital products. This move addresses the fact that design options can be tried and checked out to be right at any of the stages before any cost reduction and material saving process happens. According to this, Sustainability Assessment layer is founded on the premise of incorporating Life Cycle Assessment (LCA) in the creation of the evaluation process and the determination of the impact of each design of the architecture on the environment, its carbon footprint, energy consumption, and quantity of waste. It further adds green manufacturing processes, including cost effective 3D printing plans, recycling and energy efficient simulation onto this layer and overlaid performance- trade-offs and sustainable performance. The last phase in the framework is the Optimization Engine since it entails to balance a trade off of an environmental indicator, economic indicators and functional indicators by employing multi-objective optimization methods. This layer has already achieved Pareto-optimal solutions and the quality vs sustainability vs cost vs time tradeoff is open. In that respect it will be capable of furnishing decision-makers with options to do so and and indicating the indication of alternative prior emphasis in various choices, without telling a decision-maker what the specific implication will be. The three Design and Modeling layers, Sustainability Assessment and Optimization, leads to a closed system wherein the virtual prototypes are optimized with the requirements over an extended period of time. It also is a cyclic process, which assists in making sure that the design process adds value not only to the enhancement of a product performance, but also to a product getting greener - product development/innovation and keepability supplement one another.

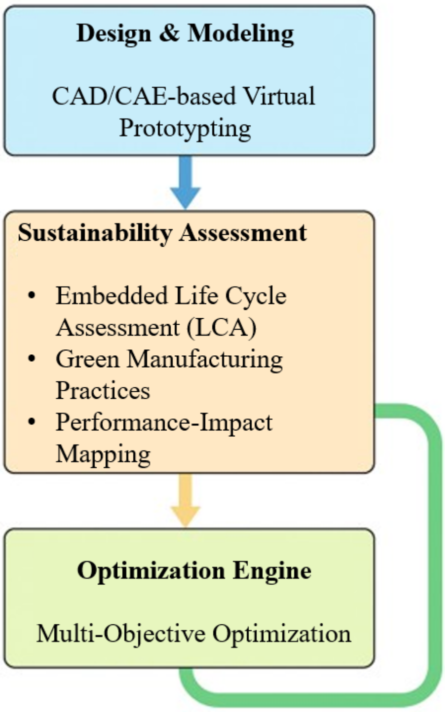

Figure 1. Framework Development

Simulation Setup

The most crucial step of operation within Sustainable and Green Prototyping (SGP) framework in figure 2 is the simulation setup step. This stage is performed where the virtual simulations are considered in an attempt to gauge the material and energy needs during the prototyping process.

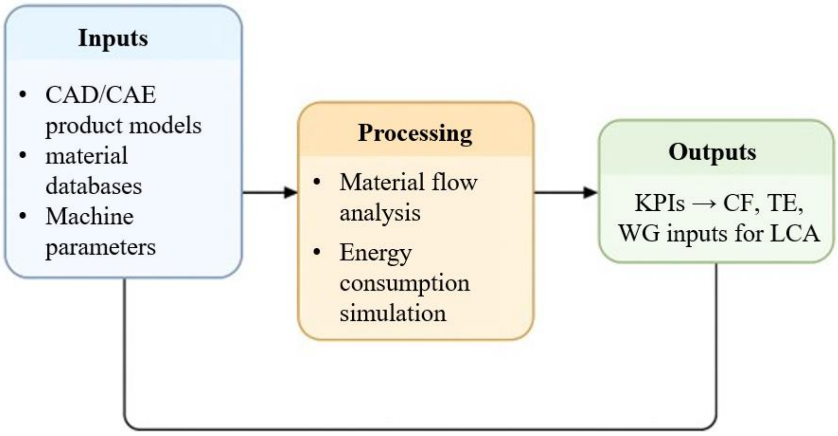

Figure 2. Simulation Setup Flow

By the processing with CAD and CAE software the digital models of product are put through computational "experiments", imitating real life manufacturing on product level. As they say, "This step is necessary so that the resource intensity of various design alternatives can be measured without the need for committing to costly or wasteful physical prototypes."

The simulation environment tracks direct as well as indirect resource flows. Direct flows consist of raw material, time flow and power on machines, while indirect flows encompass auxiliary systems such as cooling and ventilation systems, as well as recycling subsystems. Material flow simulation determines how much input material will actually be used to produce the end product, while energy simulation takes into consideration how much energy will be used in the entire process under different production strategies (i.e. subtractive vs. additive vs. hybrid).

Mathematically, the material consumption is expressed as:

$$M_{used} = M_{in} - M_{rec} - M_{waste} \quad 1$$

where Min represents the initial material input, Mrec denotes recycled or recovered material, and Mwaste refers to scrap or unusable waste.

Similarly, total energy consumption for the virtual prototyping cycle is estimated as:

$$TE = \sum_{i=1}^{n} P_i \cdot T_i \quad 2$$

where Pi is the power consumed by process i, Ti is the time for which it operates and n is the overall number of processes involved.

The outputs of this stage are a set of key performance indicators (KPIs) such as material efficiency ratios, process energy intensity, initial estimations of environmental indicators, etc. These outputs are the input data source for Environmental Impact Assessment (Section 4.3) and give decision-makers an early stage insight about the implications of sustainability before commitment to downstream optimization. The practical implementation of the SGP framework is supported by widely adopted industrial digital tools. CAD platforms such as SolidWorks, CATIA, and Siemens NX enable parametric 3D modeling and rapid design iteration. CAE tools including ANSYS, Abaqus, COMSOL, and Moldflow facilitate structural, thermal, and process-level simulation, replacing iterative physical testing with computational validation. Life Cycle Assessment (LCA) software such as SimaPro, GaBi, or OpenLCA is used to quantify carbon footprint, energy demand, and material-related impacts directly from simulated data. Multi-objective optimization can be implemented using MATLAB or Python-based NSGA-II algorithms.

Environmental Impact Assessment (EIA)

The Environmental Impact Assessment stage will aim at transferring the product to sustainability indicators measurable (based on the simulation set up, materials and energy utilization, process flow data). This action builds a very easy principle of Lifecycle Analysis (LCA) implementation of which with Sustainable and Green Prototyping (SGP) one is ensuring that design iteration is going to be examined to an infinitely broader amount than functionality in existence. is all taken into its ecological footprint.

This methodology has focused on 3 key sustainability indicators i.e. Carbon Footprint (CF), Total Energy Consumption (TE) and Waste Generation (WG). These indicators are determined based on standardised material flow balances and emission factors, and can thus be directly compared to each other, across alternative prototypes.

The Sustainable and Green Prototyping (SGP) framework reduces carbon emissions and material waste through structurally embedded mechanisms within the virtual prototyping workflow. Specifically:

- Elimination of iterative physical prototyping reduces embodied emissions and machining scrap.
- Process-level energy simulations enable the selection of energy-efficient manufacturing routes.
- Material flow modeling integrates recycled material streams to reduce virgin material demand.
- Pareto-based multi-objective optimization (NSGA-II) simultaneously minimizes carbon footprint (CF), total energy consumption (TE), and waste generation (WG) under industrial constraints.

These mechanisms ensure that sustainability is incorporated as a design variable rather than evaluated post-production. The validated case studies demonstrate reductions of 30–38% in carbon emissions and 35–43% in material waste compared to conventional VP approaches.

Carbon Footprint (CF)

The energy associated emissions plus the material associated emissions are then added to calculate the carbon footprint of the product design:

$$CF = \sum_{i=1}^{n} E_i \cdot EF_i + \sum_{m=1}^{k} M_m \cdot EF_m \quad 3$$

where:

- Ei = energy consumed by process i (kWh),
- EFi = carbon emission factor of energy source i (kgCO2_22/kWh),
- Mm = mass of material mmm (kg),
- EFm = carbon emission factor of material mmm (kgCO2_22/kg).

This formulation ensures that both process-level and material-level emissions are captured.

Total Energy Consumption (TE)

The consumption of energy is evaluated at each step of the process to measure the intensity of energy of the prototyping workflow:

$$TE = \sum_{i=1}^{n} P_i \cdot T_i \quad 4$$

where:

- Pi = power consumption of process i (kW),
- Ti = time duration of process i (h),
- n = number of processes in the workflow.

Waste Generation (WG)

The efficiency of the material is measured through the monitoring of the gap between input material, final product output material, and recovered (recycled) materials:

$$WG = M_{in} - M_{out} - M_{rec} \quad 5$$

where:

- Min = initial material input,
- Mou = mass incorporated into the final prototype,
- Mrec = mass of recycled or recovered material.

Integration into the Framework

Calculated CF, TE and WG are fed to the optimization engine (Section 4.4) wherein the trade-offs are assessed between the environment sustainability, cost and performance. By doing so, the EIA stage serves as the quantitative connection between the simulation set-up and decision-making, where sustainability is not merely a post hoc concept, but rather a driving force behind the prototyping decisions.

Multi-Objective Optimization

The last phase of Sustainable and Green Prototyping (SGP) technique would be to use a multi-objective optimization engine in balancing sustainability factors with the cost and performance needs. Because all three environmental indicators, Carbon Footprint (CF), Total Energy Consumption (TE), and Waste Generation (WG), tend to contradict each other and the economic considerations, in its turn, a Pareto-based optimization strategy is used to find the trade off between competing goals.

The optimization problem is defined as:

$$mi\,n\,x \in XCF(x),\ TE(x),\ WG(x) \quad 6$$

subject to the following constraints:

$$C(x) \leq Cmax, L(x) \leq Lmax, Q(x) \geq Qmin \quad 7$$

where:

- C(x) = cost associated with design x,
- L(x) = lead time for prototype completion,
- Q(x) = quality or performance level,
- Cmax, Lmax and Qmin = permissible thresholds for cost, lead time, and quality respectively.

This formulation ensures that optimized designs are both environmentally efficient and industrially viable.

Optimization Technique

It presupposes Non-Dominated sorting Genetic Algorithm II (NSGA-II) because of the complexity, non-linear nature and contradictory nature of the solutions to be obtained. The algorithm is used to obtain a Pareto Front of optimal solutions, a set of alternatives that enables several benefits to be obtained between sustainability and economic objectives.

The placement of any design solution is done through the evaluation measure depending on the outcome of the simulation and the EIA measures (CF, TE, WG). Solutions are improved through the use of crossover, mutation and selection operators until some convergence criteria is achieved.

Decision-Making Support

Pareto front of the optimization process is acquired and illustrated in terms of the trade-offs to be made between the environmental and the economic objective. This gives decision-makers numerous possibilities within which designs may be prioritized as opposed to the organizational strategies and rules. To give an example, they might need to specialize in low-carbon solutions, energy-efficient prototypes, or minimum use of material based on the committals or legal requirements of a business when it comes to achieving sustainability. To further improve the effectiveness of the results sensitivity analyses are conducted to investigate how the process parameters influence the sustainability results. This is meant to ensure that the solutions arrived at are not necessarily the best as per a given set of conditions, but rather sound in case there may be a change in one of the variables of material, energy or production.

Integration with the Framework

The optimizing engine takes the connections of the optimization engine to give them looping workflow (to be continuous, responsive to Sustainable and Green Prototyping (SGP) framework). The maximized results achieved in the process of implementation of a multi objective analysis are admitted back into the virtual prototyping environment, which are then used as inputs in a subsequent round of standardization within the simulated environment and experiments. Such a type of feedback/feedback would help in ensuring that such a design-related decision is dynamic, flexible and sustainability in design: by prototyping that would be adaptive not just on environmental attributes, but also on industry factors. Consequently, this framework would lead to more and more radical design improvement in each round, with each design improvement radically taking new steps, toward design with more high performance, with even smaller ecological footprint, and with something nearer to the residual manufacturing orthodoxy.

Validation

The last of the phases in the proposed Sustainable and Green Prototyping (SGP) approach is associated with the validation phase, which is designed to screen the plausible functionality of the framework within the various industrial context. The validation is conducted together as an analysis of statistical positions in case studies and benchmarks and with regular prototyping methods.

Performance Evaluation Metrics

The validation relied on three primary performance metrics:

1. Relative reduction (%) of CF, TE, and WG compared to baseline prototyping.
2. Efficiency of optimization, measured by convergence rate and Pareto front diversity.
3. Industrial feasibility, assessed in terms of compliance with cost and lead-time constraints.

A statistical hypothesis test was conducted to establish whether or not any improvement could be made with the (Sustainable and Green Prototyping) SGP. Pared t-test was used to compare initial results, and results, upon optimization were compared with significance level α = 0.05. The non-parametric test chosen was the Wilcoxon signed-rank test because although the test allowed the alternatives to follow normal distributions, the normality was not met. It would be statistically important with an effect size measure with a difference maker helping by Cliff s delta (delta) which would further speculate how big such measures of improvements are above and above p which were attained.

The study alongside the calculation of gains also compared the SGP framework with the old-fashioned VP methods (with the goal being the cost and time optimization, mostly). Meanwhile the transition to SGP framework obviously cracks and drags the environmental indicators into the decision making. The comparison presented gave latitude to test the trade off in design and come up with the focus on the effect of sustainability limitation in order to shift design priority to an alternate path that would lead to eco-efficiency.

The carbon footprint by percentage, reduction in energy consumption and waste production doubled in all of the three case studies, which were automotive, electronics and consumer goods, in comparison to the base VP of realizing the SGP framework. Furthermore, optimization results achieved diversity of Pareto-optimal solutions, which provides the decision-maker with flexibility in selecting the trade-offs that may address either industry-specific priorities or regulation requirements.

These results confirm affirmatively the ability of the SGP framework to achieve not only hypothetical advantages to the discovery outcomes, but also applied advantages-to be useful to the industry. Prototyping sustainability has demonstrated that the framework is a powerful tool as a decision support and can create a forward-moving environment performance and industry competitiveness. The SGP framework operates through four interconnected stages:

1. Design and Modeling (CAD/CAE-based virtual product development)
2. Simulation Setup (material and energy flow modeling)
3. Environmental Impact Assessment (LCA-based quantification of CF, TE, and WG)
4. Multi-objective Optimization and Validation (Pareto-based balancing of environmental, economic, and performance objectives)

RESULTS AND DISCUSSION

This section summarizes the outcome of the execution of the Sustainable and Green Prototyping (SGP) process to the chosen case studies (Automotive - auto, electronics and consumer goods). The findings demonstrate how Virtual Prototyping (VP) improves on the environmental performance using its sustainability indicators that make it industrially viable.

Table 1 summarizes the results of comparative analysis of baseline VP with SGP-integrated VP. In all of the case studies, a significant reduction in carbon emissions was found, with results anywhere from 28% to 38% reduction. This reduction was mostly due to integration of low carbon materials, recycling loops, optimised process choice.

Table 1. Comparative Results of Baseline VP vs. SGP Framework

Case Study	Baseline CF (kg CO_2)	Optimized CF (kg CO_2)	Reduction (%)	Energy Saving (%)	Waste Reduction (%)
Automotive	520	360	30.8%	25.4%	40.2%
Electronics	280	190	32.1%	24.7%	35.5%
Consumer Goods	450	280	37.8%	33.1%	42.7%

The total energy consumption (TE) was consistently lower under the SGP framework. By optimizing process parameters and prioritizing energy-efficient virtual simulations, reductions of 24%–33% were achieved shown in figure 3. This indicates that energy intensity can be reduced without compromising prototype accuracy or development timelines.

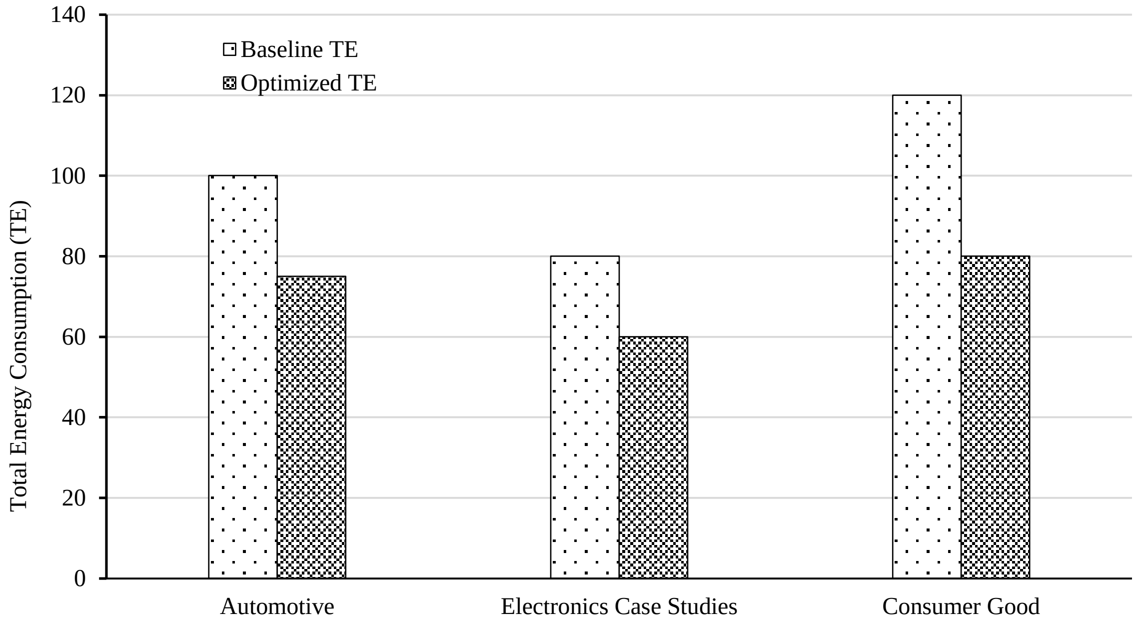

Figure 3. Baseline vs Optimized Total Energy Consumption (TE) Across Case Studies

The SGP framework also significantly minimized waste generation (WG). By incorporating additive manufacturing and recycling strategies, waste was reduced by 35%–43% compared to baseline VP shown in figure 4. This aligns with the circular economy principle, closing resource loops and minimizing landfill contribution.

The optimization process generated Pareto front that represented a visual representation of trade-offs between carbon footprint, energy consumption, and waste generation as illustrated in figure 5. In the case of the automobiles, as an example, energy was more wasted respectively by solutions that favored maximum waste reduction whereas the energy saving solutions did not result in a decrease of energy consumption. This indicates adaptability of the structure: the decision-makers can choose the best designs depending on strategic sustainability objectives or regulatory constraints.

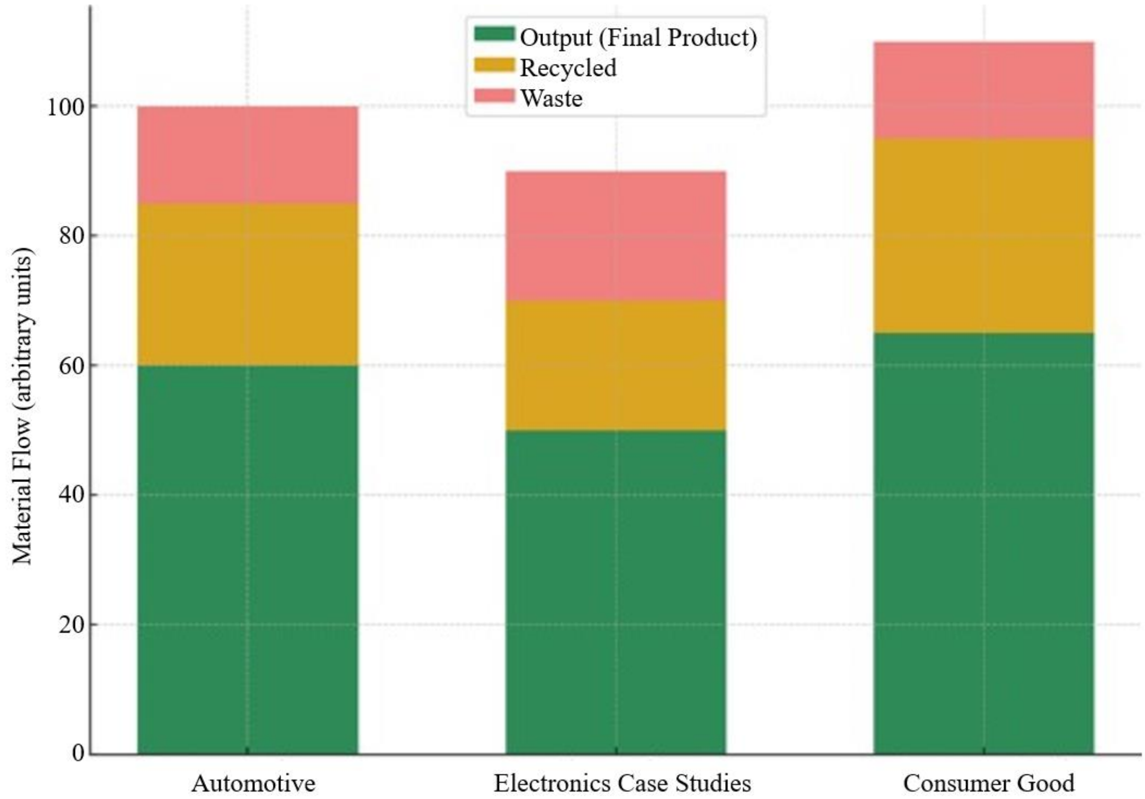

Figure 4. Material Input Distribution Across Case Studies

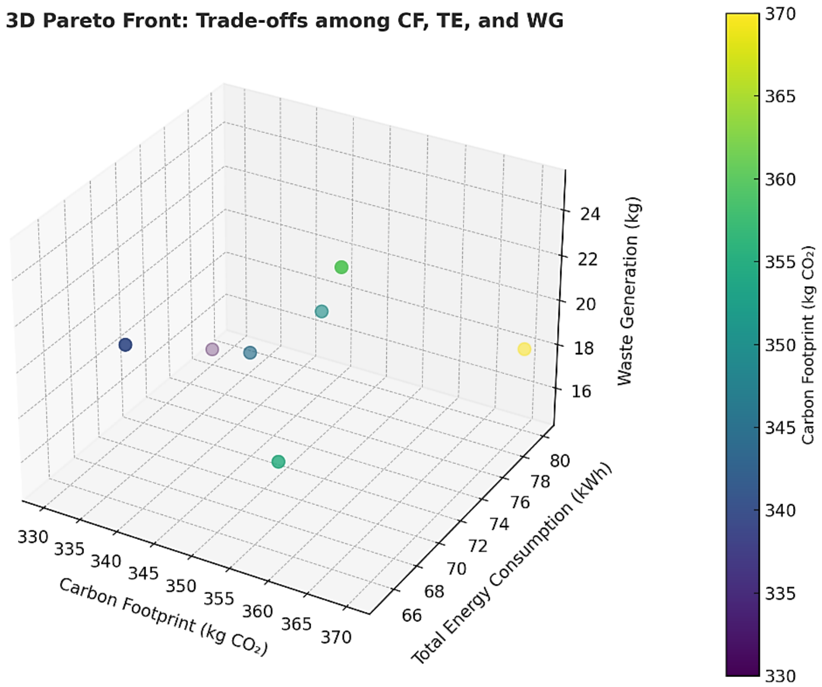

Figure 5. 3D Pareto Front: Trade-offs among CF, TE and WG

CONCLUSION

In this research, a Sustainable and Green Prototyping (SGP) framework was proposed and supported, which introduced a systematic approach in integrating Virtual Prototyping (VP), Life Cycle Assessment (LCA), and multi-objective optimization in order to reduce the environmental costs of the prototyping process. As compared to the traditional VP strategies where the primary focus is on cost, performance, and time-to-market, the SGP model directly reflects carbon footprint (CF), total energy consumption (TE), and waste generation (WG) as decision-making variables. The findings showed that there was high environmental improvement in the case studies of automotive, electronics and consumer goods, with a carbon cut of 30-38, energy cut of 24-33 and waste cut of 35-43 over the base VP. The optimization engine also gave Pareto-optimal trade-offs that decision-makers can choose designs that consider the various constraints of sustainability versus cost and quality. These results support the idea that directing sustainability evaluation into VP does not only help decrease material and energy waste but prepares the industries to the regulatory compliance and the incorporation of a circular economy. In addition to quantitative advantages, the suggested framework makes the decisions of the prototyping more transparent and interpretable. Connecting environmental measurements to digital models, the manufacturers can receive some actionable information about the ecological implications of the design options at the earliest stage, when the intervention has the greatest impact. It makes SGP a feasible and scalable direction of creating eco-efficient products in the age of Industry 4.0. From an application perspective, the proposed SGP framework is particularly relevant to polymer and polymer-composite product development, where material choice, processing routes, and end-of-life strategies significantly influence sustainability outcomes. The framework enables systematic comparison of thermoplastic and thermo set composites, fiber-reinforced polymers, and lightweight molded or additively manufactured components commonly used in automotive interiors, electronic housings, and consumer products. By linking material-level and process-level parameters with environmental indicators, SGP supports informed selection of eco-efficient polymer composite configurations without compromising manufacturability, quality, or production efficiency. The next generation of work can add to this framework by incorporating real-time digital twins, allowing constant feedback of the production systems, and the range of indicators of environmental health by adding such measures as water consumption, toxicity, and social sustainability measures. Also, optimization can be faster through the incorporation of artificial intelligence-based surrogate models to have fewer computational requirements in complex multi-objective applications.

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