Article

Increasing Energy and Material Consumption Efficiency by Application of Material and Energy Flow Cost Accounting System (Case Study: Turbine Blade Production)

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Abstract: It is often difficult to extract data on material and energy wastes and related costs in the value chain of manufacturing products. Many organizations are not fully aware of the actual cost of material and energy wastes. For this purpose, advanced costing methods should be used. This study uses material and energy flow cost accounting (MFECA) to determine material costs, losses, and waste management. The case study of this research is the manufacturing of turbine blades in the Iran Power Plant Company. In this study, using the extracted data, the manufacturing costs of turbine blades have been studied. The conventional method of production turbine blades is the machining method, which, we will see, has a significant amount of wastes of materials and energy. By studying different methods, we found that there is an alternative method called forging, which reduces losses and costs. Finally, the costs of the two methods are compared. Engineering economics techniques have also been used to compare two methods on a long-term planning horizon.

Keywords: MEFCA; cost method; turbine blade manufacturing; environmental management accounting

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1. Introduction

According to the International Energy Agency (IEA), energy consumption on the global level still increases continuously, leading to substantial carbon dioxide emissions and serious environmental problems (Gong et al., 2020). As a result, the importance of energy consumption management, especially in the manufacturing sector, is clear. On the other hand, given the limited resources in the world, material consumption management will also be of particular importance.

Producers of most goods and services are trying to take control of all material and energy flows (Lambrecht et al., 2017). Material and Energy Flow Cost Accounting is regarded as one of the most powerful accounting tools for environmental management. This approach is an effective method to address the need to increase productivity and reduce environmental impacts by promoting transparency in the use of materials and resources (ISO 14051, 2011). MEFCA is an accounting method that measures all material and energy flows in physical and monetary units. In addition, this approach also includes costs associated with financial products and losses (Kokubu and Tachikawa, 2013). The application of this method is independent of the type of production system or organization. The only requirement is for the company to be a consumer of materials and energy in its process (ISO14051.2011). The MEFCA method divides the entire production system into Quantitative Centers (QC). QCs are part of a production system in which inputs and outputs must

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be physically determined and denominated in monetary units. These areas usually include locations that change or store materials (ISO 14051, 2011; Sygulla et al., 2011). QC is the starting point for collecting data on physical units in terms of resource measurement. The material and energy used for each QC must be measured in physical units. Then, all QC information must be aggregated into a flow model.

2. Research Background

The previous version of the MEFCA method is the material flow cost accounting (MFCA). MFCA has been described as among the most basic Environmental Management Accounting (EMA) tools. The data afforded by MFCA also provides a foundation for the development of further environmental management accounting activities, which may include investment appraisal, environmental impact assessment, and short- and long-term environmental budgeting (Christ and Burritt, 2015). Given the energy efficiency becoming a challenging task for researchers, organizations, and energy consumers (Al-Qawasmi and Tlili, 2018), there was a need for a new approach that also included energy costs. Khoing that primary energy consumption has accounted for more than 60% of global CO2 emissions, leading to an increase in global warming (Maji and Sulaiman, 2019) and multiplying the importance of this subject. This method is known as MEFCA. This method has shown many applications in various industries. Behnami et al. (2019) used this method in a petrochemical wastewater treatment plant. In their research, using this novel stepwise approach, decision-makers were helped to enhance both financial and environmental performances more confidently and to define appropriate improvement plans. The usage of this method in variant production with large-scale plant manufacturers is discussed by Schmidt et al. (2019). In Germany, the MEFCA was developed many years ago to cope with the limitations on resources needed. MEFCA was first used in Japan on a large scale. ISO standards have already provided methods for this purpose (Schmidt and Michiyasu, 2013). According to Chinese companies, standard costs are used to calculate production costs for decision-making and as a contribution to budgeting. Their standards are based on the efficiency of past experiences and their annual review of standards (Nazar Khan et al., 2016). Material flow cost accounting can be discussed as a potential approach to illustrate the quantitative and monetary impacts of material flow management (Sygulla et al., 2011). An application of MEFCA can be found at the largest ceramic tile factory in the Czech Republic, Lasselsberger. The research demonstrates the importance of data obtained from the MEFCA system and its application to optimize production processes for the specific requirements of a company production process (Hyrslova et al., 2013). Using the MEFCA concept, a simulation model for the supply chain, including a Japanese gear manufacturer and its customers, was developed to visualize the large amount of waste generated by the manufacturing process that provides environmental and economic benefits to the entire supply chain (Tang and Takakuwa, 2012). Material and energy flow cost accounting system is one of the tools that are essential to following three principles of reduction, reuse, and recycling to increase productivity, reduce costs, and sustain production and consumption. This system was implemented in the factory unit of Azerbaijan too. After the implementation of this system, the highest and lowest wastage of materials and energy were estimated in treatment and packaging centers, respectively. Finally, solutions were introduced to reduce production costs and waste and reduce environmental damage. The effectiveness of the MEFCA approach was investigated in a paper production company in KwaZulu-Natal, which, based on the evidence and results of the managers, concluded that the company should integrate the MEFCA with the current system to ensure that it is sustainable in the future (Doorasamy, 2015). The reasons why manufacturing companies are looking for sustainable resources include lack of resources, environmental awareness, and the potential for cost savings. To address these issues, the MEFCA has been employed as an environmental management tool. According to the MEFCA, Printed Circuit Board (PCB) production study systematically generated several linear cost calculation models during the production process to capture actual effluent flows as well as cost-benefit analysis, so this research could improve production achievement. Making it profitable and sustainable by improving resource productivity can also provide decision support for PCB production (Wang et al., 2017).

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What Is New and What Is Known

What has already been presented in the research background showed that the MFCA technique and its more advanced version (MFECA) are valuable for the environmental assessment of production processes. A review of past research and previous experiences in the field of turbine blade production and its costing shows that the method used to produce turbine blades has not been evaluated using the MEFCA method until this article. The MEFCA method has been used in many studies to estimate material and energy waste costs. In this research, in addition to this issue, it has been used as a decision-making method for comparison between different manufacturing methods. The study of different methods for manufacturing turbine blades has also been considered by researchers. For example, Echin and Bondarenko (2014) have studied the technical specifications of manufacturing turbine blades using the forging method. Torres et al. (2020) has also studied the method of manufacturing turbine blades using laser melting. In another study, Cygan (2018) technically analyzed the manufacturing of a turbine blade using 3D printing. However, the evaluations made in these studies were mostly technical and did not address the issue of energy and material costs and wastages. Only Torres et al. (2020) conducted environmental analysis based on the carbon emission index.

3. Methodology

As stated in previous sections, the method used for this study is material and energy flow cost accounting. We will see the structure of this method in the following figure. This structure consists of the main input and the positive output and output losses.

Inputs: The inputs of the system include raw materials, energy which includes electricity and water, the system which includes tools and staff costs.

Losses: Losses of raw materials, energy, and system losses.

Waste management costs: Each step includes costs for waste and sewage disposal.

Cost of Positive Output Product: The final product of the raw material includes the energy and system cost and the remaining positive raw material.

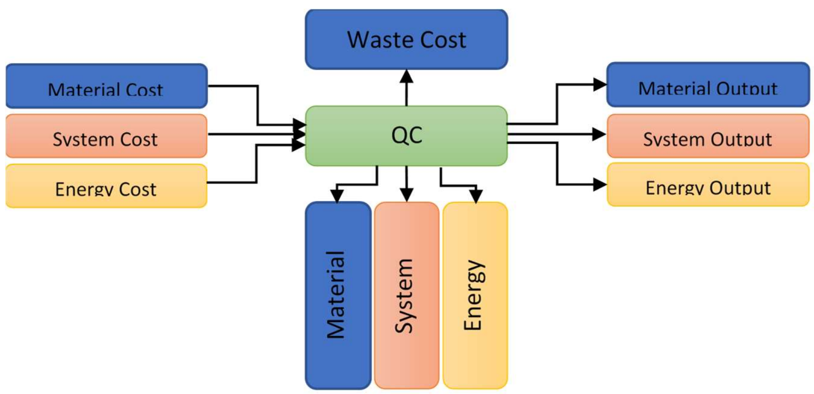

Figure 1. Material and energy flow cost accounting (MFECA) structure.

In this method, we divide the production process into several steps, each called a quantitative center. The symbols used here are in the following table. In this table indexes for material costs (MC), system costs (SC), energy costs (EC), material costs (MC), material weight (W), wasted material costs (WM), wasted system costs (WS), wasted energy costs (WE), positive material output costs (PM), positive system output costs (PS), and positive energy output costs (PM) have been declared.

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Table 1. Symbols.

Index	Symbol
input materials, system, and energy index	$index_{MC}$, $Index_{SC}$, $Index_{EC}$
input materials, system, and energy cost	$Cost_{MC}$, $Cost_{SC}$, $Cost_{EC}$
material weight and material waste	W_{MC}, W_{W}
input materials, system, and energy waste cost	$Cost_{WM}$, $Cost_{WS}$, $Cost_{WE}$
input materials, system, and energy positive output cost	$Cost_{PM}$, $Cost_{PS}$, $Cost_{PE}$

For each step, we allocate a coefficient for the quantitative center.

$$\text{index}_{MC} = \frac{\text{cost}_{MC}}{w_{MC}} \tag{1}$$

$$\text{index}_{SC} = \frac{\text{cost}_{SC}}{w_{MC}} \tag{2}$$

$$\text{index}_{EC} = \frac{\text{cost}_{EC}}{w_{MC}} \tag{3}$$

MC means material cost, SC system cost and EC energy cost. The wastage is calculated as follows:

$$\text{cost}_{WM} = \text{w}_{W} \times index_{MC} \tag{4}$$

$$\text{cost}_{WS} = \text{w}_{W} \times index_{SC} \tag{5}$$

$$\text{cost}_{WE} = \text{w}_{W} \times index_{EC} \tag{6}$$

The cost of positive output is calculated as follows:

$$\text{cost}_{PM} = (\text{w}_{MC} - \text{w}_{W}) \times (index_{MC}) \tag{7}$$

$$\text{cost}_{PS} = (\text{w}_{MC} - \text{w}_{W}) \times (index_{SC}) \tag{8}$$

$$\text{cost}_{PE} = (\text{w}_{MC} - \text{w}_{W}) \times (index_{EC}) \tag{9}$$

The case study of this research is a power plant service company. In this study, using the MEFCA method, we intend to manage the cost of raw materials and energy in producing a complete set of turbine blades. In order to produce turbine blades, a series of complicated tasks should be taken. For this, raw material of alloy steel enters the production line in large cubes. To manufacture the blades, they must be cut to a certain size. These raw materials are then put to the test step with non-destructive tests. The test cubes enter the CNC machining step to form the desired blades, with the highest losses at this step. At the polishing step, products are polished with a blade grinding machine and then passed through the quality control step. The QCs to product a set of turbine blades is as the following figure.

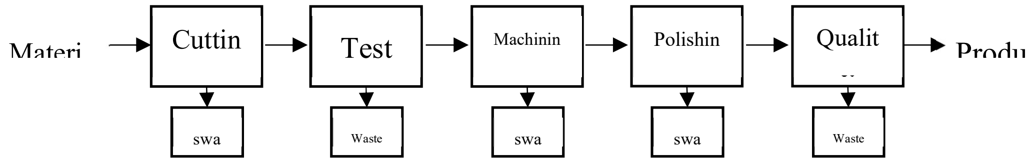

Figure 2. MEFCA structure for turbine blade production with machining method.

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4. Results

The following table shows the costs of producing a set of turbine blades by the machining method. As you can see, the amount of raw materials is 3993.75 kg, which costs 399.3 units (in this research cost units are ten million Rials). The output is also 518.57 kg, which indicates a loss of 3475.17 kg, which is a significant amount. Given this amount of wastage, we will also have a lot of energy and system losses.

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Table 2. Cost of turbine blade production with machining method.

Process Step	Cost MC	Cost Energy	Cost SC	Negative Cost	Waste EC	Waste SC	Positive EC	Positive SC	Positive Cost	Waste Management
Cutting	399.38	9.1	59.06	3.99	0.09	0.59	9.01	58.47	395.38	0.1
Test	395.38	3.12	36.17	2.58	0.02	0.24	3.1	35.93	392.81	0.1
Machining	392.81	19.74	393.47	340.01	17.09	340.58	2.65	52.88	52.79	0.5
Polishing	52.79	4.91	31.86	2.64	0.02	0.16	4.89	31.7	52.53	0.15
Quality Control	52.53	3.12	91.44	0.67	0.04	1.17	3.08	90.27	51.86	0.1
Total	399.38	40	612	347.52	17.26	342.74	22.74	269.26	51.86	0.95

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As we can see, the machining step has the highest amount of wastage, which is approximately 86.5% of the total input material.

One of the alternative methods of producing blades is the forging method. In this method, the cubes are cut to the desired blade size, then pressed into a pre-made mold using a press machine and continue the same steps as machining method. The next figure illustrates the steps of the blade production process.

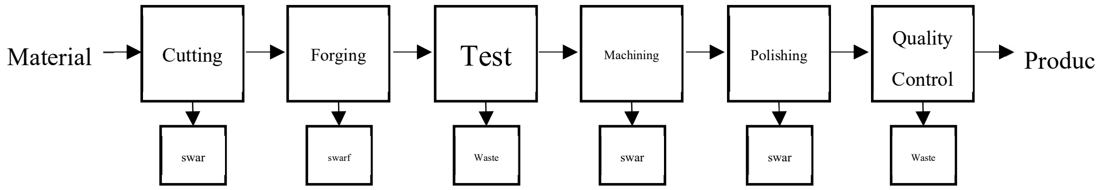

Figure 3. MEFCA structure for turbine blade production with the forging method.

We will see the costs of this method in the following table.

According to the data in this table, the amount of inputs is 1312.5 kg, of which 525.02 kg is positive output. As a result, its wastage will be 787.47 kg, which is very little waste compared to the machining method.

Now we compare the two methods used to manufacture turbine blades. According to Table 3, the input cost of machining is 1051.36 units, while for the forging method, 691.33 units, which has reduced the input cost of 360.03 units, and also reduced the material amount to 2681 kg. The cost of machining is 708, while in the forging method, it is 220, which has decreased by 488 units. Moreover, the cost of positive output is 343, which covers 32% of the total cost of production and nearly 68% is lost, while in forging method, 68% of the input cost is positive and 32% is wastage. The cost of waste management has also decreased.

Table 3. Cost of turbine blade production with the forging method.

Process Step	Cost MC	Cost Energy	Cost SC	Negative Cost	Waste EC	Waste SC	Positive EC	Positive SC	Positive Cost	Waste Management
Cutting	131.25	5.30	34.36	1.31	0.05	0.34	5.24	34.01	129.94	0.07
Forging	129.94	7.28	120.00	12.99	0.73	12.00	6.56	108.00	116.94	0.30
Test	116.94	2.08	23.36	2.27	0.04	0.45	2.04	22.91	114.68	0.10
Machining	114.68	10.23	226.53	61.88	5.52	122.23	4.71	104.29	52.80	0.20
Polishing	52.80	4.86	31.53	0.11	0.01	0.06	4.85	31.47	52.69	0.10
Quality Control	52.69	3.12	91.44	0.19	0.01	0.33	3.11	91.11	52.50	0.10
Total	131.25	32.87	527.22	78.75	6.36	135.42	26.51	391.79	52.50	0.87

Table 4. Comparison of two methods of turbine blade production.

Process Method	Waste	Positive Output				Negative Output				Input			
	WM	SC	EC	MC	MC (kg)	SC	EC	MC	MC (kg)	SC	EC	MC	MC (kg)
Machining	0.95	269.257	22.735	51.857	518.572	342.739	17.261	347.517	3475.178	611.997	39.996	399.375	3993.75
Forging	0.87	391.793	26.507	52.502	525.025	135.422	6.361	78.747	787.47	527.216	32.86	131.25	1312.5
Improvement percentage	8%	46%	17%	1%	1%	60%	63%	77%	77%	14%	18%	67%	67%

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To illustrate the comparison between the machining and forging methods, tables and graphs are provided, which can be seen below.

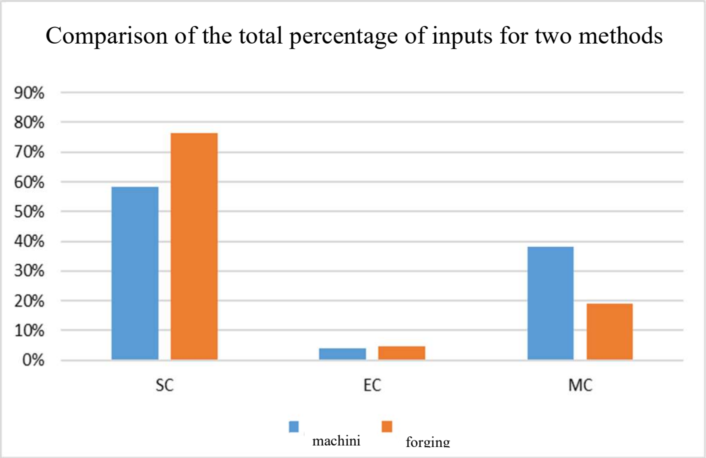

Figure 4. Comparison of the total percentage of inputs for two methods.

As shown in the above diagram, the proportion of system costs in the forging method is higher than machining, but the energy costs are about the same. For material costs, it can be seen that in the forging method, the costs are higher.

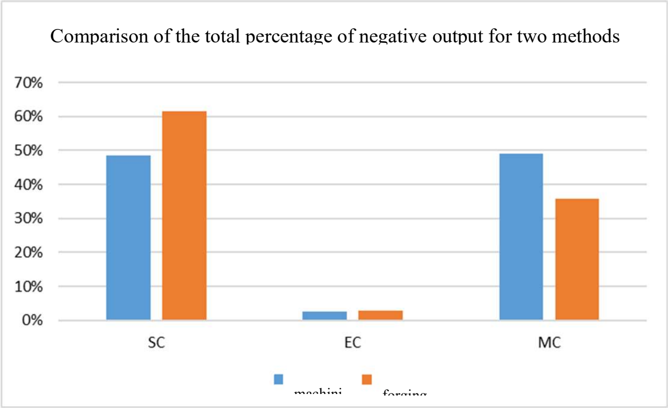

Figure 5. Comparison of the total percentage of negative output for two methods.

By comparing the percentage of total negative outputs between the two methods, it can be seen that the system costs are higher in the forging method, but the material costs in the machining method are lower.

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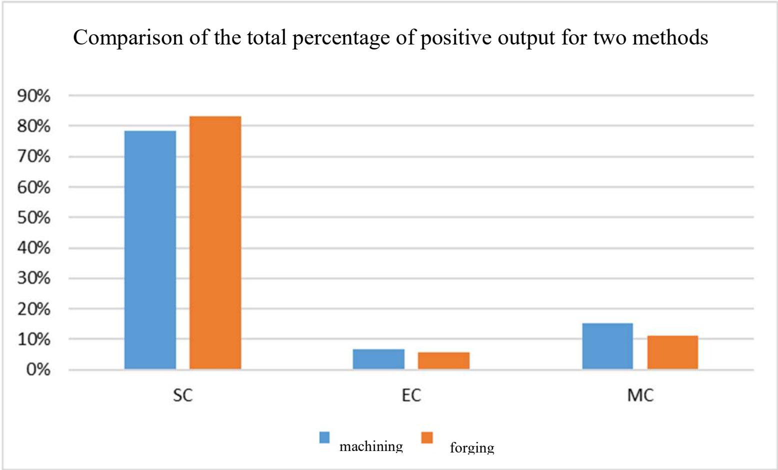

Figure 6. Comparison of the total percentage of positive output for two methods.

In addition, this paper will investigate the economic cost of turbine blade production using engineering economics techniques. The financial information used in addition to past data for these calculations is shown in the following table.

Table 5. Financial information needed to create financial flows.

No.	Item	Amount
1	Production capacity of blades in one year	15 set
2	Average selling price	15 billion Rials
3	Present value of machining equipment	1500 billion Rials
4	Service remaining life of machining equipment	40 years
5	Sacrificial value of machining equipment	100 billion Rials
6	The amount of capital needed to start a forging workshop	100 billion Rials
7	Service life of forging equipment	40 years
8	Sacrificial value of forging equipment	5 billion Rials

The following steps are used to compare the two methods of forging and machining using engineering economics techniques.

- Planning horizons (here will be 40 years with four-year time periods, there will be 10 total)
- Determination of financial flows related to initial investment (II)
- Determination of the financial flows related to the equipment's sacrificial value (SV)
- Determination of the cash flow of incomes (I)
- Determination of operating cost cash flow (OC)
- Calculation of cash flow before tax (CFBT)
- Depreciation calculation (D)
- Calculation of taxable income (TI)
- Tax calculation (T)
- Calculation of cash flow after tax (CFAT)
- Calculation of net present value of cash flow (NPV)

The initial investment in the first planning period is 1500 billion Rials. The cost of equipment after the end of life is five billion Rials. Given that each period is equal to four years and the production capacity is 15 sets of blades per year, the number of blades produced is 60 sets over a period that will generate an income of 900 billion Rials. Given the current inflationary situation, this revenue will increase by 50% for each four-year period. The same is true of operating costs. Operating costs, including total energy, system, and material costs for machining according to the calculations made in the previous research, amounted to 10.51 billion Rials for 1180 blades, which would be 534.4 billion Rials for production of 60 sets of blades. In the forging method, similarly, operating costs will be 351.3 billion Rials. Depreciation by the straight-line method for each four-year period equals 140 billion Rials for machining equipment and 14.95 for the forging method. Tax is calculated on the basis of the tax rate of 9%. The amount of taxable income is calculated and then the amount of tax is calculated. The cash flow after tax is then calculated. Finally, the present value of cash flow is determined and compared between the two methods. The interest rate is 20%. More present value in this comparison means that the method is better in terms of economic justification.

Using these calculations, the net present value of the machining method was 7770 billion Rials and in the forging method 12,120 billion Rials. These numbers represent a significant difference between these two approaches in terms of engineering economics techniques. As a result, it can be argued that the forging method is far better in terms of a long-term planning horizon.

5. Conclusions

Material and Energy Flow Cost Accounting (MEFCA) is the organizational tool used by manufacturing companies to improve the efficiency of their raw materials, energy, and systems. MEFCA's goal is to save energy and money by avoiding wastages. To achieve this, the MEFCA can be used to calculate the actual cost of the waste (even hidden costs). MEFCA is an important element of operating resource productivity for companies and is standardized through ISO 14051.

There are different methods that have been technically studied to make turbine blades, which is considered as a case study of this research. One of these methods is forging, which can be used instead of the conventional method (machining), which is technically and economically justified based on the findings of this study. However, it also had to be considered from an environmental perspective. This study performed this important step using the MEFCA technique.

We used the MEFCA method to study and compare the two methods of blade production. The input machining method was 3993.5 kg, which resulted in 87% of the wastages of material. Due to the MEFCA algorithm, most losses were related to CNC machining step. The solution to this problem was to break the pieces down to 1312.5 kg of raw material and to reduce the loss to 60% of the input (787.5 kg). Generally, in the present study, using deduced data, we investigate the costs of turbine blade production. The conventional way of producing a turbine blade is the machining method that has a lot of losses. By studying the different methods, we found that the forging method reduces losses and costs. In the end, we compare the costs of the two methods together. Engineering economics techniques are also used to compare the two methods over a long-term planning horizon. The MEFCA method can be used in all industries to cost a product which in the future will result in lower losses and cost savings.

Author Contributions:

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Al-Qawasmi, A.R.; Tlili, I. Energy efficiency and economic impact investigations for air-conditioners using wireless sensing and actuator networks. *Energy Rep.* **2018**, *4*, 478–485.
2. Behnami, A.; Benis, K.Z.; Shakerkhatibi, M.; Fatehifar, E.; Derafshi, S.; Chavoshbashi, M.M. Integrating data reconciliation into material flow cost accounting: The case of a petrochemical wastewater treatment plant. *J. Clean. Prod.* **2019**, *218*, 616–628.
3. Christ, K.L.; Burritt, R.L. Material flow cost accounting: A review and agenda for future research. *J. Clean. Prod.* **2015**, *108*, 1378–1389.
4. Cygan, R. 3d printing techniques of ceramic cores used for turbine blades manufacturing. In Proceedings of the IRF2018: 6th International Conference Integrity-Reliability-Failure, Lisbon, Portugal, 22–26 July 2018.
5. ISO. *Environmental Management—Material Flow Cost AccountingGeneral Framework*; ISO 14051:2011; ISO: Geneve, Switzerland, 2011.

 doi:10.20944/preprints202009.0402.v2

6. Doorasamy, M.; Garbharran, H. The effectiveness of using material flow cost accounting (MEFCA) to identify non-product output costs. *Environ. Econ. J.* **2015**, *6*, 70–82.
7. Echin, A.; Bondarenko, Y. Turbine blades production technique equipment built with a glance of high-gradient directional crystallization process nature. In *MATEC Web of Conferences*; EDP Sciences: Agoda, France, 2014; Volume 14, p. 13001.
8. Gong, J.W.; Li, Y.P.; Suo, C.; Lv, J. Planning regional energy system with consideration of energy transition and cleaner production under multiple uncertainties: A case study of Hebei province, China. *J. Clean. Prod.* **2020**, *250*, 119463.
9. Hyrslova, J.; Vagner, M.; Palasek, J. Material Flow Cost Accounting (MEFCA)—Tool For the Optimization oF Corporate Production Processes. *Bus. Manag. Educ.* **2011**, *9*, 5–18.
10. Kokubu, K.; Tachikawa, H.; Material Flow Cost Accounting: Significance and Practical Approach? In *Handbook of Sustainable Engineering*; Springer: Dordrecht, The Netherlands, 2013; pp. 351–369.
11. Lambrecht, H.; Hottenroth, H.; Schröer, T.; Schulenburg, F. Optimization-aided material and energy flow analysis for a low carbon industry. *J. Clean. Prod.* **2017**, *167*, 1148–1154.
12. Maji, I.K.; Sulaiman, C .Renewable energy consumption and economic growth nexus: A fresh evidence from West Africa. *Energy Rep.* **2019**, *5*, 384–392.
13. Khan, M.N.; Rizwan, M.; Islam, F. *The Extent of Application of Standard Costing: A Comparison of Chinese and Pakistani Manufacturing Firms*; Hailey College of Commerce, University of the Punjab: Lahore, Pakistan, 2016.
14. Schmidt, M.; Spieth, H.; Haubach, C.; Kühne, C. Material flow cost accounting in variant production. In *100 Pioneers in Efficient Resource Management*; Springer Spektrum: Berlin/Heidelberg, Germany, 2019; pp. 126–129.
15. Schmidt, M.; Nakajima, M. Material Flow Cost Accounting as an Approach to Improve Resource Efficiency in Manufacturing Companies. *Resources* **2013**, *2*, 358–369.
16. Sygulla, R.; Bierer, A.; Götze, U. Material Flow Cost Accounting—Proposals for Improving the Evaluation of Monetary Effects of Resource Saving Process Designs. In Proceedings of the 44th CIRP Conference on Manufacturing Systems, Madison, WI, USA, 1–3 June 2011.
17. Sygulla, R.; Gotze, U.; Bierer, A. Material Flow Cost Accounting: A Tool for Designing Economically and Ecologically Sustainable Production Processes. In *Technology and Manufacturing Process Selection*; Springer: London, UK, 2014; pp. 281–296.
18. Tang, X.; Takakuwa, S. MEFCA-Based Simulation Analysis for Enviroment-Oriented Scm Optimization Conducted by SMES. In Proceedings of the 2012 Winter Simulation Conference, Berlin, Germany, 9–12 December 2012.
19. Torres-Carrillo, S.; Siller, H.R.; Vila, C.; López, C.; Rodríguez, C.A. Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades. *J. Clean. Prod.* **2020**, *246*, 119068.
20. Wang,Y.; Kuo, C.H.; Song, R.; Hu, A.H.; Zhang, S.S. Potentials for Improvement of Resource Efficiency in Printed Circuit Board Manufacturing: A Case Study Based on Material Flow Cost Accounting. *Sustainability* **2017**, *9*, 907.