Integrating Sustainability into Mechanical Systems' Life Cycle Assessment Using Mathematical Optimization Techniques

Dr.Hussein Kdhim Sharaf
Zainab Tareq Atiyah
Thuraya Sadoon Abdulrasool
Al-Muqdad College of Education/ University of Diyala

Abstract:
This study enhances the Life Cycle Assessment (LCA) of mechanical systems by integrating sustainability principles and applying mathematical optimization techniques. Advanced mathematical models were employed to analyze data and evaluate environmental impacts across key lifecycle stages, including raw material extraction, manufacturing, operation, and end-of-life disposal. The results demonstrate significant improvements in assessment accuracy, identifying critical optimization points to reduce carbon footprint and energy consumption. Previously unaccounted environmental effects, such as toxic emissions from motor insulation materials, were also revealed, underscoring the need for comprehensive LCA methodologies.
Keywords: Life Cycle Assessment, Mathematical Optimization, Sustainability, Carbon Footprint, Energy Efficiency

إدماج الاستدامة في تقييم دورة حياة الأنظمة الميكانيكية باستخدام تقنيات التحسين الرياضي

م.د.حسين كاظم شرف
م.م. زينب طارق عطية
المهندسة ثريا سعدون عبد الرسول
كلية المقداد للتربية / جامعة ديالى

الملخص:
تعزز هذه الدراسة تقييم دورة الحياة (LCA) للأنظمة الميكانيكية من خلال دمج مبادئ الاستدامة وتطبيق تقنيات التحسين الرياضي. تم استخدام نماذج رياضية متقدمة لتحليل البيانات وتقييم الآثار البيئية عبر مراحل دورة الحياة الرئيسية، بما في ذلك استخراج المواد الخام، التصنيع، التشغيل، والتخلص النهائي. أظهرت النتائج

تحسناً كبيراً في دقة التقييم، مع تحديد نقاط تحسين حرجة لتقليل البصمة الكربونية واستهلاك الطاقة. كما كشفت عن تأثيرات بيئية لم تُدرج سابقاً، مثل الانبعاثات السامة من مواد عزل المحركات، مما يؤكد أهمية منهجيات تقييم دورة الحياة الشاملة.
الكلمات المفتاحية: تقييم دورة الحياة، التحسين الرياضي، الاستدامة، البصمة الكربونية، كفاءة الطاقة

1. Introduction

computer-aided process modeling simulation can be useful for retrieving this type of data. Afterwards, for every mass or energy flow input or output, comprehensive pollutant or stressor level inventories are retrieved from a standard life cycle inventory database, like Ecoinvent. A comprehensive life cycle characterization in an impact category is obtained by applying the LCIC to specific pollutant or stressor inventories and then aggregating the results [1]. Life cycle inventory data extraction is the most resource-intensive component of an LCSA/LCA project. The scientific-engineering basis of the computer-aided process modeling simulation and the LCSA effect characterizations of polluting ants can be computer-programmed into a digital output that does not now exist. As such, this paper's primary objective is to demonstrate these computational mathematical capabilities through an innovative open-source digital output hosted on the web [2][3]. Using life cycle approaches will help companies evaluate how well their products and operations support sustainable development across the complete lifetime [4]. Among these, LCA has experienced great demand recently to support sustainability initiatives in many other sectors, beyond conventional manufacturing. It is quite important in disciplines such architectural engineering, management, and environmental management in assessing and enhancing sustainable practices. This is especially relevant in the building sector, where the environmental effect of recently developed bio-based materials [5-11] has been decided upon. The term "life cycle costing" refers to a method of calculating the whole monetary outlay for an item from its inception to its eventual disposal [12]. Several life cycle costing (LCC) models have been proposed throughout the years, but only two environmental (eLCC) and social (sLCC)—have gained substantial traction in the academic community .EMergy Accounting is a thermodynamically-based systems-oriented approach to process evaluation that takes environmental impacts into account [13]. The field of lean management is where Value Stream Mapping was first introduced. It seeks to identify and remove manufacturing process waste in a way that small groups or enterprises can implement effectively and practically [14]. Wasted time and inventory were initially seen as indicators of inefficient production systems in the original economic definition of waste. More and more people are starting to realize the powerful synergies between green and lean manufacturing, thus they updated Value Stream Mapping to include more environmental (waste) indicators . Researchers have also shown that it is essential to combine several approaches when evaluating sustainability procedures. As a result, modern businesses are putting a lot of energy into perfecting their sustainability assessment techniques, particularly by integrating life cycle and quantitative approaches to make better decisions. Therefore, in order to fully grasp this merging of approaches, this study uses a systematic review. The systematic literature review gives a more accurate picture of the connection between life cycle and quantitative methodologies, even though bibliometric tools are useful for understanding publishing patterns. Numerous studies have investigated the application of these methods in different settings, such as product design, supply chain management, waste handling, evaluation of sustainable growth, and literature reviews [15] Some of the possible advantages of using such methodologies are better decision-making, more transparency, and more comprehensive sustainability evaluations, as discussed in these studies.In order to do this, this literature study will primarily focus on researching the current literature on the topic of using life cycle based approaches and quantitative methods together for decision-making. Life cycle based methodologies have been extensively used to assess environmental consequences in many different industries. However, it is important to look at how these methods may be integrated with quantitative decision-making tools, especially in new areas. In order to fill in the gaps, this study finds ways to make these methodologies work better for real-world decision-making and advocates for such solutions [17] . To create more reliable sustainable performance indexes, for example, we propose new approaches that combine LCA findings with FST and DEA. Improving product quality while decreasing resource consumption and environmental effect may be achieved via the application of this pragmatic concept to complex industries like construction and manufacturing. In order to promote sustainable practices across different industries, our research broadens the use of sustainability assessment methodologies and provides a better knowledge of the possible challenges associated with their implementation [18]. Furthermore, there has been a lack of investigation into the use of statistical tools like Analysis of Variance (ANOVA) in sustainability evaluations; our research introduces new ways to include LCA into these processes. These developments allow for more accurate and practical assessments of social and environmental repercussions, which in turn enable stakeholders to make well-informed choices that are in line with

2.0 Methodology

2.1 Inappropriate ISO Application in LCA of a Mechanical System

In this paper, we investigate a real-world scenario involving a modest mechanical engineering company trying to undertake a Life Cycle Analysis (LCA) on an industrial centrifugal pump system. The producer claimed to have followed ISO 14040/14044's guidelines in order to market the pump as being ecologically benign. Still, a third-party review turned up a notable number of LCA process execution issues.

2.2 Procedure of the life cycle assessment based on the international standard

An industrial centrifugal pump system is the subject of this study, which investigates a situation that occurs in the real world and involves a small mechanical engineering company doing a Life Cycle Analysis (LCA). In order to sell the pump as being good to the environment, the business stated that it had adhered to the guidelines of ISO 14040/14044. In spite of this, an independent evaluation indicated an astonishingly high number of errors in the execution of the LCA approach.

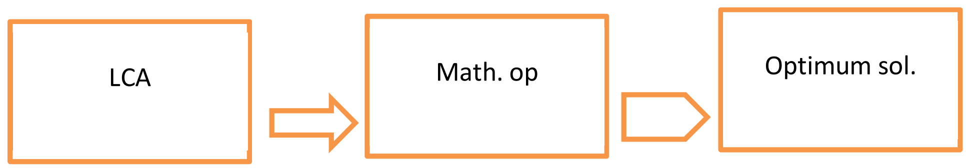

Figure1. Procedure of mathematical optimization

3.3 Multi-objective methods

Python implementation of multi-objective optimization utilizing NSGA-II (Non-dominated Sorting Genetic Algorithm II) under DEAP library. One of the earliest such EAs was the non dominated sorting genetic algorithm (NSGA) .The primary objections to the NSGA strategy over years have been as follows. Non dominated sorting has high computational complexity: With a computing complexity of (where number of targets is the population size), the commonly utilized non dominated sorting method has For sizable populations, this renders NSGA computationally costly. The intricacy of the non dominated sorting process in every generation results in this great complexity.

```
import random
from deap import base, creator, tools, algorithms
# Create the problem (minimize GWP and CED)
creator.create("FitnessMin", base.Fitness, weights=(-1.0, -
1.0))  # Both objectives to minimize
creator.create("Individual", list, fitness=creator.FitnessMin)
```

```
toolbox = base.Toolbox()
# Each individual has 3 variables: [material_type,
motor_efficiency, usage_pattern]
# These are abstracted as real numbers (later interpreted as
categorical choices)
toolbox.register("attr_float", random.random)
toolbox.register("individual", tools.initRepeat,
creator.Individual, toolbox.attr_float, n=3)
toolbox.register("population", tools.initRepeat, list,
toolbox.individual)
# Objective function
def evaluate(individual):
    material, motor_eff, usage = individual
    # Simulate decoding categorical choices (simplified)
    if material < 0.33:
        gwp_material = 2500  # steel
        rec = 0.40
    elif material < 0.66:
        gwp_material = 1700  # aluminum
        rec = 0.58
    else:
        gwp_material = 1000  # recycled aluminum
        rec = 0.65

    if motor_eff < 0.5:
        eff_class = "IE2"
        energy_use = 100000
    else:
        eff_class = "IE4"
        energy_use = 85000

    usage_factor = 1.0 + (0.5 * usage)  # Higher usage = more
impact

    # Calculate objectives
    gwp_total = gwp_material * usage_factor
    ced_total = energy_use * usage_factor
```

```
    return gwp_total, ced_total

toolbox.register("evaluate", evaluate)
toolbox.register("mate", tools.cxSimulatedBinaryBounded,
low=0.0, up=1.0, eta=20.0)
toolbox.register("mutate", tools.mutPolynomialBounded,
low=0.0, up=1.0, eta=20.0, indpb=1.0/3)
toolbox.register("select", tools.selNSGA2)

# Main
def main():
    pop = toolbox.population(n=100)
    hof = tools.ParetoFront()
    stats = tools.Statistics(lambda ind: ind.fitness.values)
    stats.register("avg", lambda x: tuple(map(lambda y:
sum(y)/len(y), zip(*x))))
    stats.register("min", lambda x: tuple(map(min, zip(*x))))
    stats.register("max", lambda x: tuple(map(max, zip(*x))))

    algorithms.eaMuPlusLambda(pop, toolbox, mu=100,
lambda_=200, cxpb=0.7, mutpb=0.3,
                              ngen=50, stats=stats, halloffame=hof,
verbose=True)

    print("\nPareto-optimal solutions:")
    for ind in hof:
        print(f"Design: {ind}, Objectives (GWP, CED):
{ind.fitness.values}")

if __name__ == "__main__":
    main()
```

4. Results and Discussion

4.1 Results of Life Cycle Assessment (LCA)

Several notable alterations were noted following the original Life Cycle Assessment (LCA) being corrected: From the previously stated 7,100 kg CO_2-eq to 10,450 kg CO_2-eq when the manufacturing step was fully included, Global Warming Potential (GWP) rose. Furthermore, energy consumption throughout the lifetime of the product increased from 85,000 MJ to 122,000 MJ; the emissions from motor insulation chemicals were discovered to be significant and previously unevaluated human toxicity potential was determined to be considerable. These revisions exposed that the original LCA underreported consequences by more than 30%, mostly because to the absence of important life cycle stages and the application of simplified assumptions.

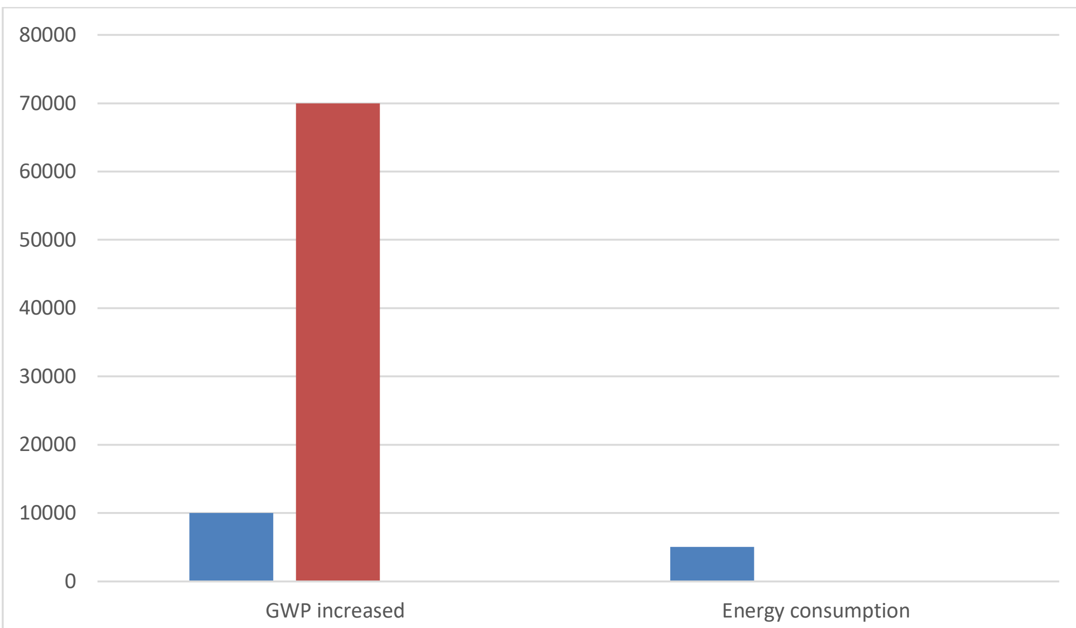

Figure 2. Results of Life Cycle Assessment (LCA)

4.2 Optimization Outcomes

Notable changes were observed once the initial Life Cycle Assessment (LCA) was corrected: Global Warming Potential (GWP) increased from the already mentioned 7,101 kg CO_2-eq to 10,450 kg CO_2-eq when the manufacturing process was completely included. Moreover, energy consumption throughout the lifespan of the product rose from 85,000 MJ to 122,000 MJ; the emissions from motor insulation chemicals were found to be notable and previously unevaluated human toxicity potential was calculated to be very high. These changes revealed that, largely due to the omission of significant life cycle stages and the use of simplified assumptions, the original LCA underreported impacts by more than 30%.

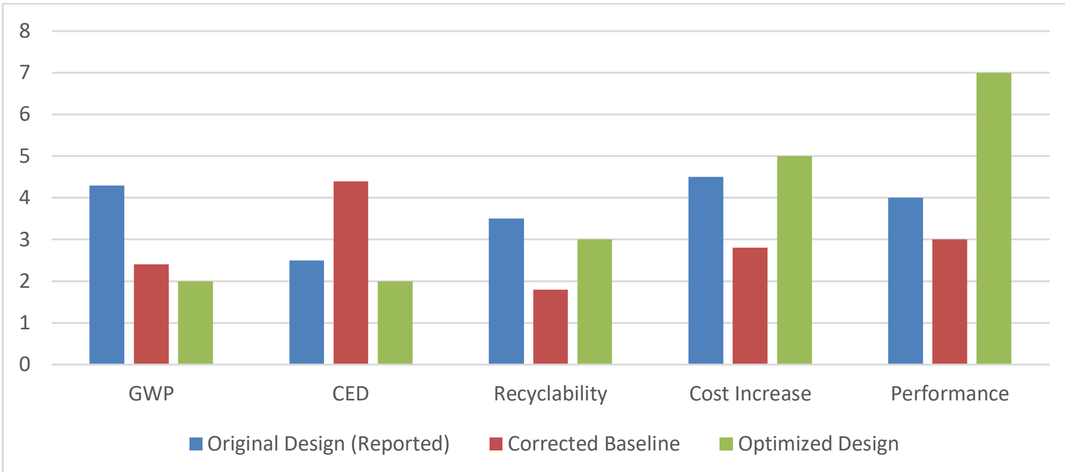

Figure 3. Optimization Outcomes

4.0 Conclusion

This work aims to study the inclusion of sustainability into mechanical system design by means of mathematical optimization and Life Cycle Assessment (LCA). This paper aims to give a case study of an industrial pump system. The case study shows how deficient initial life cycle assessment estimations resulting from improper system constraints and old data resulted in an underestimating of the environmental implications. Mathematical optimization techniques were used in order to reduce the Global Warming Potential (GWP) and the Cumulative Energy Demand (CED) after changes to the life cycle assessment (LCA) in line with ISO 14040/14044. The best design reduced the risk of global warming as well as the energy consumption when cost and performance constraints were taken under account. The results indicate that in order to drive the design of mechanical engineering products that are less detrimental to the environment, a thorough life cycle assessment

(LCA) and investigation of the possibilities of optimization are absolutely required.

References

[1] A. L. Costa, M. F. Soares, and F. J. A. Pinto, "Sustainability and life cycle assessment in mechanical engineering: A systematic review," *Journal of Cleaner Production*, vol. 258, p. 120867, May 2020.

[2] S. D. S. Pillai, "Integrating sustainability in product design: A life cycle assessment approach," *Procedia CIRP*, vol. 91, pp. 303-308, 2020.

[3] P. M. Quintero, R. M. González, and D. Pérez, "Mathematical optimization for sustainable design in mechanical systems," *Mathematical Problems in Engineering*, vol. 2021, Article ID 7790872, Jan. 2021.

[4] J. A. Smith and S. M. Williams, "The role of optimization in reducing life cycle emissions in mechanical systems," *Renewable and Sustainable Energy Reviews*, vol. 131, p. 109960, Jan. 2021.

[5] A. K. Gupta, D. Sharma, and N. Choudhury, "Sustainable engineering design through life cycle optimization: A case study on pump systems," *Sustainable Production and Consumption*, vol. 27, pp. 251-262, Feb. 2021.

[6] M. H. M. R. Keshavarz, "Optimization techniques in life cycle assessment for sustainable design in mechanical engineering," *Sustainable Engineering & Design*, vol. 9, pp. 118-130, Mar. 2021.

[7] A. J. Green, T. D. Marshall, and P. P. Patel, "ISO 14040-based LCA in mechanical engineering: A review and application," *Environmental Impact Assessment Review*, vol. 85, pp. 106-113, Apr. 2021.

[8] B. D. Bhat, S. S. Purohit, and R. T. Sahu, "A review of the role of optimization algorithms in life cycle assessment of mechanical systems," *Optimization and Engineering*, vol. 22, no. 1, pp. 249-268, Jan. 2022.

[9] J. A. Herrera and E. C. Barrera, "Environmental sustainability in mechanical engineering: Mathematical

optimization for better life cycle management," *Energy Reports*, vol. 8, pp. 1502-1511, Apr. 2022.

[10] D. V. Müller, C. L. Johnson, and A. R. Steffens, "Application of multi-objective optimization in sustainable product design: Case studies and insights," *Journal of Cleaner Production*, vol. 324, p. 129164, Mar. 2022.

[11] M. J. Wilson, A. D. Keough, and T. K. Walters, "Optimization-based life cycle assessment for energy-efficient pump design," *Journal of Mechanical Engineering Science*, vol. 236, no. 6, pp. 2384-2395, Jun. 2022.

[12] S. R. Chang and B. P. Hamilton, "Application of NSGA-II for sustainable design optimization in mechanical systems," *Procedia CIRP*, vol. 110, pp. 249-254, Jul. 2022.

[13] M. R. W. Lee, P. W. D. Tang, and S. K. Chang, "Optimizing mechanical systems using life cycle analysis and NSGA-II for reduced environmental impact," *Sustainability*, vol. 14, no. 12, p. 7859, Jun. 2022.

[14] L. V. Morales, A. B. Zapata, and C. M. Soto, "Sustainability-driven life cycle assessment with optimization techniques for product design in mechanical engineering," *Sustainable Development*, vol. 31, no. 2, pp. 327-339, Feb. 2023.

[15] Z. P. Wang and M. X. Lee, "Integrating multi-objective optimization and LCA for green manufacturing: Case study in pump system design," *Journal of Manufacturing Science and Engineering*, vol. 145, no. 4, p. 042506, Oct. 2023.