ARTICLE TEMPLATE

Technical, economic, and environmental performance assessment of manufacturing systems: The Multi-layer Enterprise Input-Output formalisation method

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ABSTRACT

In production planning and control, assessing the performance of a manufacturing system is a multi-dimensional problem, in which neglected dimensions may lead to hidden inefficiencies and missed opportunities for gaining a competitive advantage. In this paper, a data formalisation method is proposed to model a manufacturing system by simultaneously considering value creation and technical, economic, and environmental performance. The proposed method combines the techno-economic assessment of lean manufacturing and sustainable manufacturing with the data-driven approach, typical of Industry 4.0, to overcome the limitations of the lean approaches in addressing complex systems. The method is based on the integration between Multi-layer Stream Mapping and a combination of Enterprise Input-Output and Material Flow Analysis, and it also considers non-value-added activities such as transport and inventories. Pen and papers and digital approaches can simultaneously exploit the method as a shared architecture for data formalisation and integration. The implementation of the method is shown through a numerical example based on a recycled plastic pipeline manufacturing system.

KEYWORDS
Lean manufacturing; Sustainable production; Industry 4.0; Value stream mapping; Digitalisation; Operational performance; Environmental performance; Material flow cost accounting

1. Introduction

The technological revolution of Industry 4.0 (I4.0) and the necessity of a transition towards more sustainable development are impacting the methods and the tools to optimise and control the performance of manufacturing systems (Bendul and Blunck 2019). Data plays such a pivotal role in the I4.0 paradigm (Chiarello et al. 2018) that Klingenberg, Borges, and Antunes Jr (2019) proposed a classification of manufacturing technologies, methods, and tools based on their role in the data life cycle:

(1) **Data Generation and Capture.** Technologies that generate and save data at any system level: people, products, machines, and processes.
(2) **Data Transmission.** Technologies involved in data transmission to store and recover data.
(3) **Data Conditioning, Storage and Processing.** Technologies and methodologies of data protection and storage, data recovery and data conformation check, and data transformation to create knowledge.
(4) **Data Application.** Methods, tools, and technologies, exploiting collected data,

to control the value creation process.

Usually, the methods and tools for production planning and control integrate the characteristics of two or more of these four groups. They specify the required data and the procedures to collect, manipulate, and exploit them to obtain Key Performance Indicators (KPIs). Furthermore, the available methods and tools focus on a subset of the dimensions (i.e., no method considers at the same time technical, economic and environmental dimensions). To consider all the dimensions together, a combined use of tools, methods and KPIs is required (Ferretti et al. 2017). However, this creates a possible redundancy in data collection, conditioning, storage and processing. Also, aggregating results of different methods may lead to partial and incomplete system representation rather than a well-rounded overview, since the same phenomenon may be represented differently from different methods.

The inclusion of the economic and environmental dimensions beside the technical efficiency is essential to support the efficient use of resources through the implementation of the 6Rs strategies of the circular economy, namely, reduction, reuse, recycling, recovery, redesign, re-manufacture (Govindan and Hasanagic 2018). Implementing 6Rs strategies introduces loops and customised manufacturing routes into the value creation process that becomes more complex (Agyapong-Kodua et al. 2012). In general, value chain models present three main limitations (Daaboul et al. 2014):

- the value considers only the financial dimension, like the turnover of the activity costs;
- the representation of the activities follows a specific and sequential order;
- interactions between activities and their effects on created value are neglected.

On the one hand, the extensive data availability allows to control such complex systems, even in a more sustainable manner. On the other hand, it increases the complexity of production planning and control approaches (Zheng et al. 2021) that must deal with several intertwined dimensions simultaneously. Neglecting some of the dimensions may lead to hidden costs and missed opportunities by affecting the assessment of the considered ones (de Oliveira Neto and Lucato 2016).

This paper proposes a data-driven formalisation method belonging to group (3) of the aforementioned Klingenberg, Borges, and Antunes Jr (2019)'s classification. The proposed method, the Multi-layer Enterprise Input-Output (MEIO) formalisation method, combines Enterprise Input-Output (Albino, Izzo, and Kühtz 2002) and Material Flow Analysis (Rotter et al. 2004) with the Multi-layer Stream Mapping (Holgado et al. 2018) to support the simultaneous assessment of techno-economic-environmental performance and value creation. The method provides a shared architecture of data conditioning, storage, and processing, concurrently exploitable by both digital models (such as simulation and decision-making models) and pen and paper approaches (such as value analysis). Based on a fictitious but realistic system, a numerical example shows the implementation and highlights the potential advantages of the proposed formalisation method.

The remainder of the paper discusses in section 2 some of the most diffused methods to assess value creation and techno-economic-environmental performance of manufacturing systems. Section 3 introduces the MEIO method. Section 4 presents the numerical example and shows the results, while section 5 discusses the insights and concludes this paper.

2. Literature review

In the past, the monitoring of value creation and technical efficiency was an adequate proxy for economic and environmental performance. The definition of value as 'what buyers are willing to pay' (Porter and Kramer 1985) also has the environmental effect of minimising waste and use of non-essential resources (Romano et al. 2010). Nowadays, the technical performance of a manufacturing system tightly intertwines techno-economic-environmental performance and value creation, and the methods focus specifically on a subset of them at a time.

Table 1 collects some of the most studied methods and their characteristics to analyse value creation and technical, economic, and environmental performance. The literature is rich with customised versions of the general methods included in Table 1, which are often case-dependent and hardly extendable to general applications. Therefore, Table 1 shows the general version of the proposed methods for each macro class, highlighting the state of the art from a broader perspective, while a narrower overview of customised approaches follows within this section. The rows of Table 1 list the specific characteristics of each dimension of performance assessment, and the ticks indicate whether a method (in columns) covers them. The first rows in *Application field and scope* provide information about the uses of the methods and whether they can involve a single company or a supply chain. The second set of rows tracks whether a specific method exploits the benefits of adopting data-driven approaches fostered by I4.0. Then, the dimensions of performance follow.

Value creation and technical efficiency are the main objectives of lean management, which aims to make companies technically performing and reactive (Chiarini, Baccarani, and Mascherpa 2018) by reducing eight types of waste (technical dimension in Table 1) and defining the non-added-value activities (Ohno 1988). In contrast, the time spent in value-added (VA), non-value-added (NVA), and essential-non-value-added (ENVA) activities characterises the value creation dimension. The most famous lean tool to identify waste sources, both at the system design and production control levels, is the Value Stream Mapping (VSM) (first column). VSM typically focuses on a factory or a short supply chain by identifying activities contributing to produce the product required by customers (Agyapong-Kodua et al. 2012). Although VSM has been improved, for example, to deal with system sources of waste and risk management (Ramesh and Kodali 2012; Vernadat et al. 2013), it struggles to include all the used resources, and the outcomes of its application depend on the choice of the flow unit used in the analysis (Shou et al. 2017). Another method based on VSM is the Multi-Layer Stream Mapping (MSM), which extends the value creation assessment of production systems with the evaluation of resource efficiency (Holgado et al. 2018).

Lean manufacturing methods mainly follow a value chain approach, resulting in inadequate modelling of networks of companies and complex manufacturing systems, such as those involving re-entrant flows, assembly, and disassembly operations (Braglia, Carmignani, and Zammori 2006). The contamination of the I4.0 paradigm with lean manufacturing principles may lead to positive synergies overcoming the current limits (Sanders, Elangeswaran, and Wulfsberg 2016), leading the scholars' interest in conceiving combined frameworks helping operational performance (Buer et al. 2020). Potential synergies and incompatibilities are not completely clear yet (Sanders et al. 2017), since lean manufacturing may lead to the adoption of new technologies, and the new paradigm may increase the effectiveness of some lean principles (Rosin et al. 2020). Moreover, using lean methods with the increasing amount of data and system complexities fosters the risk of using new technologies in obsolete ways, by precluding

Table 1. Performance dimensions covered by the proposed methods.

		Lean approaches		**Network approaches**	**Flow approaches**		**This paper**
		Value stream mapping	**Multi-layer stream mapping**	**Enterprise input-output**	**Material flow analysis**	**Material flow cost accounting**	**Multi-layer enterprise input-output**
Application field and scope	System design	✓	✓	✓	✓	✓	✓
	Production planning	✓	✓	✓	✓	✓	✓
	Production monitoring and control	✓	✓	✓	✓	✓	✓
	Single company	✓	✓	✓	✓	✓	✓
	Supply chain			✓	✓	✓	✓
Data-driven characteristics	Benefit from real-time update	✓	✓		✓	✓	✓
	Benefit from automatic update	✓	✓		✓	✓	✓
	Benefit from big data exploitation			✓	✓	✓	✓
	Complex network systems			✓	✓	✓	✓
Technical dimension	Defects	✓	✓	✓	✓	✓	✓
	Inventory	✓	✓				✓
	Motion						
	Overprocessing						
	Overproduction	✓	✓				✓
	Transportation	✓	✓				✓
	Waiting	✓	✓				✓
	Waste of human potential						
Value creation dimension	Value-added activity	✓	✓				✓
	Essential non-value-added activity	✓	✓				✓
	Non-value added activity	✓	✓				✓
Economic dimension	Economic interactions among companies			✓			✓
	Production costs			✓		✓	✓
	Raw material and energy costs			✓		✓	✓
	Labour cost			✓		✓	✓
	Product revenues			✓		✓	✓
	Technical inefficiencies			✓		✓	✓
	Profit from 6R approaches			✓		✓	✓
Environmental dimension	Produced/consumed resources			✓	✓	✓	✓
	Wasted resources			✓	✓	✓	✓
	Resources embedded in the product		✓	✓	✓	✓	✓
	Resources disposed in the environment			✓	✓	✓	✓
	Benefits from 6R approaches			✓	✓	✓	✓
	Resource efficiency		✓	✓	✓	✓	✓

new paradigms and not achieving good results, especially in sustainable development (Tortorella et al. 2020). In contrast, the Enterprise Input-Output (EIO) method specifically focuses on analysing the interactions among processes within a company (Albino, Izzo, and Kühtz 2002), which helps to analyse and represent the exchange of resources within complex systems (e.g., supply chains). The system representation provided by

EIO helps to apply other data-driven techniques such as agent-based simulation (Yazan and Fraccascia 2020).

The Material Flow Analysis (MFA) is suitable for resource analysis in production planning and control. It statically describes the flows of resources consumed and produced by companies or processes from their introduction into the system to the sale and disposal (Rotter et al. 2004). Material Flow Cost Accounting (MFCA) introduces in MFA the economic value of resources by separately considering four streams: (i) material costs; (ii) energy costs; (iii) system costs; and (iv) waste management costs (Dierkes and Siepelmeyer 2019; ISO 14051:2011). MFCA focuses on resource management (Rieckhof, Bergmann, and Guenther 2015) by reducing waste, scraps (Lukman et al. 2016), and by improving productivity (Özbuğday et al. 2020). It evaluates environmental and waste costs to identify sources of missed revenues, poor resource efficiency exploitation, and sources of waste. This analysis provides a deep economic perception of waste costs.

The four-dimensional approach MAESTRI Total Efficient Framework combines the MSM with other lifecycle approaches to perform value analysis of process ecoefficiency (Baptista et al. 2018) in the design phase. On the contrary, the combination of MSM and MFCA allows for resource efficiency improvement in fields closer to production planning and control (Ribeiro et al. 2016).

MSM overcomes the limitation of VSM in catching the process aspects linked to resource consumption (environmental dimension in Table 1), and the combined use with MFCA is suitable for production planning and control. However:

- the lack of a formalism to decompose processes in elementary units limits the integration of lean manufacturing methods with the I4.0 paradigm (Agyapong-Kodua et al. 2012);
- MSM is value-chain oriented instead of value-network oriented;
- the integration of MSM and LCA-based approaches may be prohibitive for SMEs because they require knowledge and economic availability, whose lack can result in unhelpful results (Heidrich and Tiwary 2013).

2.1. *Contribution*

This study proposes an integrated formalisation method. Rather than combining different methods by aggregating their findings, the proposed approach models a network of processes and companies. The method develops a shared architecture for data processing and conditioning to feed other methods and tools. The combined use of the proposed formalisation method with other approaches leads to redundancy reduction in data collection, conditioning and processing while increasing data alignment and reducing the risk of partial information and hidden costs and opportunities.

The method integrates a combination of EIO and MFA with the MSM resulting in a new method, the Multi-layer Enterprise Input-Output (MEIO) method, explicitly designed to be data-driven, according to the I4.0 paradigm. This method is helpful for other data-driven approaches and oriented to support the concurrent evaluation of techno-economic-environmental efficiency and value creation for production planning and control methods. Therefore, it tackles the limits of lean principles-based methods in comprehensively assessing, quantifying, and monitoring multi-dimensional performance (Bai, Satir, and Sarkis 2019). Moreover, this study investigates the combined use of MEIO and the MSM and MFCA methods for performing the assessment of value creation process and techno-economic-environmental performance.

Finally, the MEIO method can support the system assessment under the circular economy paradigm since it monitors all resources involved in the entire production network, which is crucial for the circular economy paradigm (Bai et al. 2020). It allows to model the aforementioned 6Rs strategies by considering both value-added and non-value-added activities. The modelling of transport and inventory activities allows to identify their contribution in finished products depreciation, resource consumption, perishability of products and value creation. It contributes to filling the gap between the financial-operational and environmental levels identified by Abisourour et al. (2020); in fact, it improves both the visibility and the assessment of global environmental impacts of operational performance.

3. The Multi-layer Enterprise Input Output method

The Multi-layer Enterprise Input-Output (MEIO) method gathers the necessary information to simultaneously assess value creation and techno-economic-environmental performance of manufacturing systems. It models the manufacturing system by performing data conditioning, storage, processing, and formalisation through two entities: *resources* and *activities*.

Resources. The term *resource* refers to raw materials, energy, products, by-products, and waste. They are identified by following the two principles of MFA (Pauliuk and Heeren 2020), namely, identify the unit of analysis, and ensure material and energy balances. The first one determines how deep the resource analysis is. For example, it is possible to monitor the water flows (bottles in product industries) or hydrogen and oxygen molecules. The second principle requires tracking all resource flows through all production, stocking, and transport activities until they exit from the system. It aims to ensure the conservation of material and energy while identifying new produced and absorbed resources.

Activities. The term *activity* identifies any added or non-added value operation of the manufacturing system, such as production, transport, and inventory. Every activity tracks the resource input and output quantities by balancing incoming and outgoing materials and energy (including dissipated energy, wastes, and consumables).

The MEIO method uses three tables to represent the interactions between resources and activities, which ensure the required flexibility to collect and update data: the Resource-Activity (RA) MEIO table, the Activity-Parameters (AP) MEIO table, and the Resource-Function (RF) MEIO table. The tables can be used to create the RA MEIO graph, which is helpful for optimisation models. The tables and the graph are discussed in the following.

3.1. *Resource-Activity MEIO table*

The RA MEIO table consists of I columns, one for each activity, and J rows, one for each resource. The top part of Table 2 shows an example of the RA MEIO table for a system composed of three activities and eight resources. For each resource, the RA MEIO table indicates the quantity produced and absorbed by each activity in the 'input/output' format. The middle dash '-' means that the specific resource is not involved in the activity. For example, activity P1 in Table 2, which is an integrated line consisting of a plastic cleaner and a shredder, receives in input 500 kg/hr of a plastic mix, 500lt/hr of water, and 160 kWh of power, to obtain 498 kg/hr of shredded, cleaned plastic, 56 kg/hr of humid waste and 446 lt/hr of wastewater exiting from the system.

Table 2. Resource-Activity MEIO table (in the top) and the normalised version (in the bottom) for a system with three activities and eight resources. Stars in the normalised version identify the key resources used to normalise the others.

Resource-Activity table	**P1**	**T1**	**W1**
Plastic mix (kg/hr)	500/-	-/-	-/-
Humid waste (kg/hr)	-/56	-/-	-/-
Shredded, humid mix (kg/hr)	-/498	4500/4356	10000/9920
Power (kWh)	160/-	15/-	-/-
Used power (kWh)	-/60	-/10	-/-
Water (lt/hr)	500/-	-/-	-/-
Waste water (lt/hr)	-/446	-/144	-/80
Dissipated heat (kWh)	-/100	-/5	-/-

Normalised Resource-Activity table	**P1**	**T1**	**W1**
Plastic mix (kg/hr)	8.929/-	-/-	-/-
Humid waste (kg/hr)	-/1*	-/-	-/-
Shredded, humid mix (kg/hr)	-/8.896	300/290.4	125/124
Power (kWh)	2.857/-	1*/-	-/-
Used power (kWh)	-/1.071	-/0667	-/-
Water (lt/hr)	8.929/-	-/-	-/-
Waste water (lt/hr)	-/7.964	-/9.6	-/1*
Dissipated heat (kWh)	-/1.786	-/0.333	-/-

The 'input/output' format allows to represent perishability and damages during transport and inventory activities. For example, in Table 2, the activities T1 and W1 present a loss of finished products since during inventory and transport activities, the wet product dries, thus losing water.

In manufacturing systems, more than one machine or operator (either identical or different) can perform the same activity, affecting resource consumption and production. In the case of an activity with different machines/operators, the MEIO method represents it with additional columns, considering the multiple configurations. Conversely, the activities with identical parallel machines consider the capacity as the aggregated capacity of all the machines/operators.

The MEIO method supports both pen and paper approaches and techniques based on digital models. When feeding digital models, to avoid problems related to numerical precision, the involved quantities should have as few digits as possible, thus resource quantities have to be normalized. The bottom of Table 2 shows the normalised version of the RA MEIO table on the top; the stars in the input and output quantities indicate the key resource used to normalise the single activity (e.g., humid waste is the key resource used to normalise activity P1).

3.2. *Activity-Parameters MEIO table*

The AP MEIO table collects all Z available technical and economic information, indicated in rows, for each of the I activities indicated in columns. The information set included in the AP MEIO table represents the current system state, which allows the modelisation of the real system.

Table 3 shows the AP MEIO table for the previous example. The first rows of the table indicate the primary activity information such as ID, activity description, maximum capacity, and the number of machines, followed by technical information. Furthermore, the AP MEIO table allows to customise the information provided by including additional deterministic and stochastic parameters to extend the set of methods and approaches compatible with the shared infrastructure. For example, in P1,

Table 3. Activity-Parameter MEIO table for a three-activity system involving: activity description, distance matrix and, technical, economic, and efficiency parameters.

Activity-Parameters table	**P1**	**T1**	**W1**
Activity ID	Cleaner and shredder	Conveyor belt	Plastic bin
Number of machines, tools, units	1	1	4
Number of operators	3	-	-
Maximum capacities and process times (kg/hour)	500	4500	2500
Defective units and impurities (% on total production)	0.1	-	-
Time to fail (hour)	Exp(3)	-	-
Time to repair (hour)	Exp(0.05)	-	-
Working hours per day (hour/day)	24	24	24
Labour cost (€/man*h)	10	-	-
Speed (km/hr)	-	0.9	-
P1 distance (km) from	-	0	0.05
T1 distance (km) from	0	-	0
W1 distance (km) from	0.05	0	-
P2 distance (km) from	-	-	0
OEE parameter V (%)	0.984	-	-
OEE parameter P (%)	1.000	-	-
OEE parameter Q (%)	0.889	-	-
OEE (%)	0.874	-	-

the *time to failure* and the *time to repair* follow an exponential distribution with average equal to 3 and 0.05 hours, respectively. Furthermore, the AP MEIO table also contains customised KPIs such as the OEE parameters, which will be introduced in the numerical example of Section 4.

The AP MEIO table includes the distance matrix that specifies the connections between the activities, the transport activities, and the connection speed. The middle dash '-' indicates the absence of connections; a distance equal to 0 indicates the existence of a connection between activities; a distance larger than 0 provides the double information of the distance length and the current lack of transport activities to travel such distance.

3.3. *Resource-Function MEIO table*

The RF MEIO table identifies resource consumption and production when the processing rate changes. The RF MEIO table collects the mathematical functions that connect the production and consumption of all the resources (in rows) of each activity (in columns) following the 'input;output' format of the RA MEIO table. In each activity, the RF MEIO table identifies the activity key resource as the independent variable (X), and the production and consumption of the other resources as the dependent variable (Y). Table 4 shows the RF MEIO table for the three-activity example. In the table, referring to activity P1, the output of *Humid waste* is the independent variable, and all the other functions depend on it. For example, the quantity of *Power* has a constant term (0.5 kWh), and a variable term proportional to 2.857 times the *Humid waste* output ($Y= 2.857X + 0.5$).

The numerical coefficients are the same as the normalised RA MEIO table. However, the RF MEIO table allows for modelling the activity resource production and consumption by introducing further terms to increase accuracy. For example, in P1,

Table 4. The Resource-Function MEIO table for the three-activity process.

Resources	P1	T1	W1
Plastic mix (kg/h)	Y=8.929X;-	-;-	-;-
Humid waste (kg/h)	-;X*	-;-	-;-
Shredded, humid mix (kg/h)	-;Y=8.896X	Y=300(X-0.1); Y=290.4(X-0.1)	Y=125X; Y=124X
Power (kWh)	Y=2.857X+0.5;-	X*;-	-;-
Used power (kWh)	-;Y=1.071X	-;Y=0.667(X-0.1)	-;-
Water (lt/h)}	Y=8.929X;-	-;-	-;-
Waste water (lt/h)	-;Y=7.964X	-;Y=9.6(X-0.1)	-;X*
Wasted heat (kWh)	-;Y=1.786X+0.5	-;Y=0.333X	-;-

there is a fixed consumption of power, 0.5 kWh, independent from the production of *Shredded, humid mix* (independent variable X) that produces 0.5 kWh of thermal energy dissipated in the environment.

The RF MEIO table complexity depends on the modelling assumptions; in fact, the formalisation method can introduce complex functions and distributions to model different activity behaviours (e.g. productivity during the warm-up period, the average rate, and the overload working condition).

3.4. *The Resource-Activity MEIO graph*

From the MEIO tables, it is possible to create the RA MEIO graph, in which the nodes and the arcs represent the activities and resource flows, respectively. The graph includes two arc types modelling the potential and the existing network. The RA MEIO table provides the information to create the potential network: for each activity, there is a set of outgoing arcs for each produced resource that connects the activity with all the other activities having that resource as input. The weight of the arcs of the potential network is the distance between nodes (defined in the distance matrix of the AP MEIO table) to support digital models in assessing the cost of adding the connection. The distance matrix in the AP MEIO table also defines the existing network, and the weight of its arcs is the quantity absorbed (incoming arcs) and produced (outgoing arcs) by the nodes.

Figure 1 shows the Resource-Activity MEIO graph of the example reported in Table 2. The RA MEIO graph includes seven fictitious nodes (dashed circles T0, T2, T3, T4, T5, T6, T7) since each arc must have a source and a sink. These nodes are identified as transport activities since they deliver initial resources (T0, T2, and T3) and collect system waste (T4), by-products (T5 and T6), and products (T7). The MEIO RA graph involves two sub-graphs: the potential and the current graphs, identified by dashed (d) and solid (s) arcs, respectively. For example, d(W1,T1) indicates the dashed arc from W1 to T1 and s(P1,T1) the solid arc from P1 to T1. The potential graph involves only the main product flow (plastic mix). It performs six connections, namely, d(P1,T1), d(P1,W1), d(T1,W1) and d(W1,T1), and two loops d(T1,T1) and d(W1,W1). Arcs d(W1,T1) and d(T1,W1) are both included because, from the RA MEIO table, the *Shredded, humid mix* is both input and output for T1 and W1. For the same reason, arcs d(T1, T1) and d(W1, W1) are included in the graph.

The fictitious nodes have only outgoing or incoming arcs, whose weight is assigned according to the independent variable of the activity they are connected to (e.g., water from T2 and power from T3 refers to the independent variable of activity P1, that is, X_{P1}). Conversely, the arcs between real nodes (solid ones) have the weight set according to the independent variable of the source node (e.g., the weight of arc s(P1,T1) depends on the independent variable X_{P1}). When the entire system is balanced, the incoming and outgoing arcs of the nodes respect the material and energy balances.

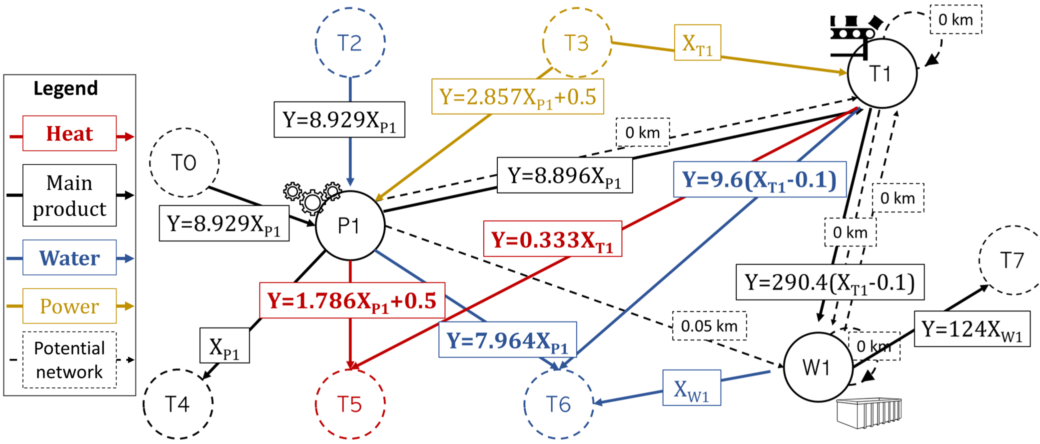

Figure 1. Resource-activity graph for the example of the three-activity system.

The RA MEIO graph highlights that MEIO can model the 6Rs strategies to improve resource efficiency. For example, arcs d(T1,T1) and d(W1,W1) can model the reuse strategy in which a scrap of a process can be reused as input of the process itself (because it has a similar quality of the primary input). The 6Rs strategies from repair to recovery ideally follow the same circular arc of reuse. However, rather than closing the loop into the same activity, they go back to precedent activities; here disassembling, recycling, repairing, and recovering activities transform the output resource into a raw material ready to re-enter the manufacturing system.

4. Numerical example

This section discusses a numerical example to show the implementation of the MEIO method on a recycled plastic pipelines manufacturing system by developing the MEIO tables and drawing the RA MEIO graph. Section 5 will use the same example to apply the MFCA and MSM approaches to assess the techno-economic-environmental performance of the addressed system through the use of the MEIO tables here devised.

4.1. *Empirical context*

Figure 2 shows the recycled plastic pipeline manufacturing system involving three production activities (P1, P2, and P3), two transport activities (T1 and T2) and two inventory activities (W1 and W2).

P1 receives the plastic waste mix ready to be washed and shredded. The company earns 0.45 €/kg to treat the plastic waste mix, and P1 can nominally treat 500 kg/h.

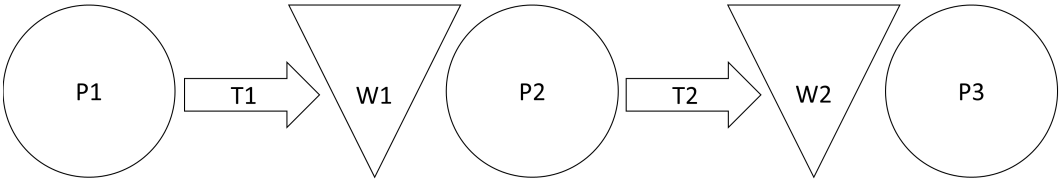

Figure 2. Recycled plastic pipeline manufacturing system.

P1 requires three operators, and it works on three 8-hour daily shifts. At the end of the line, 10% of the entire production is lost by falling out of the conveyor belt. The clean, humid and shredded plastic mix that falls on the floor is a waste, successively disposed of in the landfill. P1 requires 500 lt/h of water, and it consumes 160 kWh.

The conveyor belt (T1) connecting P1 with the stocking area W1 is 0.05 km long, it can move up to 4500 kg with a constant speed of 0.9 km/h by absorbing 1 kWh.

The stocking area W1 contains four bins for the shredded plastic mix holding up to 2500 kg each, and they feed the two-machine process P2.

P2 is a pelletiser line consisting of two parallel machines transforming the shredded plastic mix into a homogeneous product, the plastic pellet, by adding some chemical additives. Each of the two lines can treat up to 350 kg/h of the shredded plastic mix by proportionally adding up to 20 kg of chemical additives and consuming 0.25 kWh of power per kg. The homogeneous product, the plastic pellet, is packed in bags of 10.3 kg, accumulated to fill the capacity of the truck that delivers the bags of pellet to the final production process. During the three 8-hour shifts, some interruptions to the flow of shredded plastic mix cause jams (on average one every 3 hours with 15 minutes to solve them); moreover, 8% of the produced pellet has a poor quality because of an ineffective mix with the chemical additives.

The truck (T2) has a capacity of 5.5 t/delivery, equivalent to 534 bags of pellet per delivery. It covers a distance of 10 km by consuming 0.066 lt of diesel and producing 33 g equivalent of CO_2. The truck connects P2, which is in the plant area devoted to recycling urban waste, to the storage area W2, located in the area of the plant devoted to the production of products in recycled plastic.

The stocking area W2 consists of a pellet bin able to store up to 10 tons of plastic pellet. The last activity is the extrusion process (P3) to produce plastic pipelines with 200 and 600 mm diameter, with a length of 10 m and a weight of 29.765 kg, and a length of 2 m and a weight of 5.95 kg, respectively. The extrusion line works on two 8-hour shifts, one for each product, including the setup to change production, which takes 30 minutes, and it can treat 750 kg/h of pellet by consuming 168 kWh and requiring 50 kg of chemical additives. The nominal production time is 0.04 h for a 200 mm diameter pipeline and 0.008 h for a 600 mm diameter pipeline. The defectivity is 0.001 and 0.005 for the 200 mm diameter pipeline and the 600 mm, respectively. The disposal in the landfill of defectives, poor quality pellet, and the discarded shredded plastic mix is a cost for the company since the disposal fee is 25 $€/m^3$. Melted plastic jams the extruder on average every 16.67 h and 83.33 h during the 200 mm and 600 mm diameter pipeline production, respectively, and 0.83 h are on average required to restore the production.

Table 5 summarises all the involved resources providing their market prices/purchasing costs. The company earns a commission for each treated kg of plastic mix. The disposal cost is the same for all wastes sent to the landfill, that is, the shredded humid waste felt out of the conveyor belt, the poor quality pellet and the defective pipelines. The shredded plastic mix has a market price of 0.6 €/kg, while the plastic pellet reaches 1 €/kg (the bags have 10.3 kg of pellet; thus, they have a market price of 10.3 €). Power, water, chemical additives, and fuel are the other resources involved in the system, and the indicated costs refer to their purchasing. The production processes produce heat, which is dissipated in the environment rather than used as a resource having a purchasing cost of 0.5 €/kWh. The environmental cost of CO_2 comes from the cost of the CO_2 equivalent emissions; however, it is scarcely relevant for the proposed example.

Table 5. Economic parameters for produced and purchased resources.

Resources	Price	Cost	Resources	Price	Cost
Plastic mix (€/kg)	0.45	-	**Power (€/kWh)**	0.17	-
Humid waste (€/kg)	-	1	**Used power (€/kWh)**	-	-
Shredded, humid mix (€/kg)	0.6	-	**Water (€/lt)**	0.004	-
Plastic pellet (€/kg)	1	-	**Waste water (€/lt)**	-	-
Under q. pellet (€/kg)	-	0.0262	**Dissipated heat (€/kWh)**	0.5	-
Bags of pellet (€/bags)	10.3	-	**Pipeline d200 (€/piece)**	35	-
CO_2 (€/delivery)	-	0.00005	**Pipeline d600 (€/piece)**	7	-
Chemical additives (€/kg)	1.5	-	**Defective pipeline d200 (€/piece)**	-	0.78
Fuel (€/delivery)	0.0014	-	**Defective pipeline d600 (€/piece)**	-	0.156

4.2. *Application of the MEIO method*

The MEIO table development consists of 4 phases, described in the following.

Phase 1. The first phase develops the RA MEIO table by: 1) identifying the activities and resources; 2) applying the two MFA principles. The aim is to identify some potentially neglected resources during the initial data collection and to define the unit of measure for all the resources. Table 6 shows the normalised RA MEIO table, while Table A1 in Appendix A shows the initial not normalised RA MEIO table, which reports the nominal data provided by the machine manufacturers and defined by agreement for transport services.

The emerging inconsistencies from the initial application of the material and energy balances (first MFA principle) requires further analysis to identify the neglected resource flows. For example, in P1, the sum of water with the initial plastic mix does not correspond to the output of the process, because it considers only the shredded mix and the waste of the process, and it neglects how the water used in the process could be re-used. Therefore, from further analysis, 446 out of the provided 500 lt/h are disposed of as wastewater; the remaining 54 kg follow both the humid waste and the shredded plastic mix. Also, the entire line consumes 160 kWh, but the effective use of power is estimated at 60 kWh, while the rest becomes dissipated heat energy. Furthermore, there is a material loss during activities; for example, in T1 and W1, the water mixed with the plastic raw material leads to weighing inputs and outputs, causing a 3.2% weight reduction due to water falling out of the conveyor belt and evaporating.

To facilitate the understanding, P2 reports redundant information about the output,

Table 6. Normalised Resource-Activity MEIO table for the plastic pipeline manufacturing chain.

Resource-Activity table	P1	T1	W1	P2	T2	W2	P3
Plastic mix (kg/hr)	8.929/-	-/-	-/-	-/-	-/-	-/-	-/-
Humid waste (kg/hr)	-/1*	-/-	-/-	-/-	-/-	-/-	-/-
Shredded, humid mix (kg/hr)	-/8.896	300/290.4	125/124	4.716/-	-/-	-/-	-/-
Plastic pellet (kg/hr)	-/-	-/-	-/-	-/4.587	-/-	-/10.3	15/-
Under q. pellet (kg/hr)	-/-	-/-	-/-	-/0.399	-/-	-/-	-/-
Bags of pellet (bags)	-/-	-/-	-/-	-/0.445	8.08/8.08	1*/-	-/-
CO_2 **(g/delivery)**	-/-	-/-	-/-	-/-	-/0.5	-/-	-/-
Chemical additives (kg/hr)	-/-	-/-	-/-	0.27/-	-/-	-/-	1*/-
Fuel (ml/delivery)	-/-	-/-	-/-	-/-	1*/-	-/-	-/-
Power (kWh)	2.857/-	1*/-	-/-	1.179/-	-/-	-/-	3.36/-
Used power (kWh)	-/1.071	-/0.667	-/-	-/1*	-/-	-/-	-/2.22
Water (lt/hr)	8.929/-	-/-	-/-	-/-	-/-	-/-	-/-
Waste water (lt/hr)	-/7.964	-/9.6	-/1*	-/-	-/-	-/-	-/-
Dissipated heat (kWh)	-/1.786	-/0.333	-/-	-/0.179	-/-	-/-	-/1.14
Pipeline d200 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/7.991
Pipeline d600 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/7.96
Defective pipeline d200 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/0.009
Defective pipeline d600 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/0.041

that is, both the bulk pellet production in terms of kg/h and the number of pellet bags. Furthermore, in T2, the required fuel and produced CO_2 are assessed over the assigned journey since the truck always follows the same route.

Phase 2. The RF MEIO table collects all the functions of the system activities, making them available for digital models that can vary the level of consumption and production of the activity by varying its production rate or transportation speed. Table 7 shows the RF MEIO table for the plastic pipeline production chain.

The production and consumption functions have some constant terms, for example, *Shredded, humid mix* in T1 (0.1) and *Power* in P1 (0.5), modelling the power absorbed by those devices in monitoring and supporting tasks.

Furthermore, some functions can be independent of the actual key resource consumption and production, such as, in T2, the fuel consumption and the CO_2 production. All the functions related to P2 are multiplied by two, as P2 has two parallel machines.

Phase 3. This phase collects activity information and KPIs for economic and environmental performance for the AP MEIO table. Table 8 presents the AP MEIO table of the plastic pipeline production chain.

The first parameters describe the activity itself, the number of used resources, and the potential labour requirement and maximum capacity. *Maximum capacity* indicates kg/h for production activities and maximum inventory capacity and truckload for inventory and transport activities.

In P3, the multiproduct allocation parameters (α and β) indicate the allocation of production capacity to each produced product. Information about the defectives, failures, setups, and time to restore machine productivity can be specified with more than one value, separated by semicolons, if they have different values for different

Table 7. Resource-Function MEIO table for the plastic pipeline manufacturing chain.

Resources	P1	T1	W1	P2	T2	W2	P3
Plastic mix (kg/h)	Y=8.929X;-	-;-	-;-	-;-	-;-	-;-	-;-
Humid waste (kg/h)	-;X	-;-	-;-	-;-	-;-	-;-	-;-
Shredded, humid mix (kg/h)	-;Y=8.896X	Y=300(X-0.1); Y=290.4(X-0.1)	Y=125X; Y=124X	Y=2(4.716X);-	-;-	-;-	-;-
Plastic pellet (kg/h)	-;-	-;-	-;-	-;Y=2(4.587X)	-;-	-;Y=10.3X	Y=15X;-
Under q. pellet (kg/h)	-;-	-;-	-;-	-;Y=2(0.399X)	-;-	-;-	-;-
Bags of pellet (pcs.)	-;-	-;-	-;-	-;Y=2(0.445X)	X;Y=X	X;-	-;-
CO$_2$ (g/delivery)	-;-	-;-	-;-	-;-	-;Y=5	-;-	-;-
Chemical additives (kg/h)	-;-	-;-	-;-	Y=2(0.27X);-	-;-	-;-	X;-
Fuel (ml/delivery)	-;-	-;-	-;-	-;-	Y=0.6;-	-;-	-;-
Power (kWh)	Y=2.857X+0.5;-	X;-	-;-	Y=2(1.179X+0.5);-	-;-	-;-	Y=3.36X+0.5;-
Used power (kWh)	-;Y=1.071X	-;Y=0.667(X-0.1)	-;-	-;2X	-;-	-;-	-;Y=2.22X
Water (lt/h)	Y=8.929X;-	-;-	-;-	-;-	-;-	-;-	-;-
Waste water (lt/h)	-;Y=7.964X	-;Y=9.6(X-0.1)	-;X	-;-	-;-	-;-	-;-
Wasted heat (kWh)	-;Y=1.786X+0.5	-;Y=0.333X	-;-	-;Y=2(0.179X+0.5)	-;-	-;-	-;Y=1.14X+0.5
Pipeline S (kg/h)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=7.991X
Pipeline L (kg/h)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=7.96X
Defective pipeline S (kg/h)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=0.009X
Defective pipeline L (kg/h)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=0.041X

products; otherwise, only one value is reported. The labour unit cost indicates the total cost paid by the company for an hour of work of an operator. In contrast, the operating costs are proportional to the production rate.

As the MEIO method will be used coupled with MSM in performance analysis, in Section 5, Table 8 also includes the Overall Equipment Efficiency (OEE) to estimate the process maximum effective capacity. Companies and practitioners widely use OEE because of its clarity and ease of use (Muchiri and Pintelon 2008). According to the version proposed by De Ron and Rooda (2006), the OEE (Equation (1)) can be estimated by multiplying the availability of machines V (Equation (2)), the performance efficiency P (Equation (3)), and the percentage of products with good quality Q (Equation (4)).

$$OEE = V \cdot P \cdot Q \tag{1}$$

$$V = \frac{loading\,time - downtime}{loading\,time} \tag{2}$$

$$P = \frac{theoretical\,cycle\,time\,X\,processed\,amount}{operating\,time} \tag{3}$$

$$Q = \frac{processed\,amount - defect\,amount}{processed\,amount} \tag{4}$$

Table 8. Activity-Parameters MEIO table for recycled plastic pipeline production chain.

Activity-Parameters	**P1**	**T1**	**W1**	**P2**	**T2**	**W2**	**P3**
Activity ID:	Cleaner and shredder	Conveyor belt	Plastic bin	Pelletizer	Truck	Pellet bin	Pipeline extruder
Number of machines, tools, units	1	1	4	2	1	1	1
Number of operators	3	-	-	-	-	-	-
Maximum capacities and process times	500	4500	2500	350	5500	10000	750
Parameters for multiproduct allocation	-	-	-	-	-	-	α: 0.5; β: 0.5
Defective units and impurities (% on total production)	0.1	-	-	0.08	-	-	0.001; 0.005
Mean time to fail	3	-	-	3	-	-	16.66; 83.33
Mean time to repair	0.05	-	-	0.25	-	-	0.83; 083
Mean Time to setup	-	-	-	-	-	-	7.5
Mean setup time	-	-	-	-	-	-	0.5
Working hours per day	24	24	24	24	16	16	16
Labour cost	10	-	-	-	-	-	-
Operational cost	-	-	-	-	80	-	-
Speed (km/hr)	-	0.9	-	-	35	-	-
P1 distance (KM) from	-	0	0.05	-	-	-	-
T1 distance (KM) from	0	-	0	-	-	-	-
I1 distance (KM) from	0.05	0	-	0	-	-	-
P2 distance (KM) from	-	-	0	-	0	10	-
T2 distance (KM) from	-	-	-	0	-	0	-
I2 distance (KM) from	-	-	-	10	0	-	0
P3 distance (KM) from	-	-	-	-	-	0	-
OEE parameter V	0.984	-	-	0.923	-	-	0.971
OEE parameter P	1.000	-	-	1.000	-	-	0.938
OEE parameter Q	0.889	-	-	0.913	-	-	0.997
OEE	0.874	-	-	0.843	-	-	0.908

Phase 4. The last phase involves the RA MEIO graph creation. Figure 3 shows the RA MEIO graph for the numerical example, in which the dashed and solid arcs identify the potential and the existing network, created by exploiting data from RA and AP MEIO tables, respectively.

The RA MEIO graph has the twofold goal of enabling the adoption of graph approaches during the network design phase and the adoption of performance monitoring approaches based on indicators.

5. Performance analysis

The following performance analysis shows the potential benefits in redundancy, time and cost reduction achievable by adopting the MEIO formalisation method as a shared architecture. MSM and MFCA methods are fed by the MEIO tables to assess value creation and techno-economic-environmental performance. The performance analysis highlights the data alignment brought by the MEIO method, which limits the cases of partial information, conflicting results, and the possibility to neglect aspects (which usually happens when aggregating results of several methods to obtain multi-dimensional performance).

In the following, the MSM is first applied to the numerical example, then the economic-environmental assessment is performed through the MFCA.

5.1. *Value creation and technical efficiency: the multi-layer stream mapping*

The MSM considers the system constantly working at the effective maximum rate (i.e., considering also failures and defectives). The AP MEIO table provides the current network configuration and the OEE values. Figure 4 shows the VSM of the MSM

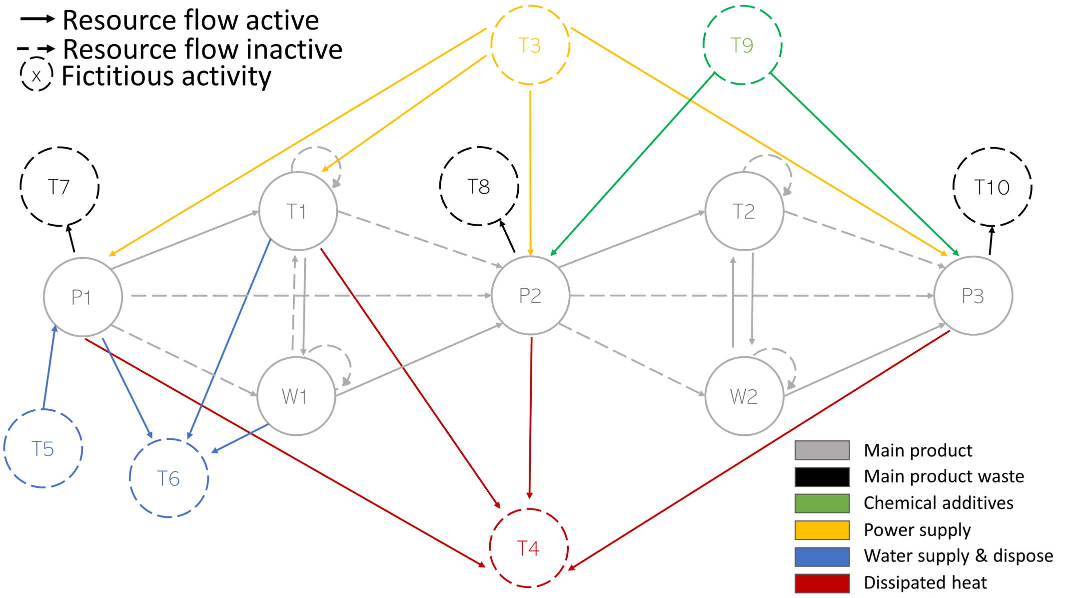

Figure 3. The RA MEIO graph for the recycled plastic pipeline manufacturing system.

approaches, in which triangles on grey arrows indicate buffers, inventories, and transport activities, and grey boxes value-added activities (i.e., manufacturing processes), which report the activity name and the four OEE parameters. The number above triangles and boxes indicate the number of machines, tools, and bins involved in the activity. The black broken arrows show the informative flows, while straight red arrows highlight the monitoring. Red dashed arrows follow the material flow.

The time unit is minutes, while each activity considers 1 kg of the primary raw material to assess value creation.

The white boxes report the total cycle time (CT) and the contribution of VA, ENVA, and NVA activities to the CT. Equations (5)-(8) report the CT determination in formulae, and the numerical calculation for activity P1 as example. The nominal capacity is provided by the AP MEIO table, and the total CT is in Equation (8).

$$CT_{VA} = \frac{60}{NOMINAL\,CAPACITY_{P1}} = \frac{1}{500} = 0.12\,min \tag{5}$$

$$\begin{aligned} CT_{ENVA} &= \frac{60}{NOMINAL\,CAPACITY_{P1} \cdot P \cdot V} - CT_{VA} = \\ &= \frac{60}{500 \cdot 1 \cdot 0.984} - 0.12 = 0.002\,min \end{aligned} \tag{6}$$

$$\begin{aligned} CT_{NVA} &= \frac{60}{NOMINAL\,CAPACITY_{P1} \cdot Q} - CT_{VA} = \\ &= \frac{60}{500 \cdot 0.889} - 0.12 = 0.015\,min \end{aligned} \tag{7}$$

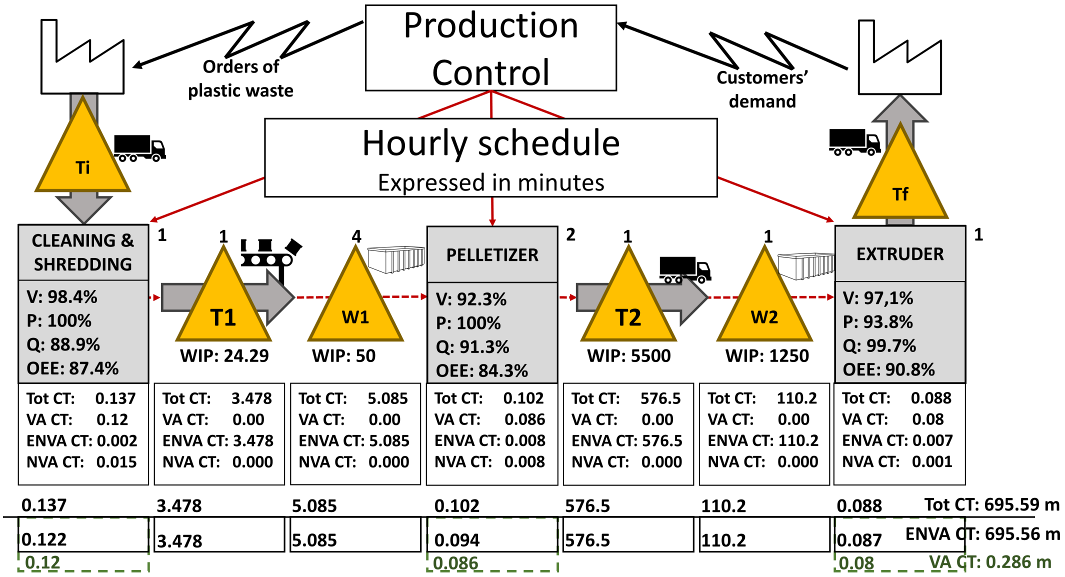

Figure 4. Value Stream Mapping of plastic pipelines manufacturing chain.

$$CT = CT_{VA} + CT_{ENVA} + CT_{NVA} = 0.12 + 0.002 + 0.015 = 0.137\,min \tag{8}$$

The production management assumes as acceptable (*essential*) the working time spent in failures, setups, transport and inventories, while the defects represent NVA activities. The VA activities are far smaller than ENVA activities, especially the waiting time for truck delivery and the large inventory of W2 (98.7% of total CT).

The RA MEIO table supports the resource efficiency analysis, reported in Table 9, which concludes the MSM approach. The showed percentage represents the used quantity of the resources by distinguishing, within each activity, the input and the output resources. For example, in P1, the *Plastic mix* is not entirely converted into *Shredded, humid mix*, since a little of it (i.e., 10% of the mix) falls out of the line during the machining. In contrast, the *Shredded, humid mix* arrived at the end of the line is entirely assigned to the conveyor belt T1. Thus, only 90% of plastic mix gains value. In P1, only 29% of the *Power* creates value since, according to the RF MEIO table, the rest becomes dissipated heat. The used power (i.e., that 29% of *Power*), is 90% efficient (*Used power* is 90%). In fact, the 10% of inefficient power use is related to the 10% of plastic mix fallen out of the line. The same holds for *Water*.

MSM highlights that some resources, such as wastewater, dissipated heat, and the under quality plastic pellet remain unexploited. Moreover, it also shows the loss of the raw materials that were added to a resulting defective or wasted product. For example, in P2, part of the chemical additives mixed with plastic pellets results in a defective output successively discarded.

Adopting the MEIO formalisation method led the MSM to focus also on the transformation of consumables, energy, and raw materials in waste and by-products. In fact, through *Phase 1*, many resource flows have been included in the analysis leading to the detailed findings of the resource efficiency analysis. For example, MSM shows the 10% of inefficient use of water in P1, but the use of the MEIO method also high-

Table 9. Resource efficiency evaluated according to Multi-Layer Stream Mapping. The percentage indicates the amount of exploited resource.

Resource efficiency	**P1**	**T1**	**W1**	**P2**	**T2**	**W2**	**P3**
Plastic mix (kg/hr)	90%	-	-	-	-	-	-
Humid waste (kg/hr)	0%	-	-	-	-	-	-
Shredded, humid mix (kg/hr)	100%	97%	99%	92%	-	-	-
Plastic pellet (kg/hr)	-	-	-	-	-	100%	100%
Under q. pellet (kg/hr)	-	-	-	0%	-	-	-
Bags of pellet (bags)	-	-	-	100%	100%	100%	-
CO_2 (g/delivery)	-	-	-	-	0%	-	-
Chemical additives (kg/hr)	-	-	-	92%	-	-	100%
Fuel (ml/delivery)	-	-	-	-	100%	-	-
Power (kWh)	29%	65%	-	55%	-	-	57%
Used power (kWh)	90%	97%	-	92%	-	-	100%
Water (lt/hr)	90%	-	-	-	-	-	-
Waste water (lt/hr)	0%	0%	0%	-	-	-	-
Dissipated heat (kWh)	0%	0%	-	0%	-	-	0%
Pipeline d200 (kg/hr)	-	-	-	-	-	-	100%
Pipeline d600 (kg/hr)	-	-	-	-	-	-	100%
Defective pipeline d200 (kg/hr)	-	-	-	-	-	-	0%
Defective pipeline d600 (kg/hr)	-	-	-	-	-	-	0%

lights that the entire amount of water is used only once, in P1; further analyses should investigate the exploitation opportunities through the 6Rs strategies.

MSM neglects the economic aspect of the performance assessment, such as the economic cost of defectives and their impact on the inefficient use of materials. Also, the potential value of disposed waste rather than its exploitation through the 6Rs strategies is not quantified. In the following section, the application of the MFCA method sheds some light on these points. As MFCA and MSM both use the same data provided by the MEIO tables, the results of the two methods are coherent with each other.

5.2. *Economic and environmental efficiency: the Material Flow Cost Accounting*

The MFCA indicates both quantities and economic values helpful to measure environmental-economic performance. This analysis focuses on three streams of resources: raw materials, energy, and labour.

MFCA monitors the resource flow from their introduction into the system until they exit by observing the activities producing and consuming them. All the resource flows are coupled with their economic value or their costs, such as environmental costs, disposal costs, operating costs. Table 10 reports the flows and the economic values related to the case example. In the table, each activity has two columns to indicate quantities (Q) and economic value (+/-), reporting used and consumed quantities and contribution to the profit of each activity, respectively. Activities W2 and T2 are not reported due to their limited relevance. According to the general accounting rules, the finished products assume their market value at the end of an activity, becoming an operating cost at the beginning of the next activity. For instance, in Table 10, the initial 1867 kg of plastic leads to the production of 1736 kg of pipelines, which includes the addition of 102 kg (in P2) and 115 kg (in P3) of chemical additive.

Table 10. Produced and purchased quantities of each resource and their contribution to the final profit.

Resources	**P1**		**T1**		**W1**		**P2**		**P3**	
	Q	**+/-**	**Q**	**+/-**	**Q**	**+/-**	**Q**	**+/-**	**Q**	**+/-**
Plastic mix	1867.33	840.3	-	-	-	-	-	-	-	-
Humid waste	209.13	-209.13	-	-	-	-	-	-	-	-
Shredded, humid mix	1860.43	1116.26	1800.89	-	1786.48	-	1786.48	-1071.89	-	-
Plastic pellet	-	-	-	-	-	-	1737.62	1737.62	1736.29	-1736.29
Under q. pellet	-	-	-	-	-	-	151.15	-3.96	-	-
Bags of pellet	-	-	-	-	-	-	168.57	1736.29	-	-
CO_2	-	-	-	-	-	-	-	-	-	-
Chemical additives	-	-	-	-	-	-	102.28	-153.42	115.75	-173.63
Fuel	-	-	-	-	-	-	-	-	-	-
Power	599.38	-101.9	6.3	-1.07	-	-	448.00	-76.16	390.20	-66.33
Used power	223.98	-38.08	4.2	-0.71	-	-	378.81	-64.4	256.97	-43.69
Water	1867.33	-7.47	-	-	-	-	-	-	-	-
Waste water	1665.52	-6.66	60.49	-0.24	14.41	-0.06	-	-	-	-
Wasted heat	375.41	-187.7	2.1	-1.05	-	-	69.19	-34.6	133.23	-66.61
Pipeline S	-	-	-	-	-	-	-	-	31.08	1087.66
Pipeline L	-	-	-	-	-	-	-	-	154.86	1083.99
Defective pipeline S	-	-	-	-	-	-	-	-	0.04	-0.03
Defective pipeline L	-	-	-	-	-	-	-	-	0.8	-0.12
Hours	3.8	114	-	-	-	-	2.76	-	2.54	-

Differently from the general accounting rules, MFCA accounts for the costs of wastes and unexploited resources (Zhou et al. 2017). Moreover, it introduces some fictitious operating costs (not charged to the company) to underline the value of unexploited resources. For example, dissipated heat is accounted for with the price of district heating and wastewater with the market price of water for industrial facilities. General accounting rules neglect the defectives and consider the purchasing costs for the raw materials and resources as operating costs, together with the costs of waste disposal. MFCA unbundles the operating costs referred to the waste production charging it to the wastes, while the costs that effectively contribute to the production become the new operating costs. Furthermore, MFCA accounts for the unexploited resources with their opportunity costs.

Table 10, developed by identifying the resource quantities through the RA MEIO table, is used to create Table 11, which shows the manufacturing system accounting by combining general accounting and MFCA rules. The first part of Table 11 follows the general accounting rules to determine the net activity profit, subsequently enriched by the potential profit coming from the reuse of unexploited resources (wastewater and dissipated heat). The second part of the table presents the total costs of the resources embedded in the wastes, according to the MFCA principles.

The MFCA enriches the MSM findings by highlighting the hidden costs of failures and defectives and their environmental impacts on inefficient resource use.

The aggregation of MSM and MFCA findings provides a multi-dimensional perfor-

Table 11. General and material flow cost accounting for the manufacturing chain of plastic pipelines.

General Accounting and Material Flow Cost Accounting	**P1**	**T1**	**W1**	**P2**	**P3**
Raw material value					
Plastic mix	840.3	0	0	0	0
Shredded humid mix	1116.26	0	0	-1071.89	0
Bags of pellet	0	0	0	1736.29	-1736.29
Pipeline S	0	0	0	0	1087.66
Pipeline L	0	0	0	0	1083.99
Other raw material	0	0	0		
Chemical additives	0	0	0	-153.42	-173.63
Fuel	0	0	0	0	0
Power	-101.9	-1.07	0	-76.16	-66.33
Water	-7.47	0	0	0	0
Labour					
Workhours	-113.91	0	0	0	0
Cost of waste disposal					
Humid waste	-209.13	0	0	0	0
Under q. pellet	0	0	0	-3.96	0
Defectives pipeline S	0	0	0	0	-0.03
Defectives pipeline L	0	0	0	0	-0.12
CO_2	0	0	0	0	0
Net profit	1524.15	-1.07	0	430.86	195.25
Potentially reus. resources					
Waste water	6.66	0.24	0.06	0	0
Dissipated Heat	187.70	1.05	0	34.60	66.61
Net profit with reus. Resources	1718.52	0.22	0.06	465.46	261.86
Resources trapped in Waste					
Labor	-12.76	0	0	0	0
Raw material	-125.48	-36.3	-8.64	-151.15	-6.81
Chemicals	0	0	0	-12.98	-0.58
Power	-4.26	-0.02	0	-5.45	-0.15
Water	-0.84	0	0	0	0
Total cost of waste	-143.34	-36.32	-8.64	-169.58	-7.53

mance assessment of the manufacturing system. The MEIO formalisation method has avoided redundancies in data collection, processing, and conditioning activities and has allowed data alignment. The MEIO method provides several additional insights neglected by the simple use of MSM and MFCA. For instance, it shows the improvement opportunities through new layout configurations highlighted by the RA MEIO graph and the match between activity producers and consumers of the same resource. Also, it shows that dissipated heat may be used to reduce the humidity content of the valuable resources to reduce the misconception of losing valuable materials from an activity to the other.

Furthermore, the MEIO method improves the findings of the other methods; for example, it identifies that the *Shredded, humid mix* has a consistent amount of water that decreases from an activity to the other, reducing valuable resource quantity, later quantified by the MFCA. Moreover, the MEIO method highlights that the power required by the conveyor belt is proportional to the weight of the material that it conveys, and the MFCA quantifies the inefficient consumption of power caused by the water weight together with the finished product.

6. Conclusion

This paper proposes a new method, the Multi-layer Enterprise Input-Output (MEIO), which integrates the MSM with a combination of MFA and EIO. MEIO allows to develop a shared architecture that can be used to support the simultaneous assessment of techno-economic-environmental performance and value creation of manufacturing systems. The method allows to aggregate the findings of other methods focused on a subset of dimensions, thus reducing redundancies in data collection, processing and conditioning while improving data formalisation.

The alignment of environmental, technical, economic, and value creation information between operational and strategical levels is crucial to avoid decision making with obsolete or incomplete data. Hence, the method might support decision-makers in production planning and control of complex production systems, especially those focused on 6Rs strategies. Moreover, the MEIO method can integrate data from real manufacturing system and nominal data of new processes, to support the strategical decision making in the system design phase. Specifically, as it considers techno-economic-environmental performance, it can be used for the monitoring and the extension of industrial symbiotic networks, in which the waste of a company becomes the raw material of another.

MEIO can also be an easy to use method to allow companies (currently focused only on technical performance) to investigate their economic and environmental performance, showing them how crucial they are. In fact, the relationships between system performance and all the identified resources, including waste and by-products, are as crucial as those involving finished products; thus, there is no more privileged resource path to be analysed. The MEIO method enhances the rapid implementation of tools currently used to investigate technical performance on finished products, such as MSM, by rearranging the focus from the primary finished products to the other critical materials.

This study follows a static data-driven approach, however, the MEIO tables can be automatically updated with routines connected to Programmable Logic Controllers, Manufacturing Execution Systems, and ERP modules. Moreover, MEIO can support other methods through the shared architecture, or it can be used alone to develop KPIs to monitor manufacturing system performance. It can also be combined with other digital models (such as in Cyber-Physical Systems and Decision Support Systems based on optimisation and simulation models) to consider value creation and techno-economic-environmental performance simultaneously. However, this great flexibility needs an effort to customise the use combined with each of the different approaches.

Future research directions start from the limitations of this paper. The RF MEIO table can be improved to consider also multivariate functions; in fact, the production and the absorption of a resource can depend on the production and consumption of more than one other. Modern production systems involve 'plug and play' machines and robots able to change their roles according to contingent situations. Thus, the methods exploiting a priori knowledge of the system can rapidly become obsolete; further research can be devoted to the development of data-driven strategies to automatically identify and update new activities. Moreover, the update process of MEIO tables requires further studies to identify and distinguish the occurrence of failures or exceptional events from the detection of trends that modify the activity parameters.

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Appendix A. The RA MEIO table

Table A1. The initial Resource-Activity MEIO table for the plastic pipeline manufacturing system.

Resource-Activity table	**P1**	**T1**	**W1**	**P2**	**T2**	**W2**	**P3**
Plastic mix (kg/hr)	500/-	-/-	-/-	-/-	-/-	-/-	-/-
Humid waste (kg/hr)	-/56*	-/-	-/-	-/-	-/-	-/-	-/-
Shredded, humid mix (kg/hr)	-/498	4500/4356	10000/9920	700/-	-/-	-/-	-/-
Plastic pellet (kg/hr)	-/-	-/-	-/-	-/681	-/-	-/10000	750/-
Under q. pellet (kg/hr)	-/-	-/-	-/-	-/59	-/-	-/-	-/-
Bags of pellet (bags)	-/-	-/-	-/-	-/66	533/533	971*/-	-/-
CO$_2$ (g/delivery)	-/-	-/-	-/-	-/-	-/33	-/-	-/-
Chemical additives (kg/hr)	-/-	-/-	-/-	40/-	-/-	-/-	50*/-
Fuel (ml/delivery)	-/-	-/-	-/-	-/-	66*/-	-/-	-/-
Power (kWh)	160/-	15*/-	-/-	175/-	-/-	-/-	168/-
Used power (kWh)	-/60	-/10	-/-	-/148.5*	-/-	-/-	-/111
Water (lt/hr)	500/-	-/-	-/-	-/-	-/-	-/-	-/-
Waste water (lt/hr)	-/446	-/144	-/80*	-/-	-/-	-/-	-/-
Dissipated heat (kWh)	-/100	-/5	-/-	-/26.5	-/-	-/-	-/57
Pipeline d200 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/399.95
Pipeline d600 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/397.95
Defective pipeline d200 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/0.045
Defective pipeline d600 (kg/hr)	-/-	-/-	-/-	-/-	-/-	-/-	-/2.05