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Methodology for Commodity Cost Estimation Through Production Line Analysis and Simulation

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Abstract. In a growing competitive environment, it is essential to have a clear idea of a product's total expenditure by estimating the component costs and correctly allocate cost drivers. Assigning exact commodity consumption costs is one of the most complicated aspects of cost engineering activities, which should be performed during the product design stage using Product Lifecycle Management (PLM). However, during the design stage, information is not complete, and it is not sufficient to guarantee the cost estimate's adequacy and reliability. Therefore, it is necessary to monitor the production process to identify each cost variable carefully. This article aims to propose a methodology to evaluate the proper commodity consumption during manufacturing activities for the assessment of the total part cost. Moreover, it helps to generate validated data useful for decision support systems. The proposed approach is studied by analyzing a machining production line of an Italian manufacturer of components for the automotive industry. It consists of three main parts: (i) description of the production line, (ii) definition of IT architecture, and (iii) asynchronous digital twin design. Thus, after the model's validation, the simulated data allows to analyze and estimate production expenditure accurately by the exact allocation of commodity consumption.

Keywords: Cost Estimation, Material Flow Cost Allocation, Production Management, Production Engineering, Discrete Event Simulation

1 Introduction

Sustainability is a growing concept for the nowadays society. For instance, in 1987, the report "Our common future" from the UN Commission for Environment and Development defined sustainability as a central pillar for humanity's development [1]. In 2015, the UN described the 17 Sustainable Development Goals (SDG) to transform our world, promoting prosperity while protecting the planet [2]. The latest definition of sustainability is given in [3,4]. More in detail, according to Johan Rockström in [3], the "three pillars" approach (based on economy, environment, and society) has driven a fragmented assessment of the development process, where economic growth overcomes natural and human resources. On the other hand, according to [3], the economy is seen as a tool to reach social goals generating prosperity while remaining within the Earth's Life Support System (i.e., the finite natural resources and the limited capacity

of the environment to absorb pollution). Different studies have been provided in literature for the assessment of the energy, cost, and carbon footprint metrics for the Life Cycle Assessment of a product.

Focusing on the cost metric, traditionally, cost management consists of defining which costs are generated by direct material cost, direct labor, and finally, all remaining charges are classified as overhead. Inside overhead expenses, it is possible to consider: rents, indirect labor cost, insurance cost, and utilities [5]. Material cost and direct labor cost are easily attributable to production, while assigning the correct overhead costs is more complicated. The traditional method consists of allocating all fixed costs considering the time spent in production, assuming that all different products need the same amount of every single overhead cost [6]. Thus, traditional allocation methods cause distortion on final product cost due to an incorrect definition of cost drivers. They fail to give correct insight to support the decision-making process [5]. Commodity costs are incorporated inside overhead expenses, and making decisions that improve the efficiency and sustainability of the process is problematic because it is not clear where energy, material, and other commodity wastage are made.

This paper provides a new methodology for cost management based on simulation. The proposed method allows keeping track of cost variations during the production phases compared to what was estimated in the design phase. The management of the product cost throughout its life cycle is a crucial phase of the PLM approach. This work aims to define a new costing method that considers both the theory concerning activity-based costing and the sustainability outlook of material cost flow accounting. We merged the process-based procedure of ABC, maintaining clear interest for the material and resources flow. ABC and MFCA are combined in a factory's simulated digital twin in order to provide insight into the actual cost of a single item produced. The proposed strategy emphasizes commodity consumption (electric energy, water, lubricant, etc.), cost-generating elements that are disposed of as NPOs, and their profligate waste has a substantial impact on the environment. This work fills a research gap by proposing a new standardized methodology for cost estimation using a line simulation.

This work is structured as follows. The second section offers a quick outlook of the current research state of the art in cost allocation. The third section describes the theoretical methodology we used to allocate costs. The fourth section presents an actual industrial application of the proposed method through a case study. The case study is presented in three different subparagraphs: (i) description of the production line, (ii) definition of IT architecture, and (iii) asynchronous digital twin design. The fifth section shows some preliminary results of the proposed model and discusses its goodness employing its validation. Finally, the conclusions section is dedicated to the discussion of future improvements.

2 Literature review

This section evaluates the following topics: (a) activity-based costing, (b) material flow cost allocation, and examples of (c) simulation-based accounting procedures.

2.1 Activity-Based Costing

Fernandes et Al. used activity-based costing to take into account correct energy consumption in manufacturing [6]. That process manages to transform the cost of energy consumed from overhead to a direct production cost, similar to labor and materials expenses. The activity-based method, also known as the ABC method, permits allocating indirect costs to search for actual relationships linking expenses to cost centers. The method's implementation follows three different steps: (a) Cost Center Identification, understanding which resources are used to produce the final good; (b) Activities Identification, analyzing all the activities that take place in the product creation, from its development to its selling; (c) Resource Driver Definition, a cost-driver of activity is a factor that directly explains how the operation incurs costs using resources (e.g., marketing activity uses staff, energy, etc.); (d) Cost Allocation through Activity Drivers Definition, the final stage consists of calculating the activity's share of the product's cost in proportion to the specific activity cost-drivers use [7]. That method requires a precise and complete understanding of the product, and it makes it possible to clearly understand where costs and, eventually, waste are generated. In literature, there are cases of the ABC approach used to assess system sustainability; for instance, Cagno et Al. proposed an augmented ABC approach aimed at estimating the environmental impact, adding a flow analysis on the analyzed system [8]. A simple scheme of the ABC method [9] can be found in **Fig. 1**.

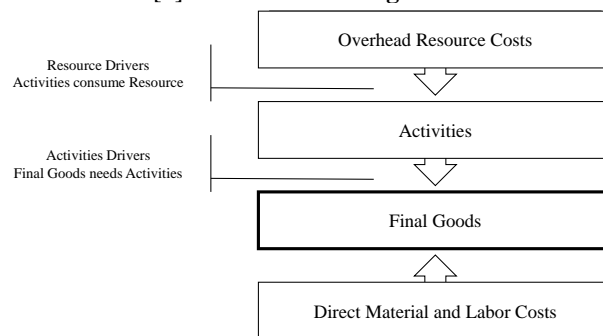


Fig. 1. Activity-Based Costing scheme.

2.2 Material Flow Cost Allocation

In the last decades, environmental management accounting (EMA) has emerged. EMA is a management accounting approach focused on physical flow. A business process can be described as a system that takes resources as input and transforms them into outputs. It can be possible to distinguish those outputs: product or value-added activities and wastes. Wastes are a cost for the company, and, on the other side, they have a negative impact on the environment [10]. An EMA approach uses internal information about the physical flows that pass through the firm's boundaries and evaluates the related environmental costs [11]. The EMA approach's main scope is to

pinpoint the non-product output (NPO), generating many costs. It is possible to define two different kinds of non-product output. (a) Direct NPOs like raw material. These NPOs are usually disposed of as solid waste. Still, in some industries, they could be treated as wastewater if the final product is liquid or released into the atmosphere if the final product is a gas. In this category, it is possible to insert also auxiliary material like glue, paint, and packaging fabrics. (b) Indirect NPOs like energy and water; in this cluster, it is possible to categorize all resources and materials that are not directly part of the final good [11]. Generally, operating materials are considered not-product output since they are not incorporated in the product; there may be exceptional cases such as the beverage industry where only a water percentage is a waste [11].

One of the main tools of EMA is the Material Flow Cost Allocation (MFCA). According to Christ and Burritt, the application of a flow measurement system follows a series of steps. First, defining the analyzed system's boundaries; the second step consists of defining a flow model (a diagram capable of mapping everything that enters and exits the system). According to Kokubu and Tachikawa, this element is crucial to measure the balance of material and keep track of waste [12]. The third step is to determine the amount of input and output going in and out of the system in order to find a balance. The principle that guides this balance is that everything that enters the system, whether energy or material, is not destroyed but is transformed into other forms. Finally, The obtained physics values are converted in a monetary amount [13]. A simple scheme of Material Flow Cost Accounting can be found in **Fig. 2**. MFCA projects are generally defined and guided by academia; researchers have a direct consulting and expertise role due to the normative impact of research literature in this field [14]. In addition, there is a growing need for industrial applications to raise awareness of waste and unnecessary consumption during manufacturing activities.

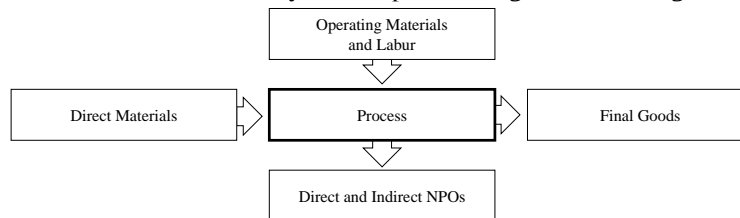


Fig. 2. Material Flow Cost Accounting scheme.

2.3 Simulation-Based Accounting

In literature, there are some cases of published works on cost management based on simulation. Larek et Al. proposed a Discrete Event Simulation Model to estimate a CNC machine's power consumption starting from the job's G-code. Their approach is flexible and usable for various processes, and the use of simulation can give a more precise insight compared to complex analytical models [15]. Spedding et Al. proposed one of the first applications of a simulation-based approach for ABC accounting. Their methodology focused on manufacturing line surplus capacity. They allocate costs, both direct (i.e., direct labor and energy consumption) and indirect (i.e., asset

depreciation), using the time spent in a workstation as a driver for allocation, and they calculate by difference all non-direct explainable costs. That methodology helps to focus on non-value-added activities, like idle time [16]. In recent days, Calvi et Al. proposed a renewed process for an ABC approach based on simulation. They provide an in-depth detailed description of a simulator representing a re-manufacturing stage of a closed-loop supply chain for electronic devices. Also, in that case, the driver used to allocate cost is the time spent in each activity [17].

A simulation approach for cost management provides many advantages. (i) First of all, it is possible to have an exact value of the actual cost incurred during the activity. (ii) The activity-based driven modeling of discrete event simulation fits very well with an ABC cost analysis. (iii) Finally, this dynamic approach permits a what-if scenario analysis that can help managers during the decision-making process. In literature, it is possible to find a wide variety of simulation-based techniques to solve different issues. Despite the proven ability to deliver significant benefits, there are few examples of cost management applications [17].

3 Cost Allocation Definition

This paragraph defines a new methodology to implement a second-stage cost allocation. The first-stage allocation is the assignment of the costs on the activities. While, the second-stage allocation includes the attribution of the costs on the single produced elements, defining how much a single object has cost [18].

1. *System Perimeter Definition*: the first step of the proposed approach is to define the boundaries of the system, define what process is intended to be analyzed, where it starts, and where it finishes.
2. *Activity Identification and Flow Model Design*: the second step consists of identifying all activities involved in the project, both direct and indirect. For all single activities determined, a definition of the Flow Model Diagram is needed to keep track of all physical and non-physical resources that enter the system.
3. *Data Gathering*: the defined activities need a detailed data monitoring plan, starting from the designed model flow. A detailed analysis has to be pursued for each activity, and data collection points have to be identified, such as sensors or connected to central information infrastructure.
4. *Simulation Development*: it is possible to represent the activities by simulating them starting from the data obtained. The simulation model can be directly connected to the process's information system; it could be defined as the process's digital twin in such a case. In the alternative, the data could be inserted asynchronously, using an intermediary system. In such a case, the model could be defined as an asynchronous digital twin or an unconnected digital twin [19]. It would also be appropriate to explain what digital twins are and how the concept contributes to the study. According to [19], it is possible to define four categories of DT, (1) Unconnected DT, (2) Connected DT, (3) Embedded DT, and (4) Aggregated DT. The first typology (1) is used when the digital model describes physical logics, but it is not feasible to connect the two interfaces (physical and digital world) directly. In-

deed, the proposed methodology expresses the maximum potential when it communicates in real-time with the physical system (2,3 and 4)

5. *Direct Item Cost Allocation*: it is straightforward to allocate all direct material costs. It is also possible to carry out a simple allocation based on time for all those operating costs incurred during direct work on the goods produced. The direct cost for a single product after this phase should be:

$$C_i^D = \sum_j \sum_k T_{ji} R_{jk} + M_i, \quad (1)$$

where C_i is the direct cost for the i-th produced item, T_{ji} is the time spent for the i-th item on the j-th activity, and R_{jk} is the time-related cost rate of the k-th operating resource (energy, water, depreciation, etc.) for the j-th activity. Finally, M_i is the direct material cost for the i-th product.

6. *Indirect Item Cost Allocation*: the second cost allocation step provides a quantified evaluation of all not-directly allocable expenditures. We can categorize Indirect Costs into two different types: (a) indirect costs from auxiliary activities (i.e., cost incurred during product design, administration activities, etc.); (b) indirect costs due to system overcapacity (i.e., worker idle time, idle consumption, etc.). The indirect cost C_i^I for a single product, can be written as:

$$C_i^I = \sum_k \rho_{ik} A_k^{tot} + \sum_j \sum_k \frac{T_{ji}}{T_j^U} R_{jk} T_j^{UN}, \quad (2)$$

where the first part of the equation represents (a) the indirect cost from auxiliary activities, A_k^{tot} is the overall cost of the auxiliary activity k, and ρ_{ik} is an allocation factor based on different conditions. The second part of the equation represents (b) the indirect overcapacity cost, T_j^U is the total utilization time for the activity j, T_j^{UN} is the time that an activity j-th spent in an idle state. $\sum_k T_j^{UN} R_{jk}$ is the total cost for the j-th activities in a non-value-added state. This total cost is allocated on the single item using the percentage of time which the item above passes in the phase T_{ji}/T_j^U .

7. *NPOs Evaluation*: all item has an assigned value C_i^S equal to the evaluated total cost spent to produce it at that stage:

$$C_i^S = C_i^D + C_i^I. \quad (3)$$

If a product is discarded due to a defect, all accumulated value should be redistributed as an NPO to the final goods. This value is firstly associated with the process that generates the failure if it is possible. This value is allocated to the final product in a second phase when it leaves the system's boundaries using a similar logic of the indirect overcapacity cost, seen in the previous step:

$$C_i^{NPO} = \sum_j \sum_n \frac{T_{ji}}{T_j^U} C_n^S. \quad (4)$$

The cost C_i^{NPO} for non-product output allocated to the single i-th item is calculated as the percentage of time spent on the j-th process multiplied by the total cost of

the n wastes caused by the j -th activity $\sum_n C_{jn}^S$. At the end of the process, all item has an associated cost equal to C_i^T that can be calculated as follow:

$$C_i^T = C_i^D + C_i^I + C_i^{NPO}. \quad (5)$$

4 Case Study

We applied the proposed method to a production line of an Italian developer and manufacturer of components operating in the automotive industry. The analyzed case study is described in this section.

4.1 Description of the production line

In this subparagraph, the production line object of this study is presented. The line's purpose is to manufacture wheel hubs for cars. The reader can find a simple scheme of the line in **Fig. 3**.

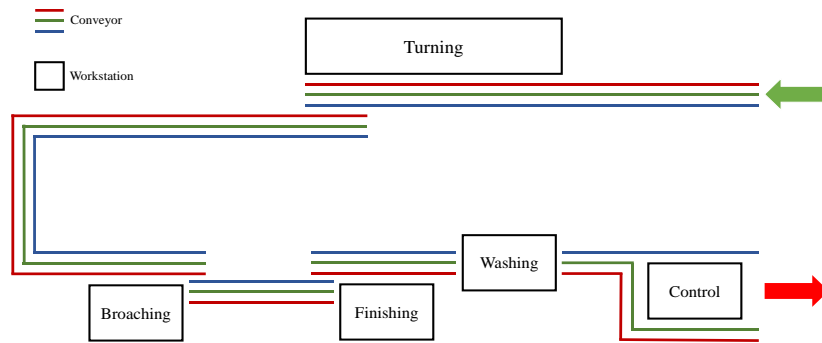


Fig. 3. Production line layout.

The line could work on three different kinds of pieces (A, B, and C), two of them (B and C) with the same diameter. The parts are transported by three different conveyors, represented by three lines in **Fig. 3**, pieces of the same kind are always placed on the same conveyor. The line could be reconfigured in order to produce diverse mixes of the three parts by changing the conveyors' destination. The semi-finished products that come from the foundry are placed on boxes at the start of the line. Here an operator feeds the line setting the semi-finished at the beginning of the correct conveyor. Unless there is a case of operator negligence, the conveyors are filled with pieces, so it is possible to consider this buffer virtually infinite.

Turning

The first workstation consists of five parallel machines; all of them are in charge of doing two operations on each side of the piece. When a pre-product arrives from the conveyor, a robotic arm places it in a shuttle (position alpha). The shuttle brings the object inside the CNC machine. Here, the first operation (OP1) is performed. Mean-

while, if a second piece is waiting in the queue, the shuttle leaves the working area to take it. As the first operation is finished, the CNC machine drops the part inside the shuttle (position beta), and it takes another piece from position alpha to perform OP1. Before placing a new object inside alpha, the robotic arm turns the piece from position beta to position gamma. Suppose two different items inside the shuttle, one in position alpha and one in position gamma. In that case, the CNC machine will perform two separate operations: OP1 to the pieces in alpha and a second operation (OP2) on the parts in position gamma. After OP2 is finished, the CNC drops the item in position delta from where the robotic arm takes it and places it inside the conveyor. A scheme of the combination of the two first operations can be found in **Fig. 4**.

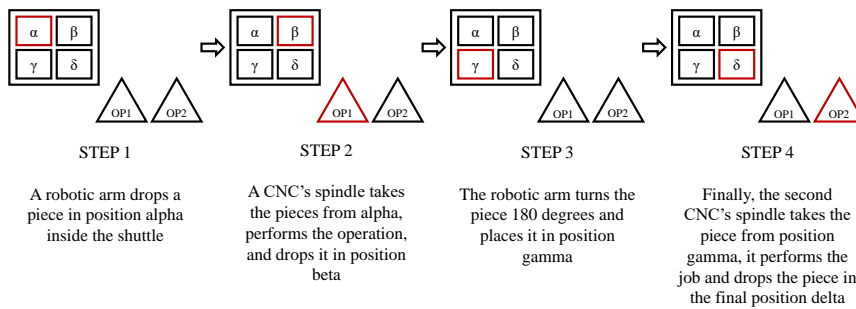


Fig. 4. Logic description of the two first operations (OP1 and OP2) on a single piece.

Broaching and Finishing

Three different broaching machines compose the second workstation, any of them is in charge of a single kind of product. When a product arrives from the conveyor, a robotic arm takes it and places it inside the corresponding broaching machine. Here the third operation (OP3) is performed. When OP3 is finished, the robotic arm takes back the piece and place it inside the corresponding conveyor. The two objects with the same diameter (B and C) require the same type of processing and time. Therefore, each broaching machine can process the kind of pieces based on the line set for a specific day. Finally, two parallel lathes carry out the finishing operation (OP4). Both machines can be set according to the daily production planning, but they tend to be programmed identically to machine all types of wheel hubs (A, B, C).

Washing

The fourth operation (OP5) is piece washing; a washing machine performs this procedure following four different steps: (i) pre-wash, (ii) wash, (iii) rinse, and (iv) dry. In order to evaluate the procedure's total cost, it is crucial to define process times and the use of water and solvents. Generally, a mixture of water and oil is used to prevent the parts from rusting.

Geometric Control and Laser Marking

Finally, at the end of the line, two parallel tools complete the pieces' geometric control (OP6). The first instrument checks the A parts, and the other controls the pieces B and C. Scrap are placed in a box and subjected to a second wash; if the machine notifies a second measure error, the piece is rejected. A laser machine marks all not scrapped parts (OP7). This mark makes it possible to trace geometric information and its position inside the process.

4.2 Description of the IT infrastructure

One of the project's central parts is the IT infrastructure needed to gather data from the production line. An industrial edge gateway manages the plant infrastructure, controlling the line's PLC through internal software (SINTRA). Any workstation is equipped with sensors to measure electric energy, water, compressed air, and lubricant-coolant liquid. All sensors are connected with SINTRA via an I/O link module. In order to measure ambient variables (e.g., external temperature, barometric pressure, etc.), we add to the system a sensor box. All data generated by the line are collected and managed by software developed ad hoc for this project (HOME). Data collected in a network attached storage includes machines' status from PLC, commodity consumption from sensors, and ambient value from the sensor box. This data is directly accessible by internal users or through a VPN by external users. Due to the company's confidentiality requests, the simulator has been designed externally and fed by data asynchronously. **Fig. 5** shows the architecture scheme of the previously described infrastructure.

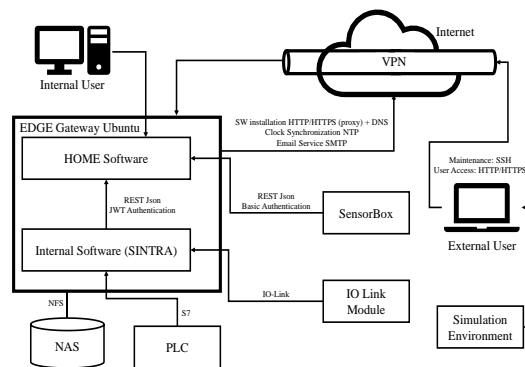


Fig. 5. Architecture scheme.

4.3 Asynchronous Digital Twin Design

Using the accounting theory described in the second paragraph, we developed a digital twin prototype able to ideally copy the line's behavior described at the beginning of this third section. Due to the project still in its early stages, we decided to focalize only on the line's electric energy consumption, and we considered it as a generic

commodity able to drive direct costs C_i^D (i.g., direct machining consumption), indirect costs C_i^I (i.g., idle consumption), and non-product output costs C_i^{NPO} (i.g., electricity used to produce waste parts). Our approach can be easily extended into a more complex context, evaluating different sources of direct and indirect costs, such as other commodity consumptions (e.g., water, compressed air, and lubricant-coolant liquid, etc.), amortization of the machines and overheads, and adding costs generated by ancillary business units. Moreover, focusing on a single variable makes more explicit the novelty aspect of this work. The proposed approach diversifies a cost such as electric energy consumption into three different components. Each component provides additional information on the process, highlighting its effectiveness or inefficiency. The simulation model is developed using FlexSim, a discrete-event simulation model software. It replicates the actual line in detail; the user sets the productive mix (A, B, and C products), and he assigns each machine's task before launching the simulation (see Fig. 6). Before the run, the software requires two parameters: the update frequency and a flag variable whose outcome is a detailed electric energy report. When the simulation is finished, the user receives three separate outputs. The first one is a general aggregated dashboard with the following information: total produced pieces, total wastes, total direct electric energy consumption, total indirect electric energy consumption, and electric energy consumption dissipated in waste products. The second one is the first stage cost allocation report, and it describes energy consumption for each workstation divided into the three defined components (C_i^D , C_i^I , and C_i^{NPO}). The third document is the aforementioned detailed electric energy report with a second stage cost allocation. Finally, the third dashboard presents the precise cost of any single piece produced by the line, and again the report emphasizes the cost breakdown.

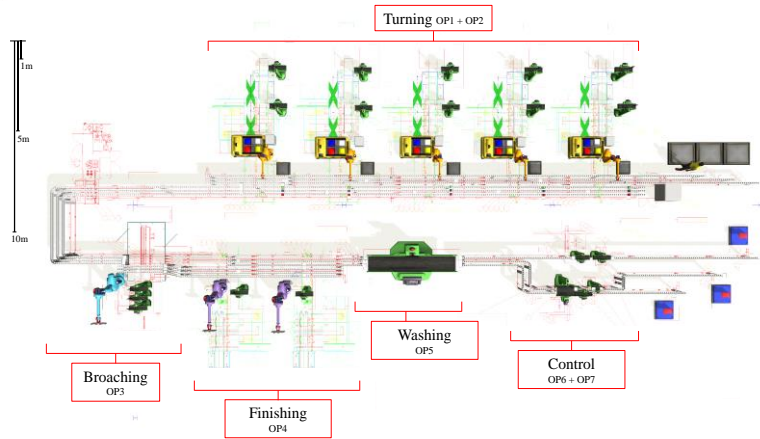


Fig. 6. Simulated model of the production layout.

The simulation model is built on a scale of 1:1 starting from the production line CAD drawing. The parameters used in the simulation environment are based on internal references and machine nameplates. We decided to focus this work on product A. Therefore, from now on, all data are referred only to it. Product A is the main one: in

about three observed months, product A consists of more than 91% of produced pieces while product B 6% and C are less than 3%. The reader can find a summary of the main line's time and speed parameters in **Table 1**. Process time for products B and C is longer due to the greater diameter and the general more significant dimensions. **Table 2** displays the electric power requested by different machines during three phases: processing, idle, and scheduled down. We assumed that the machine tool is turned off if it is not working due to shifts or organizational reasons, so the scheduled down requested power is 0 kW. Finally, we insert a probability of 10% for every piece to have dimensions out of control during the geometric control and be rejected as waste; this value aligns with the company's historical information.

OP1/OP2 processing time	93 s				
OP3 processing time	56 s				
OP4 processing time	43 s				
OP5 processing time	6 s				
OP6 processing time	24 s				
OP7 processing time	19 s				
Conveyor speed	0.67 m/s				
Shuttle speed	0.25 m/s				
Robot operation time	3 s				
		Processing	Idle	Scheduled Down	
		OP1 + OP2	65 kW	25 kW	0 kW
		OP3	25 kW	14 kW	0 kW
		OP4	45 kW	25 kW	0 kW
		OP5	10 kW	1 kW	0 kW
		OP6	1.5 kW	1 kW	0 kW
		OP7	3.5 kW	1.5 kW	0 kW

Table 1. Time and speed parameters.

Table 2. Electric power parameters.

The line works in a continuous cycle during the 24 hours. On the weekend, the line is stopped at 6 a.m. Saturday and restarts at 6 a.m. on Monday. The line operates on three continuous shifts: the first from 6 a.m. to 2 p.m., the second from 2 p.m. to 10 p.m., and finally the last from 10 p.m. to 6 a.m. During shift changes, production slowdowns have been included in the simulation model, and this information is obtained by the company and from the direct analysis of production data. Generally, this slowdown has an impact on the half an hour before and after the shift change. We mimic the downturn with a machinery pause of 60 minutes. We also inserted a time break in the middle of each shift (10 a.m., 6 p.m., and 2 a.m.); this behavior is realistic and partially confirmed by data.

5 Results and Discussion

5.1 Production Output

To test and validate our model, we ran the simulation for about two months: from the 5th of October 2020 to the 19th of December 2020. We compare the obtained simulated results with the actual production output extracted from the line's PLC. We eliminate from our analysis the days 7th, 8th, and 9th of December: in these three days, the plant was closed due to an Italian public holiday. We also deleted the 30th of November; on this day, the IT system aggregated the data in a wrong format.

The first step was to validate different machine processing times. **Table 3** displays the comparison between simulated processing times and the company's actual processing time.

	Avg Sim Time	Sim Std. Dev.	Actual Time
Turning Time	04:19 s	00:04 s	04:21 s
Broaching Time	00:58 s	00:01 s	00:58 s
Finishing Time	00:45 s	00:01 s	00:45 s
Washing Time	00:06 s	00:00 s	00:06 s
Quality Control Time	00:24 s	00:01 s	00:24 s
Laser Marking Time	00:19 s	00:01 s	00:20 s

Table 3. Validation of the different process times for the production of the single component A.

After processing time validation, we examined the simulated total production output to evaluate if it correctly predicts the real one. During the two months, excluding the four outlier days, the line produced 86.029 pieces while the simulation produced 87.203, an error of 1.36%. We calculated the average and sample standard deviation of produced pieces for all combinations of hours and days to have more detailed information about this error. **Fig. 7** displays the average production of a week for the real manufacturing plant (green line) and the simulated model (brown line). Each value is calculated as a mean of the same day's production in the same hour for the considered sample. On Saturday after 6 a.m., Sunday and Monday morning, before 6 a.m., when the plant is closed, the two lines are perfectly overlapping, and on weekdays (120 hours in total), the two lines are similar. The simulation model correctly represents the breaks during and between shifts. However, simulation systematically overestimates the production rate as shown by cumulative average week production reported in **Fig. 8**. On average, the simulated manufacturing line produces 88 pieces a week more than the real line. The nature of this error can be easily discovered by analyzing raw data: the hourly production in the real world has a more significant variability than the simulated. Frequent line interruptions cause this variability (e.g., breakdowns, periodic maintenance, stops asked by management, etc.). These interruptions drastically drop down the production rate and generate variability. Despite this, the line's digital twin replicates production without interruption quite well. However, it will be necessary to collect data for more extended periods in order to try to model the distribution and frequency of outages in the simulation model.

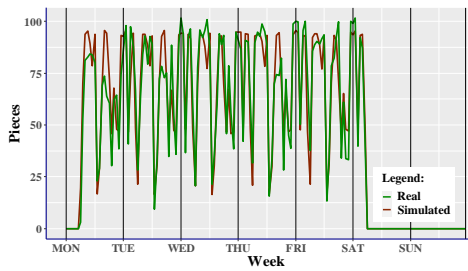


Fig. 7. Mean hourly production

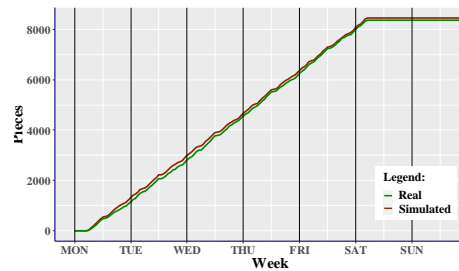


Fig. 8. Cumulative mean hourly production.

Fig. 9 shows the difference between the week average actual hourly production with the simulated one. The systematic error is emphasized in the image by a red line: the simulation model overvalues the real output of 0.732 pieces per hour; the average

is calculated considering only the 120 working hours a week, an average relative error of 1.05%. On the other hand, the actual process is more variable than the simulated one: on average, the real standard deviation is 87% more than the modeled one. The average relative error committed for every hour of the week is represented in **Fig. 10**. As aforementioned in this section, this more significant variability is caused by frequent breakdown and maintenance periods. This behavior is not described in the simulation model due to a lack of knowledge of the complex phenomenon.

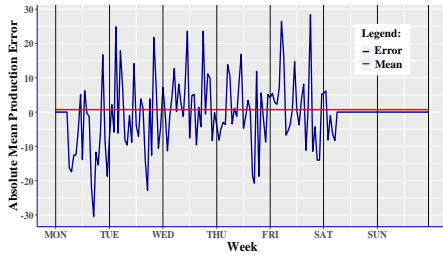


Fig. 9. The difference between simulated and real mean production.

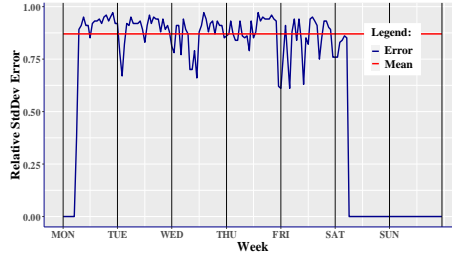


Fig. 10. The relative error between simulated and real standard deviation.

5.2 Energy Consumption and Cost

We use the designed model to calculate the line cost for a generic production week due to its electric energy consumption. A cost of electricity equal to 0.17 €/kWh has been used. This value is the declared electricity cost for the examined company. It is in line with the average Italian electricity cost (0.15€/kWh) considering the Eurostat report indicating the electricity cost for non-household users in Italy consumption up to 2000MW per year [20]. The final results are presented in **Table 4**. The digital line produced 8475 pieces during a production week, with an overall energy cost of 5904 €. Only 76% of the total cost is spent on value-added activities (C_i^D). The 14% is paid in idle (C_i^I), and another 10% is consumed due to waste (C_i^{NPO}). **Fig. 11** summarize the results showing the overall estimated cost incurred by the company during a generic week.

Production	8475 pcs.
Direct Cost	4462.88 €
Indirect Cost	850.56 €
NPOs Cost	590.84 €

Table 4. Energy Consumption Dashboard after a generic week.

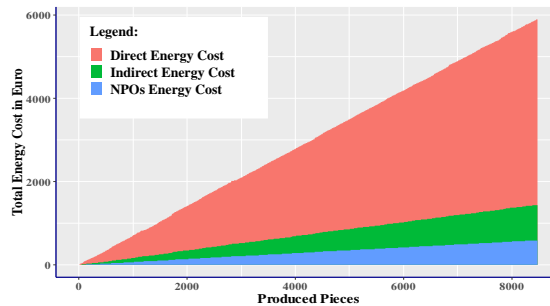


Fig. 11. Production costs divided into three components (C_i^D , C_i^I , and C_i^{NPO}).

6 Conclusions

In this paper, we proposed a new simulation-based accounting model. The novelty of the approach consists of allowing a better classification of costs and commodity consumptions to evidence manufacturing wastes and inefficiencies. This work has several limits, which can be improved under different aspects. (a) The performed analysis has been limited to a single product. However, the study of a more diversified product mix would have given more realistic results. (b) We limited our work to the study of electrical energy consumption. In the future, we can use more complete data gathered from the information system. New data could help to improve our simulation model and permit the forecast consumption of water, compressed air, and cooling liquids. (c) We validated our model, collecting production data for less than three consecutive months. This factor represents one of the most significant limitations of our work. Therefore, we are planning to collect data for a more extended period. (d) Moreover, a more realistic description of the line is needed to create a more reliable digital twin. Future works will focus on developing a sensitivity analysis to estimate cost driver variables and eventually give insights to companies aiming to improve their processes. Once validated, the model could be used to forecast scenarios and provide "to be" configurations. As discussed in the methodology section, the proposed approach provides more significant value when integrated directly with sensors to build a connected digital twin. In the examined case study, such integration was not possible due to corporate security reasons. In the future, we hope to find collaboration from companies to develop a case study of our complete methodology to appreciate all the advantages. Suppose the simulation model would be directly connected to the process's information system. In that case, more information could be collected, and new challenges would be raised, such as how to keep Digital Twin consistent data consistent.

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