

31st CIRP Conference on Life Cycle Engineering (LCE 2024)

A Unit Product Energy Mapping Framework for Operation Management in Manufacturing Industries

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Abstract

Sustainability has emerged as a primary concern across a wide range of industries, particularly in manufacturing due to its energy-intensive nature. To understand the environmental impact of manufacturing processes and make them less detrimental to the environment users monitor and track energy consumption data. Although this approach is valuable in assessing the overall impact, energy consumption mapping needs to be conducted per product to compare and assess different process strategies. Available research in literature, provides unit process energy consumption models in isolation from manufacturing operations, neglect of machine and operational variations, and limited consideration of detailed data acquisition for indirect energy consumption. This paper presents a comprehensive framework designed to address the existing gaps in the literature on energy consumption mapping within the manufacturing industry. The proposed framework provides a solution by offering a structured approach to data collection, analysis, and utilization within manufacturing processes, aiming to achieve two main outcomes: the calculation of embodied energy per unit product and the provision of systematically analysed data for operation management to enhance energy efficiency. Four key steps constitute the framework: data acquisition, simulation and modelling, impact assessment, and operation management. The data acquisition step involves the identification of manufacturing process flows, equipment specifics, and process parameters, emphasizing machine operation requirements and power readings. These elements are systematically logged into a database providing essential information for both embodied energy calculation and simulation purposes. Results obtained from simulations are subjected to analysis in the impact assessment step to assess embodied carbon and overall environmental impacts. The collective findings from the first three steps are then utilized for operation management.

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Peer-review under responsibility of the scientific committee of the 31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Keywords: Energy consumption mapping; Energy efficiency; Embodied energy; Manufacturing operation management; Systems scheduling

1. Introduction

In today's industrial landscape, manufacturing plays a central role in driving economic growth. However, this crucial sector is also a major contributor to global energy consumption and greenhouse gases (CO₂eq) emissions. According to the World Energy Outlook Report, in 2022, the industrial sector accounted for 37% of the world's total energy use, with manufacturing alone responsible for 76% of this energy consumption [1]. As the world collectively strives to achieve the goal of "Net-Zero" emissions, the manufacturing sector faces significant challenges. The industry's significant share in

global energy consumption and CO₂eq emissions places it in the spotlight of environmental concerns. Moreover, manufacturing companies occupying supplier positions for larger companies find themselves under additional pressure. This is primarily due to the escalating demands from customers, who are also striving to control their own energy consumptions as part of their efforts to achieve "Net-Zero" goals. They seek accurate information about the energy usage and CO₂eq emissions associated with the products they purchase. This dual pressure to reduce environmental impact and meet customer demands poses a significant challenge to manufacturing companies.

In the manufacturing industry, addressing the challenges of sustainability involves the adoption of four types of practices geared toward fostering more sustainable development: product modification, product improvement, process modification, and process improvement [2]. The concept of modification entails a change in either the product or the manufacturing process, whereas improvement maintains the existing elements but enhances their efficiency. The successful implementation of both modification and improvement practices requires a comprehensive understanding of manufacturing systems.

A variety of models, frameworks, and methods have been developed to enhance the understanding on the sustainability of products and processes. Among them, Life Cycle Assessment (LCA) has an increased interest, as a well-developed sustainability assessment tool. Moreover, in 2015, the European Commission designated LCA as one of the reference models for evaluating the impact assessment of policies within the European Union (EU) within its “better regulation guidelines” [3]. In the context of LCA, an evaluation is conducted on the input and output data across various stages of a product's life or a manufacturing process [4]. In many cases, comprehensive details about the data for these stages are limited, and most of the time, each stage is modeled as a black box or using generic datasets. While this high-level analysis is valuable in assisting decision-makers to choose environmentally friendly options for reducing impacts, it falls short in providing precise information to customers about their purchased products to meet reporting requirements or in identifying potential enhancements in consumption to further decrease the impacts of the process or product [5]. Additionally, it was highlighted in another study [6] that energy consumption per product is the most relevant energy performance indicator for comparing and assessing different process strategies.

In response to this challenge, numerous studies have extensively investigated the energy consumption of machines and processes with a primary focus on mapping energy flow more effectively at the system and process level [7]. While these studies have provided valuable insights, the practical application of energy mapping approaches remains limited at the product level, particularly in high complexity production facilities. These limitations bring the necessity of a systematic framework capable of supporting comprehensive data acquisition and utilization. In addition, existing effort in leveraging energy consumption results of machines and processes have predominantly concentrated on optimizing machine design or process parameters. However, usage of optimization potentials with the operation management is limited [8]. This paper addresses these crucial gaps by focusing on the establishment of a framework specifically delivering embodied energy per unit product. The aim is to provide customers with embodied energy information for the purchased product and to utilize the accrued data for operation management. Embodied energy per unit product refers to the total of all the energy required to produce the product from cradle-to-gate [9]. The proposed framework will provide approach to collecting, analyzing, and applying energy related data at manufacturing processes of the product. The details of the available methods in the literature are discussed in Section

2, to provide a thorough examination of the existing methods to better inform the creation of the holistic framework.

The motivation behind the creation of this framework was further supported by an industry level survey conducted as part of the Metallic Aerospace Structures Technologies for Eco-social Returns (MASTER) project, in which the authors are involved. MASTER is a collaborative project with six partners from manufacturing industry and academia, all sharing the goal of providing sustainable and net-zero systems in aerospace manufacturing industry. As part of this project, a survey, “Industrial Practices on Sustainability” was conducted to assess the sustainability strategies employed by the participating companies. Based on the results, it was concluded that, despite having available data and action plans at both corporate and process levels, the understanding of individual products in terms of energy consumption and environmental impact was notably limited. These findings underscored the critical need for the framework.

2. Mapping Energy Consumption within Manufacturing Industry: Literature Review

Concerning the environmental sustainability analysis of discrete manufacturing processes, numerous studies mapping energy consumption have been conducted in the literature. Due to limitations in available Life Cycle Inventory (LCI) databases regarding the overall environmental impact of discrete manufacturing processes, Kellens et al. [10], introduced the CO₂PE! Initiative (cooperative effort on process emissions in manufacturing). CO₂PE! coordinates international efforts aimed at documenting and analyzing the environmental impacts of a wide range of current and emerging manufacturing processes, while also providing methods for mapping energy consumption in unit process manufacturing. Under this initiative, unit process energy consumption models have been developed for both subtractive [11], [12], [13] and forming based [14], [15], [16] processes. Specific energy consumption (SEC), representing the energy consumed by the machine tool to process 1 cm³ material, is utilized in both cases for modelling. These studies offer detailed insights into mapping energy consumption during actual material process operations and auxiliary operations. A detailed examination of power requirements on the machine has categorized power consumption into three groups: standby power (auxiliary systems such as lighting, displays, computer panel etc.), idle power (process-ready power) and the actual process power. Standby power remains constant for a specific machine while idle power is specific to both the machine design and the tool path. Process power varies based on the material and size of the workpiece and process parameters such as machining speed and feed rate [17]. Although these studies provide critical information for defining the energy consumption of operating states in a given machining processes based on material and manufacturing process parameters, they do not take into consideration other factors, such as machine tools for customized products [18], operator activities and processing environment [8]. In addition, these assessments on machining processes need to be complemented with methods that map

energy consumption throughout the entire manufacturing facility.

To expand the mapping of energy consumption to the manufacturing facility level and attribute the energy consumed by the process and the facility to the product, an energy breakdown methodology has been proposed [19], [20]. According to this method, energy consumption can be divided into two main categories: direct energy (DE) and indirect energy (IE). DE represents the energy required to manufacture a product in a specific process flow, while IE is the energy necessary to maintain the overall production environment. Further subdivision of DE includes value-added energy (VA), which aligns with the process energy defined in the previous paragraph and auxiliary energy (AE), which encompasses the sum of stand-by energy and idle energy. While defining VA energy is relatively straightforward, considering the unit process energy consumption studies mentioned in the previous paragraph, defining AE and IE requires additional analysis based on operational requirements and company behaviors.

Recent research has extensively employed both Value Stream Mapping (VSM) and Industry 4.0 technologies to map energy consumption across entire manufacturing facilities and promote better energy efficiency practices [21], [22]. VSM, recognized as a Lean Management tool, is commonly utilized to observe, and analyze the material and information flow within the value chain. When complemented with energy mapping, VSM offers a structured model illustrating not only the flow of products but also their corresponding energy consumption [23]. The incorporation of Industry 4.0 technologies further enhances this process by enabling automatic and dynamic collection, mapping, and modeling of the energy flow within a manufacturing operation. This integration provides a real-time understanding of energy utilization throughout the production process.[7]. Although these applications offer comprehensive energy flow mapping in manufacturing processes and facilitate real-time data collection, they lack specific details regarding data collection for IE. Additionally, they do not account for variations among machines, operational requirements, and limitations. Furthermore, these applications lack a comprehensive data logging system essential for detailed data analysis and utilization in operational management.

In summarizing the literature review, it becomes evident that the existing literature on energy consumption mapping within the manufacturing industry for unit products lacks comprehensive coverage. Several critical aspects are notably absent, and addressing the identified gaps listed below is required for effectively solve the energy efficiency challenges in manufacturing operations.

- The development of unit process energy consumption models has occurred in isolation from the broader context of manufacturing operations. This approach often neglects the interconnected flow of products within the manufacturing operations.
- Machine and operation requirements, including factors such as machine cooling time and furnace temperature fluctuations, are frequently overlooked and not systematically recorded for subsequent data analysis. This

limited analysis reduces the precision of energy consumption assessments and limits the ability to develop targeted energy efficiency strategies.

- Detailed data acquisition related to IE consumption linked to specific manufacturing processes or products is either limited or entirely disregarded in existing studies. This limitation inhibits the accurate allocation of energy consumption to each product.
- The absence of a dedicated data logging system tailored to the unique parameters of each manufacturing process and the specific operational requirements further compounds the challenges. The establishment of such a system is crucial for effectively collecting and analyzing data, enabling the formulation of informed energy efficiency strategies and the identification and resolution of operational inefficiencies.

In addressing the identified gaps, the primary objective of this study is to introduce a systematic framework designed to collect, analyze, and apply the energy related data specifically within the manufacturing processes of the unit product. Employing a categorization approach for data collection, the aim is to define VA and AE consumptions and allocate direct and indirect energy usage. This categorization strategy facilitates an understanding of the embodied energy of the unit product. The analysis and application of the collected data enables the reuse of collected data for evaluating future outlines of manufacturing operations and operation management strategies to enhance efficiency.

3. Unit Product Energy Mapping Framework

The concept of unit product energy mapping involves collecting data on the energy consumption of manufacturing steps for a unit product and categorizing them based on consumption types. The proposed framework is designed to yield two primary outcomes, embodied energy per unit product and systematically analyzed data for operation management, aimed at efficiently reducing energy consumption. Comprising four key steps illustrated in Fig. 1, the framework encompasses data acquisition, simulation and modeling, impact assessment and operation management. The subsequent sections provide the details of each step for comprehensive understanding.

3.1. Data acquisition

The real-time collection of data in manufacturing processes presents a significant challenge for industries, owing to the complex nature of these processes, the diversity of products and tools, and the challenges associated with measurement processes, including cost, time, and expertise constraints [18]. Addressing these challenges, it becomes crucial to conduct data acquisition in a structured way, categorizing all consumptions with their corresponding variables. Furthermore, the accrued data has to be reused to identify consumptions related to process variations to reduce the workload and cost associated with remeasurement for each individual process condition. The procedure for the data acquisition was structured as follows:

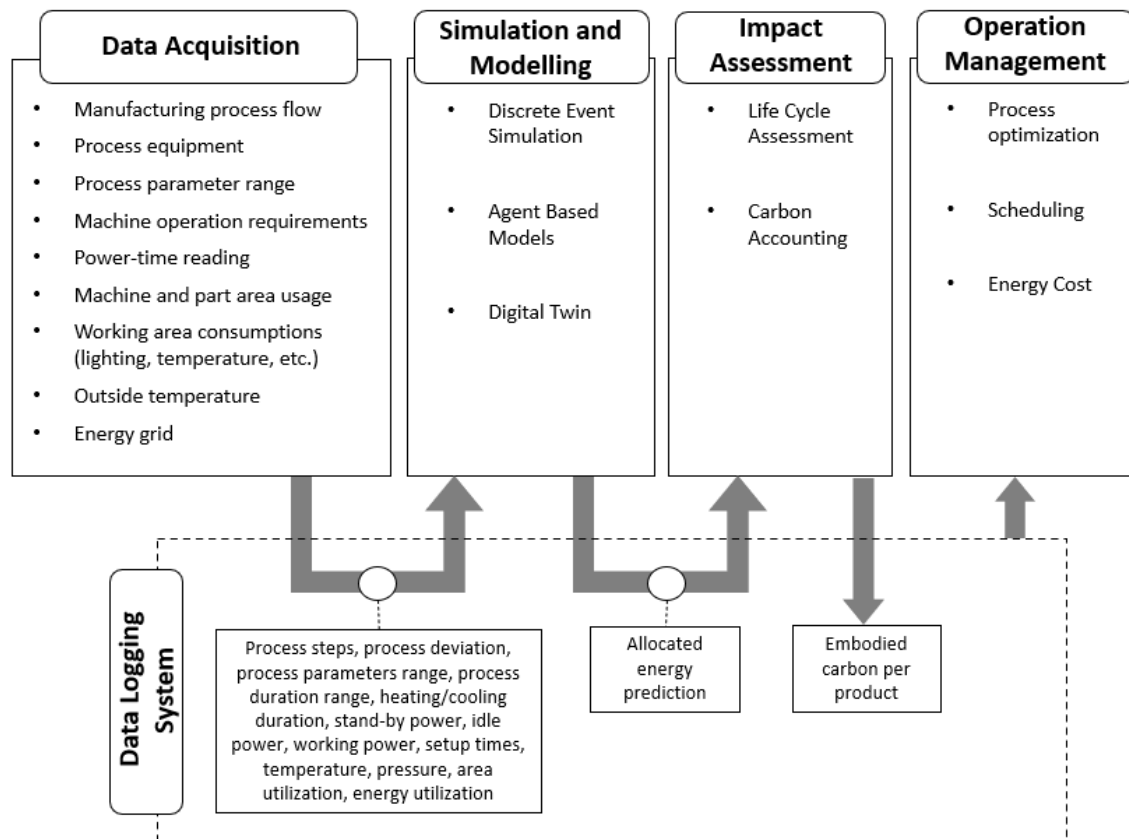


Fig. 1. Framework of energy consumption mapping for unit product embodied energy.

1. Mapping the manufacturing process flow, detailing each process step and the methods for part movement between processes.
2. Identification of process equipment and specifications, such as control system, cooling/heating system, tool specifications, axis configuration and work envelope.
3. Selection of process parameter range, within which the machine functions to produce a product with the desired properties utilizing information from literature or experimental work.
4. Recording electricity usage, power usage, fuel consumption, gas usage, water usage, temperature, and pressure from machines utilizing smart sensors, smart meters, energy monitoring devices, and thermocouples.
5. Recording infrastructure and environmental data, encompassing data on machine and part area usage, environment lighting, heating, air ventilation and their correlated energy consumptions.
6. Identification and categorization of consumption types fall under DE (value added and auxiliary energy) and IE consumptions. For instance, auxiliary energy includes machine operation requirements such as specific temperature or pressure conditions that must be reached before machine operates or the cooling down period after processing, which necessitates waiting time before handling the part.
7. Identification of the energy grid considering the percentage of renewable and non-renewable energy, which may fluctuate based on the time of day or year.
8. Logging identified and recorded data into database to define embodied energy of the manufactured product and reuse the data for simulation purposes and predicting allocated energy for different variable configurations.

This comprehensive approach to data acquisition not only enhances the understanding of energy consumption patterns but also facilitates a detailed analysis and precise allocation of both DE and IE consumption. Additionally, it provides detailed data essential for simulating manufacturing facilities with all critical details, thereby ensuring accurate predictions of embodied energy for each product produced with various parameter configurations. Simulation results on required energy, operation time, waiting time, tool change duration and other relevant factors provide a foundation for informed decision-making in energy-efficient operation management strategies within manufacturing processes.

3.2. Simulation and modelling

Simulation and modelling techniques facilitate a comprehensive representation of dynamic environments, stochasticity, and complex non-linear interrelationships within manufacturing systems. This capability allows for the analysis of different parameter configurations, “what-if scenarios” and process planning [24]. Consequently, it enhances the accuracy of energy consumption predictions, and supports decision making on operation management.

In the second step of the framework, simulation and modelling utilize various simulation paradigms such as discrete

event simulation (DES), agent-based modelling (ABM) and digital twins. These simulation methodologies enable a dynamic and detailed representation of manufacturing processes. By incorporating intricate details such as machine layouts, equipment specifications, facility conditions, and input/output parameters, simulation models are generated. Models are validated by comparing the simulation outputs with actual measured outputs, using process and operational parameters as well as environmental data obtained from the data logging system.

3.3. Impact assessment

The impact assessment stage within the framework is where embodied carbon is quantified for each product and specified for both value-added and auxiliary processes. This phase employs established impact assessment tools, such as carbon accounting and LCA. Carbon accounting is a process that involves measuring, reporting, and allocating greenhouse gas emissions from human activities [25]. On the other hand, LCA is a systematic tool used to evaluate the environmental impacts of products throughout their life cycle, spanning from raw material extraction to end-of-life treatment. While the current application primarily focuses on quantifying embodied carbon, LCA offers a broader perspective by allowing the definition of midpoint (e.g., global warming, water use, human toxicity, ionizing radiation) and endpoint (human health, ecosystem quality, resources) impact categories for both the product and each manufacturing process [4]. These assessments facilitate the comprehensive comparison of different process configurations in terms of their embodied carbon and other environmental impacts. This, in turn, aids decision-making processes to achieve less impactful operations. Moreover, the impact assessment supports the provision of detailed information to customers regarding the embodied carbon of their purchased product.

3.4. Operation management

The final step of the framework, operation management, involves the effective utilization of systematically acquired and analyzed data from the previous steps. The goal is to achieve a significant reduction in energy consumption, CO₂eq emissions, and energy cost through strategic process optimization and operation scheduling. Based on the insights gained from the predicted energy usage, process duration, and waiting times, various optimization strategies and operation schedules can be implemented. Below, two examples are provided for optimization and scheduling, with an aim on minimizing energy related emissions and cost:

- **Case 1 - Renewable energy utilization:** In the pursuit of reducing CO₂eq emissions, companies are increasingly prioritizing the use of renewable energy over non-renewable sources. However, availability of renewable energy is a challenge since the amount of available renewable energy can vary due to several factors, primarily linked to the availability of sunlight and wind. Recognizing this variability, an informed approach to operation scheduling

can be performed using insights from the data logging system. In this example, a thorough assessment of the manufacturing flow and energy requirements for each manufacturing process and product is conducted. The aim is to identify an operational scenario that maximizes productivity while optimizing the utilization of available renewable energy. For instance, processes with high energy demand can be strategically scheduled for days with abundant sunlight. By aligning the energy-intensive tasks with periods of optimal renewable energy availability, companies can effectively minimize the reliance on non-renewable energy alternatives and reduce associated carbon emissions.

- **Case 2 – Energy cost:** In the case of energy cost management, the price of electricity per unit undergoes fluctuations throughout the day in response to shifts in demand and supply dynamics. To capitalize on these variations and achieve cost efficiencies, an informed operation scheduling can be performed. Knowing the energy needs of each manufacturing process and product from the data logging system, each process can be strategically scheduled at optimal time. For instance, energy-intensive manufacturing tasks can be scheduled during off-peak hours when electricity costs are typically lower due to decreased overall demand.

Incorporating these process optimization and operation scheduling into the framework ensures an adaptive approach to operation management. By aligning manufacturing processes with favorable energy conditions and strategically optimizing resource utilization, companies can achieve tangible reductions in embodied energy, environmental impact, and operational costs.

4. Conclusion

This paper presents a comprehensive framework for energy consumption mapping per unit product in manufacturing industries. The detailed data acquisition step of the framework ensures a thorough understanding of manufacturing processes, enabling the generation of high-detail simulation models. These models, incorporating process and operational parameters alongside environmental data, facilitate the representation of dynamic environments and complex interrelationships within manufacturing systems. Validated models contribute to enhancing the accuracy of energy consumption predictions and calculation of embodied energy per product, in cases where actual measurements are not available. The results derived from simulations are subsequently subjected to analysis in the impact assessment section to evaluate the environmental impact of products. Finally, the operation management step utilizes systematically acquired and analysed data to drive efficiency in energy consumption, CO₂eq emissions, and energy costs. Optimization and scheduling strategies, exemplified by cases such as renewable energy utilization and energy cost, showcase the practical application of the framework to achieve sustainable and cost-effective operations.

As a result, this framework provides manufacturing industries with a strategic tool to navigate the complexities of energy consumption, offering a roadmap for enhanced energy mapping, operational efficiency, and a significant contribution towards achieving net-zero goals. This paper represents the first phase of a project about the transitioning to sustainable manufacturing. The next phase of the project will consist of the practical application of the framework to real industry cases which will require to creation of an actual data logging system, the definition of data transfer methods and reporting mechanisms. This practical application will give the opportunity to deal with the complexity of production sites allowing for further enhancement of the framework.

Acknowledgements

This work was performed as part of the Metallic Aerospace Structures Technologies for Eco-social Returns (MASTER) project, which has received funding from the UKRI ATI program under grant agreement 103040.

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2024-05-07

Elsevier

<https://doi.org/10.1016/j.procir.2024.01.119>

Yukse YA, Haddad Y, Cox R, Salonitis K. (2024) A Unit Product Energy Mapping Framework for Operation Management in Manufacturing Industries. Procedia CIRP. Volume 122, 2024, pp 873-878