Technical, economic, and environmental performance assessment of manufacturing systems: the multi-layer enterprise input-output formalization method

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

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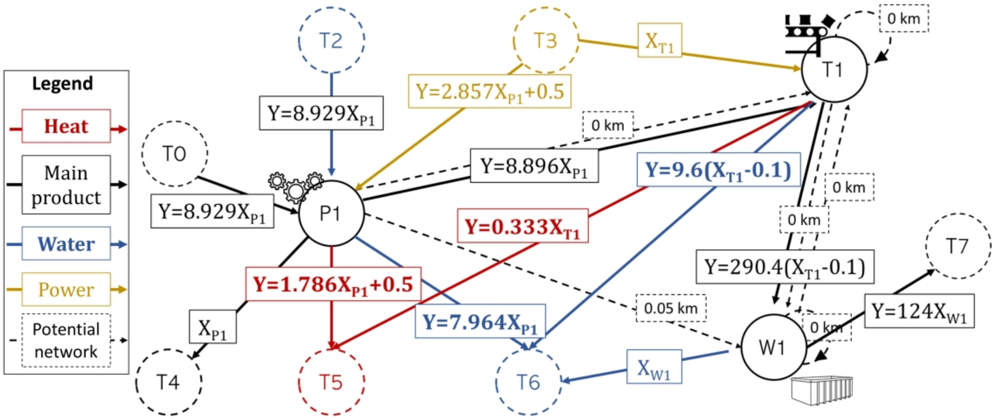


Figure 1. Resource-activity graph for the example of the three-activity system.

861x484mm (118 x 118 DPI)

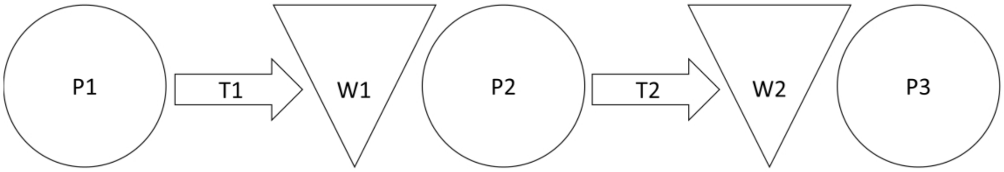


Figure 2. Recycled plastic pipeline manufacturing system.

861x484mm (118 x 118 DPI)

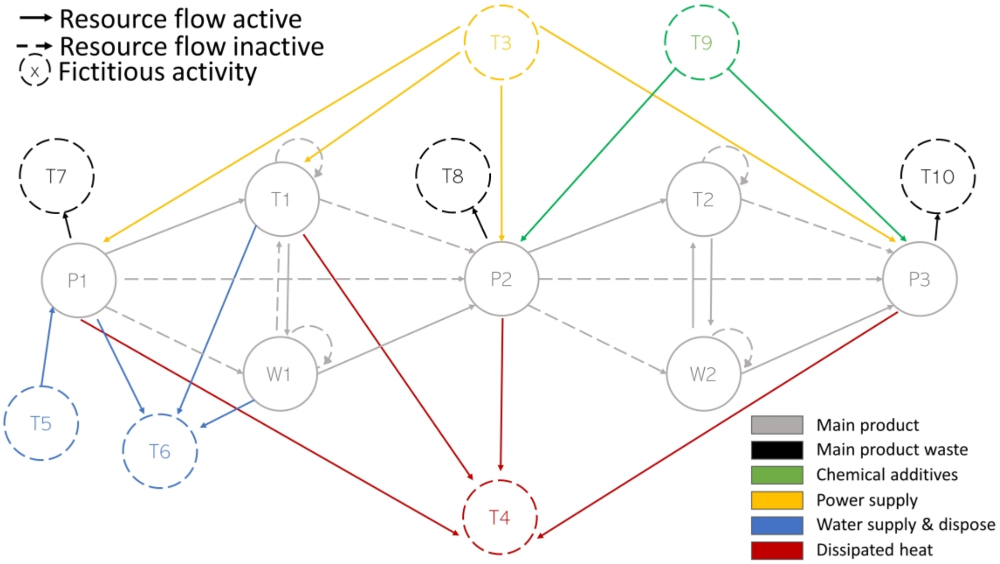


Figure 3. The RA MEIO graph for the recycled plastic pipeline manufacturing system.

861x484mm (118 x 118 DPI)

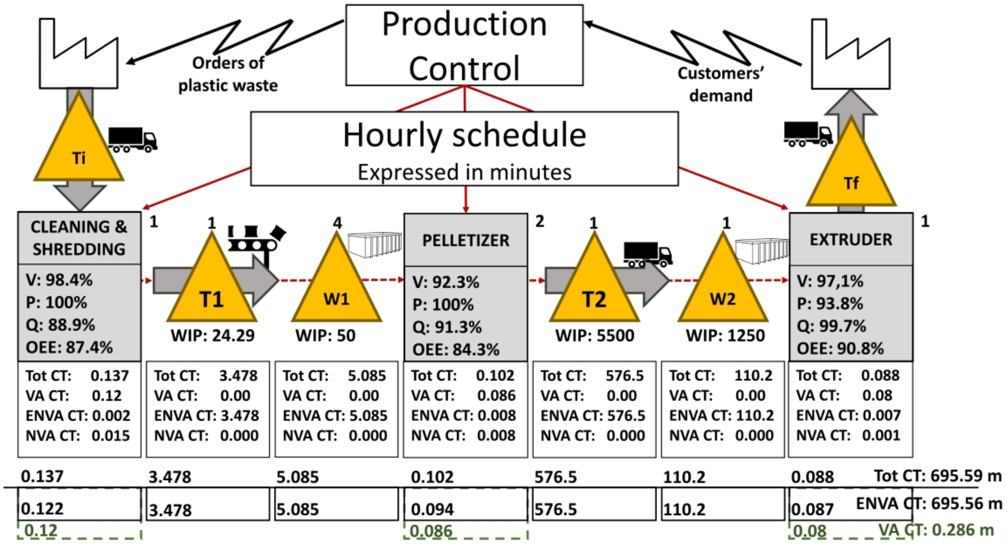


Figure 4. Value Stream Mapping of plastic pipelines manufacturing chain.

861x484mm (118 x 118 DPI)

Table 1. Performance dimensions covered by the proposed methods.

Approaches		Lean approaches		Network approaches	Flow approaches		This paper
Characteristics of the methods		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 activities	✓	✓				✓
	Essential non-value-added activities	✓	✓				✓
	Non-value-added activities	✓	✓				✓
Economic dimension	Economic interactions among companies			✓			✓
	Production costs			✓		✓	✓
	Raw material and energy costs			✓		✓	✓
	Labour costs			✓		✓	✓
	Product revenues			✓		✓	✓
	Technical inefficiencies			✓		✓	✓
	Profit from 6Rs approaches			✓		✓	✓
Environmental dimension	Produced and consumed resources			✓	✓	✓	✓
	Wasted resources			✓	✓	✓	✓
	Resources embedded in the product		✓	✓	✓	✓	✓
	Resources disposed of in the environment			✓	✓	✓	✓
	Resource efficiency		✓	✓	✓	✓	✓
	Benefits from 6Rs approaches			✓	✓	✓	✓

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	-/-

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-failure (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	-	-

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

Resource-Function table	P1	T1	W1
Plastic mix (kg/hr)	Y=8.929X;-	-;-	-;-
Humid waste (kg/hr)	-;X*	-;-	-;-
Shredded, humid mix (kg/hr)	-;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/hr)	Y=8.929X;-	-;-	-;-
Waste water (lt/hr)	-;Y=7.964X	-;Y=9.6(X-0.1)	-;X*
Dissipated heat (kWh)	-;Y=1.786X+0.5	-;Y=0.333(X-0.1)	-;-

Table 5. Economic parameters for produced and purchased resources.

Resources	**Price**	**Cost**
Plastic mix (€/kg)	0.45	-
Humid waste (€/kg)	-	1
Shredded, humid mix (€/kg)	0.6	-
Plastic pellet (€/kg)	1	-
Under q. pellet (€/kg)	-	0.0262
Bags of pellet (€/bags)	10.3	-
CO_2 (€/delivery)	-	0.00005
Chemical additives (€/kg)	1.5	-
Fuel (€/delivery)	0.0014	-

Resources	**Price**	**Cost**
Power (€/kWh)	0.17	-
Used power (€/kWh)	-	-
Water (€/lt)	0.004	-
Waste water (€/lt)	-	-
Dissipated heat (€/kWh)	0.5	-
Pipeline d200 (€/piece)	35	-
Pipeline d600 (€/piece)	7	-
Defective pipeline d200 (€/piece)	-	0.78
Defective pipeline d600 (€/piece)	-	0.156

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

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

Resources	**P1**	**T1**	**W1**	**P2**	**T2**	**W2**	**P3**
Plastic mix (kg/hr)	Y=8.929X;-	-;-	-;-	-;-	-;-	-;-	-;-
Humid waste (kg/hr)	-;X	-;-	-;-	-;-	-;-	-;-	-;-
Shredded, humid mix (kg/hr)	-;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/hr)	-;-	-;-	-;-	-;Y=2(4.587X)	-;-	-;Y=10.3X	Y=15X;-
Under q. pellet (kg/hr)	-;-	-;-	-;-	-;Y=2(0.399X)	-;-	-;-	-;-
Bags of pellet (bags)	-;-	-;-	-;-	-;Y=2(0.445X)	X;Y=X	X;-	-;-
***CO_2* (g/delivery)**	-;-	-;-	-;-	-;-	-;Y=5	-;-	-;-
Chemical additives (kg/hr)	-;-	-;-	-;-	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/hr)	Y=8.929X;-	-;-	-;-	-;-	-;-	-;-	-;-
Waste water (lt/hr)	-;Y=7.964X	-;Y=9.6(X-0.1)	-;X	-;-	-;-	-;-	-;-
Dissipated heat (kWh)	-;Y=1.786X+0.5	-;Y=0.333X	-;-	-;Y=2(0.179X+0.5)	-;-	-;-	-;Y=1.14X+0.5
Pipeline d200 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=7.991X
Pipeline d600 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=7.96X
Defective pipeline d200 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=0.009X
Defective pipeline d600 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=0.041X

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

Activity-Parameters table	**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 (kg/hour)	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-failure (hour)	3	-	-	3	-	-	16.66; 83.33
Mean-time-to-repair (hour)	0.05	-	-	0.25	-	-	0.83; 0.83
Mean-time-to-setup (hour)	-	-	-	-	-	-	7.5
Mean setup time (hour)	-	-	-	-	-	-	0.5
Working hours per day (hour/day)	24	24	24	24	16	16	16
Labour cost (€/man*h)	10	-	-	-	-	-	-
Operational cost (€/hour)	-	-	-	-	80	-	-
Speed (km/hr)	-	0.9	-	-	35	-	-
P1 distance (km) from	-	0	0.05	-	-	-	-
T1 distance (km) from	0	-	0	-	-	-	-
W1 distance (km) from	0.05	0	-	0	-	-	-
P2 distance (km) from	-	-	0	-	0	10	-
T2 distance (km) from	-	-	-	0	-	0	-
W2 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

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

Resources	**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%

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	-	-	-	-
Dissipated heat	375.41	-187.7	2.1	-1.05	-	-	69.19	-34.6	133.23	-66.61
Pipeline d200	-	-	-	-	-	-	-	-	31.08	1087.66
Pipeline d600	-	-	-	-	-	-	-	-	154.86	1083.99
Defective pipeline d200	-	-	-	-	-	-	-	-	0.04	-0.03
Defective pipeline d600	-	-	-	-	-	-	-	-	0.8	-0.12
Hours	3.8	114	-	-	-	-	2.76	-	2.54	-

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 d200	0	0	0	0	1087.66
Pipeline d600	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 reusable 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 reusable 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

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

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

WORD COUNT: 13555

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

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 new 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 principles of Material Flow Analysis and a new data structure that exploits some characteristics of the Multi-layer Stream Mapping and the Enterprise Input-Output methods to obtain a data-driven approach, typical of Industry 4.0. The proposed method can deal with complex systems and allows to consider also non-value-added activities such as transport and inventories. The implementation of the method and its advantages are shown through a numerical example based on a recycled plastic pipeline manufacturing system. The method shows positive synergies and mutual benefits between sustainable production, lean principles, and data-driven approaches and technologies of Industry 4.0. The method improves the alignment of environmental, technical, economic, and value creation information between operational and strategical levels, removing redundancies in data collection, conditioning, and processing activities, thus reducing partial information, hidden risks and opportunities, and inconsistencies.

Keywords: lean manufacturing; sustainable production; Industry 4.0; operational performance; environmental performance; material flow cost accounting

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 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 specify the required data and the procedures to collect, manipulate, and exploit them to obtain Key Performance Indicators (KPIs). Therefore, the methods vertically integrate the characteristics of two or more of these four groups by allocating resources for the activities of each group.

On the other hand, the scientific literature highlights the need to consider the environmental dimension in the performance assessment to achieve viable and sustainable systems, for example, by integrating green and lean approaches (Zekhnini et al. 2021). Considering simultaneously technical, economic, environmental, and value creation dimensions requires combining tools, methods and KPIs (Ferretti et al. 2017). However, the concurrent application of several methods creates a possible redundancy in data generation, transmission, collection, conditioning, storage and processing. Also, aggregating results of different methods may lead to partial and incomplete and inconsistent 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, beyond the technical efficiency, becomes essential in the cases of systems that aim to maximise 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). However, 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 simultaneously deal with several intertwined dimensions. Neglecting some of the dimensions may lead to hidden costs and missed opportunities by affecting the assessment of the considered ones (de Oliveira, Cardoso, and Lucato 2016).

This paper proposes a data-driven and network-oriented formalisation method focused only on the group (3) of the aforementioned Klingenberg, Borges, and Antunes Jr (2019) classification. The proposed method, the Multi-layer Enterprise Input-Output (MEIO) formalisation method, supports the simultaneous assessment of techno-economic-environmental performance and value creation by quantifying the types of waste, often originated by technical inefficiencies, and their economic impacts. It combines the principles of Material Flow Analysis (Rotter et al. 2004) and a new data structure that exploits some of the characteristics of the Enterprise Input-Output (Albino, Izzo, and Kühtz 2002) and the Multi-layer Stream Mapping (Holgado et al. 2018). 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).

The research methodology is based on what is reported in the portal of research methods (Anne Håkansson, 2013). The research method used in this paper belongs to the class of applied research methods, and it has an abductive approach involving deductive and inductive phases. The deductive phase consisted in identifying the literature gaps by desk research. The aim was to investigate, in both cross-sectional and longitudinal fashion, the industrial production literature about the principal methods used to analyse production systems and assess their technical, environmental, and economic dimensions and their value creation. Then, the research design exploited such gaps to drive the development of the new formalisation method. The final part of the research design used an inductive approach by proposing a numerical example to show the implementation of the method in a realistic system. The results drove the discussion on the contribution of the proposed method to the literature review.

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 section 6 concludes this paper.

Literature review

In the past, monitoring 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 (Dieste, Panizzolo, and Garza-Reyes 2020). 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 highlights the specific characteristics of the most studied methods in the performance dimensions considered by this paper. It 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 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 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 rows *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, that is, *Data-driven characteristics*, 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 (Jünge et al. 2021). 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 versatility of lean approaches allows their adoption in fields different from the production and supply chains like project management, where they support the project evaluation (Dabestani et al. 2017).

Recently, continuous improvement strategies involve both lean principles and green approaches to develop more sustainable conceptual models (Teixeira et al. 2021) and self-assessment models to adopt sustainable best practices (Cherrafi et al. 2021). The lean tools have also been used to improve and develop green indicators (Hartini, Ciptomulyono, and Anityasari 2020), as in the case of the green productivity improved through the green VSM (Prayugo and Zhong 2021), and achieve better results in the Global Reporting Initiative indicators that measure the economic, social, and environmental performance of a company (Lambrechts et al. 2019). Combining lean tools and indicators can be effective both in technical and environmental dimensions (Swarnakar, Singh, and Tiwari 2020), as in the case of the green modified VSM (Zhu, Zhang, and Jiang 2020) and the sustainable-setup-SM (Ebrahimi, Khakpour, and Saghiri 2021).

The most famous lean tool to identify inefficiency sources at the system design and continuous improvement 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).

Table 1. Performance dimensions covered by the proposed methods.

Approaches	Lean approaches	Network approaches	Flow approaches	This paper

Characteristics of the methods		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 activities	✓	✓				✓
	Essential non-value-added activities	✓	✓				✓
	Non-value-added activities	✓	✓				✓
Economic dimension	Economic interactions among companies			✓			✓
	Production costs			✓		✓	✓
	Raw material and energy costs			✓		✓	✓
	Labour costs			✓		✓	✓
	Product revenues			✓		✓	✓
	Technical inefficiencies			✓		✓	✓
	Profit from 6Rs approaches			✓		✓	✓
Environmental dimension	Produced and consumed resources			✓	✓	✓	✓
	Wasted resources			✓	✓	✓	✓
	Resources embedded in the product		✓	✓	✓	✓	✓
	Resources disposed of in the environment			✓	✓	✓	✓
	Resource efficiency		✓	✓	✓	✓	✓
	Benefits from 6Rs approaches			✓	✓	✓	✓

Several VSM-based methods focus on some environmental aspects; for example, the Waste Flow Mapping analyses the sources of waste (Kurdve et al. 2015); the Environmental SM (Garza-Reyes et al. 2018) combined with the Plan-Do-Check-Act approach, and the Overall Greenness Performance-VSM (Muñoz-Villamizar et al. 2019) foster the continuous improvement in reducing waste and implementing more sustainable practices. Also, VSM-based methods support the transition towards the circular economy; for example, the Green Performance Map focuses the continuous improvement approach on the circular economy for the shop floor (Kurdve and Bellgran 2021), and the

Sustainable VSM considers the resources involved in the 6Rs strategies (Faulkner and Badurdeen 2014) in several industrial fields (Brown, Amundson, & Badurdeen 2014). VSM and VSM-based methods are generally employed within the lean approach of the continuous improvement based on the discrete steps of Plan-Do-Check-Act, even when the 6Rs strategies are considered (Hedlund et al. 2020). Therefore, they are rarely used for dynamic and real-time approaches, as in the case of the combined use of VSM and Discrete Event Simulation in the Economic and Environmental VSM (Alvandi et al. 2016). VSM generally remains a pen-and-paper approach (e.g., (Lodding and Koch 2021)); it has difficulties to include all the involved resources concurrently with their techno-economic-environmental and value creation dimensions and the 6Rs strategies in a dynamic fashion. Moreover, the outcomes of its application depend on the choice of the flow unit used in the analysis (Shou et al. 2017). The Multi-Layer SM (MSM) extends the VSM to integrate the assessment of the value creation of production systems and their resource efficiency (Holgado et al. 2018). These characteristics make the MSM useful for analysing reverse logistics supply chains (Ahmed and Zhang 2021).

Lean and agile principles are often combined when some factors external to the company are considered in the analyses, such as raw material purchasing and product demand. At the intercompany level, *leagile* (an integrated lean and agile use) approaches focus on identifying decoupling points to maximise technical efficiency, adapt to customer demand, and reduce costs (Shahin et al. 2016). At the intracompany level, lean and agile approaches support quality improvement and internal cost reduction (Shahin and Rezaei 2018). However, approaches based on lean principles 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, and employees' organisation (Soliman and Saurin 2020).

The investigation of value, economic and environmental performance in product-service systems are generally addressed with other approaches such as the provider value analysis (Matschewsky, Sakao, and Lindahl 2015) that investigate product performance during its entire life cycle (Matschewsky, Lindahl, and Sakao 2020).

The contamination of the I4.0 paradigm with lean manufacturing principles may lead to positive synergies overcoming the current limits (Ding, Ferras Hernádez, and Agell Jan 2021), 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 support the evaluation of 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 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 and 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.

Several approaches integrate VSM and other methods to extend their effectiveness to other performance dimensions and their adaptability in other fields; for example, the combined VSM-MFCA allows environmental and economic assessment of company performance (Thanki and Thakkar 2016), and the VSM-LCA approach extends the VSM static approach by including life cycle environmental performance (Salvador et al. 2021). 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).

However, the following gaps remain:

- 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);
- VSM-based methods, including MSM, are mainly value-chain oriented instead of value-network oriented;

- adopting several methods may lead to redundancies in data collection, transmission, processing, and conditioning activities leading to partial and inconsistent information and hidden risks and opportunities;
- the integration of some approaches may be prohibitive for SMEs (e.g., MSM and LCA-based) because they require knowledge and economic availability, whose lack can result in unhelpful results (Heidrich and Tiwary 2013).
- these approaches struggle to properly exploit data to benefit from the I4.0 paradigm and consider all the involved resources in the process network by including simultaneously technical, economic, environmental, and value creation dimensions and their quantities for dynamic analyses and production monitoring.

Contribution

This study proposes an integrated formalisation method. The method develops a shared architecture for data processing and conditioning to feed other methods and tools. The use of the proposed formalisation method 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 by gathering the necessary information to simultaneously assess techno-economic-environmental performance and value creation.

The proposed method, the Multi-layer Enterprise Input-Output (MEIO), is based on the main principles of Material Flow Analysis, EIO and MSM, and a new data structure composed of three tables, explicitly designed to be data-driven, according to the I4.0 paradigm. The new data structure connects the information about the resources consumed and produced by all the activities of a system with the economic and technical parameters of the activity and the technological aspect that allow to modify the activity rate. The information provided by the data structure can be used to draw a resource activity graph that supports the analysis of the as-is system and the several alternatives to optimise. This method supports both data-driven and pen-and-paper approaches in the concurrent evaluation of techno-economic-environmental efficiency and value creation for production planning and control systems. Therefore, though the method exploits the lean principles, the new data structure helps to tackle the limits of lean principles-based methods in comprehensively assessing, quantifying, and monitoring multi-dimensional performance (Bai, Satir, and Sarkis 2019).

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) by improving both the visibility and the assessment of global environmental impacts of operational performance.

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, identifying the unit of analysis and ensuring 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, waste, 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.

Resource-Activity MEIO table

The RA MEIO table consists of I columns, one for each activity, and J rows, that is, 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.

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 the wet product dries during inventory and transport activities, 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 activities with different machines/operators, the MEIO method represents them 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.

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 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 normalised. 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).

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, the time-to-failure and the time-to-repair follow an exponential distribution with means 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.

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-failure (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	-	-

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), arbitrarily chosen to reduce the complexity of the calculations in pen-and-papers approaches, 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. For example, in the table, referring to activity P1, the output of *Humid waste* has been chosen as the independent variable, and all the other functions depend on it. The quantity of *Power* has a constant term (0.5 kWh) and a variable term proportional to 2.857 times the *Humid waste* output ($Y= 2.857X + 0.5$).

Therefore, 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, such as the constant terms. For example, the fixed consumption of *Power* of 0.5 kWh, in P1, is independent of the production of *Humid waste* (independent variable X) and produces 0.5 kWh of *Dissipated heat* dissipated in the environment.

The mathematical functions model the consumption and production of the resources when the process rate changes by estimating the relationships from data or following the producer's nominal parameters.

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

Resource-Function table	P1	T1	W1
Plastic mix (kg/hr)	Y=8.929X;-	-;-	-;-
Humid waste (kg/hr)	-;X*	-;-	-;-
Shredded, humid mix (kg/hr)	-;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/hr)	Y=8.929X;-	-;-	-;-
Waste water (lt/hr)	-;Y=7.964X	-;Y=9.6(X-0.1)	-;X*
Dissipated heat (kWh)	-;Y=1.786X+0.5	-;Y=0.333(X-0.1)	-;-

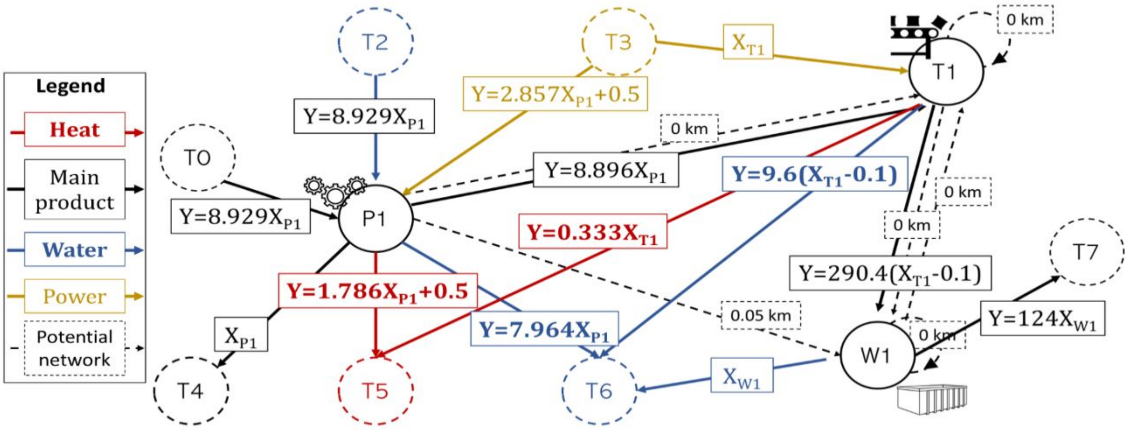
The RF MEIO table complexity depends on the modelling assumptions; in fact, the formalisation method can introduce complex functions and distributions to model different activity behaviours (e.g. productivity during the warm-up period, the average rate, and the overload working condition).

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, a set of outgoing arcs for each produced resource 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.

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



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.

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 to 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.

Numerical example

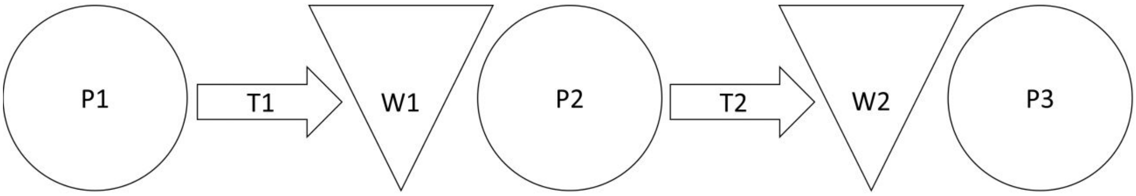
This section discusses a numerical example to show the implementation of the MEIO method on a recycled plastic pipelines manufacturing system by developing the MEIO tables and drawing the RA MEIO graph. Section 5 will use the same example to apply both the MFCA and MSM approaches to assess the techno-economic-environmental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

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. 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 (*Shredded, humid 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.

Figure 2. Recycled plastic pipeline manufacturing system.



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 humid 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 humid 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 humid 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 pellet* 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 humid mix* cause jams (on average one every 3 hours with 15 minutes to solve them); moreover, 8% of the produced *Plastic 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 *Fuel* 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 plant area devoted to producing products in recycled plastic.

The stocking area W2 consists of a *Pellet bin* able to store up to 10 tons of *Plastic pellets*. 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 *Plastic pellets* 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*, *Under quality pellets*, and the discarded *Shredded humid mix* is a cost for the company since the disposal fee is 25 €/m3. 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: the *Shredded humid waste* felt out of the conveyor belt, *Under 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
Plastic mix (€/kg)	0.45	-
Humid waste (€/kg)	-	1
Shredded, humid mix (€/kg)	0.6	-
Plastic pellet (€/kg)	1	-
Under q. pellet (€/kg)	-	0.0262
Bags of pellet (€/bags)	10.3	-
CO_2 (€/delivery)	-	0.00005
Chemical additives (€/kg)	1.5	-
Fuel (€/delivery)	0.0014	-

Resources	Price	Cost
Power (€/kWh)	0.17	-
Used power (€/kWh)	-	-
Water (€/lt)	0.004	-
Waste water (€/lt)	-	-
Dissipated heat (€/kWh)	0.5	-
Pipeline d200 (€/piece)	35	-
Pipeline d600 (€/piece)	7	-
Defective pipeline d200 (€/piece)	-	0.78
Defective pipeline d600 (€/piece)	-	0.156

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) require 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 humid mix* and the waste: furthermore, it neglects how the used *Water* could be reused. Therefore, from further analysis, 446 out of the provided 500 lt/h are disposed of as *Waste water*; the remaining 54 kg follow both the *Humid waste* and the *Shredded humid mix*. Also, the entire line consumes 160 kWh, but the effective use of power (*Used 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: the bulk *Plastic pellet* production in terms of kg/h and the number of *Bags of pellet*. Furthermore, in T2, the required *Fuel* and produced CO_2 are assessed over the assigned journey since the *Truck* always follows the same route.

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

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 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.

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

Resources	**P1**	**T1**	**W1**	**P2**	**T2**	**W2**	**P3**
Plastic mix (kg/hr)	Y=8.929X;-	-;-	-;-	-;-	-;-	-;-	-;-
Humid waste (kg/hr)	-;X	-;-	-;-	-;-	-;-	-;-	-;-
Shredded, humid mix (kg/hr)	-;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/hr)	-;-	-;-	-;-	-;Y=2(4.587X)	-;-	-;Y=10.3X	Y=15X;-
Under q. pellet (kg/hr)	-;-	-;-	-;-	-;Y=2(0.399X)	-;-	-;-	-;-
Bags of pellet (bags)	-;-	-;-	-;-	-;Y=2(0.445X)	X;Y=X	X;-	-;-
CO_2 (g/delivery)	-;-	-;-	-;-	-;-	-;Y=5	-;-	-;-
Chemical additives (kg/hr)	-;-	-;-	-;-	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/hr)	Y=8.929X;-	-;-	-;-	-;-	-;-	-;-	-;-
Waste water (lt/hr)	-;Y=7.964X	-;Y=9.6(X-0.1)	-;X	-;-	-;-	-;-	-;-
Dissipated heat (kWh)	-;Y=1.786X+0.5	-;Y=0.333X	-;-	-;Y=2(0.179X+0.5)	-;-	-;-	-;Y=1.14X+0.5
Pipeline d200 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=7.991X
Pipeline d600 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=7.96X
Defective pipeline d200 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=0.009X
Defective pipeline d600 (kg/hr)	-;-	-;-	-;-	-;-	-;-	-;-	-;Y=0.041X

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

Activity-Parameters table	**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 (kg/hour)	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-failure (hour)	3	-	-	3	-	-	16.66; 83.33
Mean-time-to-repair (hour)	0.05	-	-	0.25	-	-	0.83; 0.83
Mean-time-to-setup (hour)	-	-	-	-	-	-	7.5
Mean setup time (hour)	-	-	-	-	-	-	0.5
Working hours per day (hour/day)	24	24	24	24	16	16	16
Labour cost (€/man*h)	10	-	-	-	-	-	-
Operational cost (€/hour)	-	-	-	-	80	-	-
Speed (km/hr)	-	0.9	-	-	35	-	-
P1 distance (km) from	-	0	0.05	-	-	-	-
T1 distance (km) from	0	-	0	-	-	-	-
W1 distance (km) from	0.05	0	-	0	-	-	-
P2 distance (km) from	-	-	0	-	0	10	-
T2 distance (km) from	-	-	-	0	-	0	-
W2 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

As the MEIO is a formalisation method, it will be used coupled with other methods to perform several analyses. The numerical example shows the use of the MEIO method with MSM to evaluate the technical efficiency and the value creation, while the Overall Equipment Efficiency (OEE) is used 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). Furthermore, OEE can consider maintenance, machine availability, and final quality, especially in the most accurate versions, such as the one proposed by Shahin and Isfahani (2015) for continuous production lines. Due to the focus of the paper on the MEIO application and the lack of more specific production data, the OEE is calculated according to the easier version proposed by De Ron and Rooda (2006). The OEE (Equation (1)) is 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)).

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

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

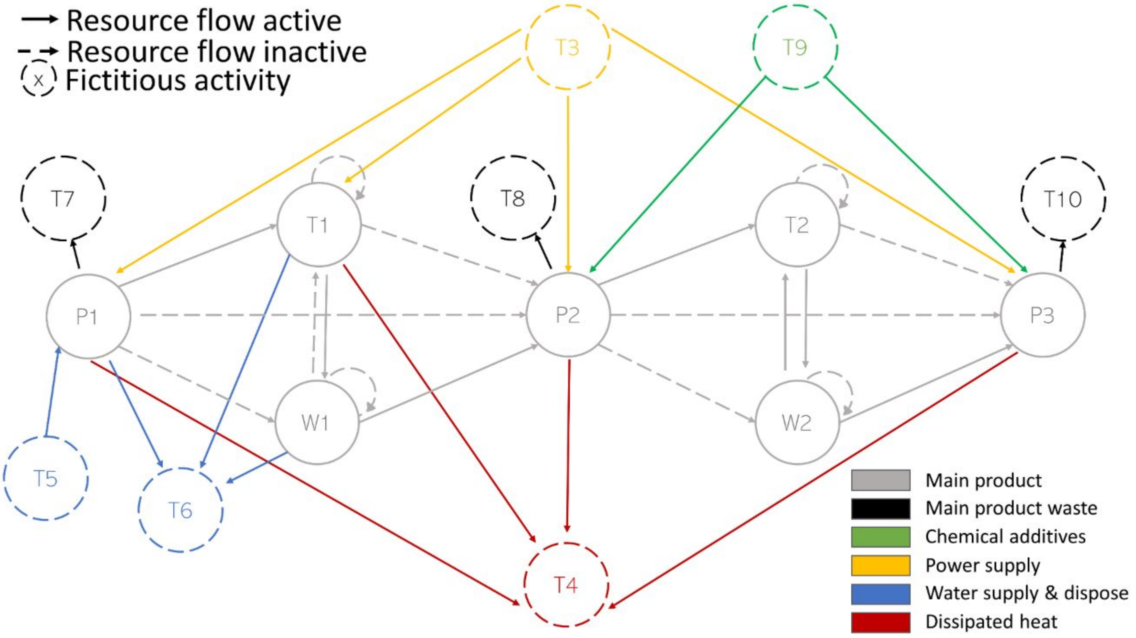
$$P = \frac{theoretical\ cycle\ time\ \cdot\ processed\ amount}{operating\ time} \tag{3}$$

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

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.

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



Performance analysis

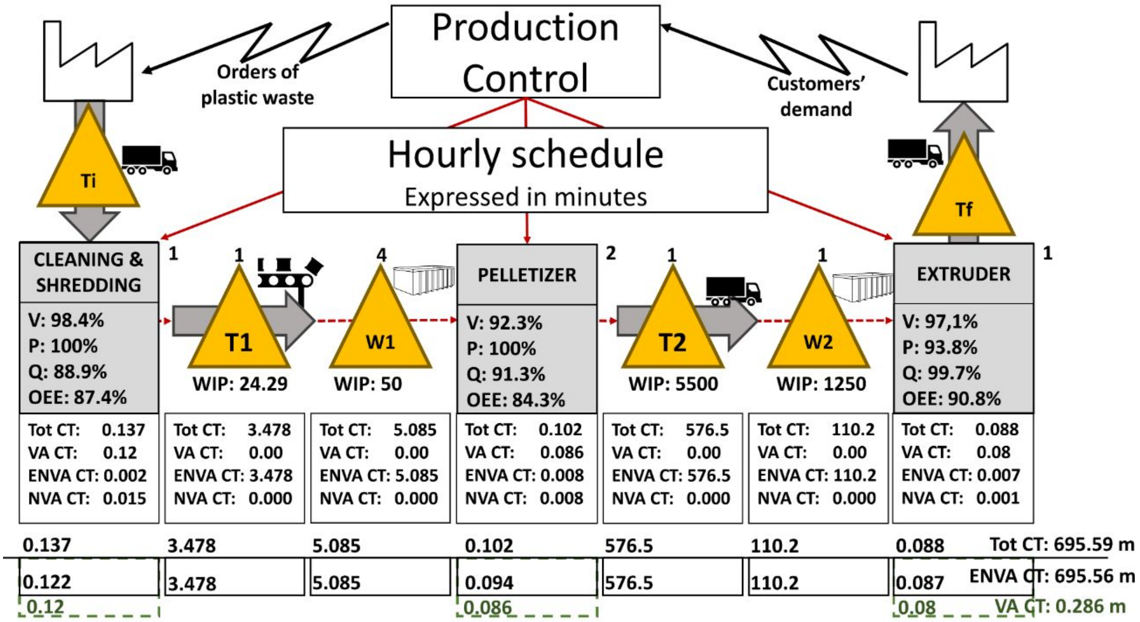
The following performance analysis shows the potential benefits in redundancy, time and cost reduction achievable by adopting the MEIO formalisation method as a shared architecture. The MEIO tables feed MSM and MFCA methods to assess value creation and techno-economic-environmental performance. The performance 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.

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 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.

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



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 an example. The AP MEIO table provides the nominal capacity, and the total CT is in Equation (8).

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

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

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

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

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 the input and output resources within each activity. 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* that arrives 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 the rest becomes *Dissipated heat* according to the RF MEIO table. 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 *Waste water*, *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.

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

Resources	**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%

Adopting the MEIO formalisation method led the MSM to also focus on transforming consumables, energy, and raw materials into waste and by-products, which would not have been considered otherwise. 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 highlights 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.

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 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 mix* 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 additives*.

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. 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	-	-	-	-
Dissipated heat	375.41	-187.7	2.1	-1.05	-	-	69.19	-34.6	133.23	-66.61
Pipeline d200	-	-	-	-	-	-	-	-	31.08	1087.66
Pipeline d600	-	-	-	-	-	-	-	-	154.86	1083.99
Defective pipeline d200	-	-	-	-	-	-	-	-	0.04	-0.03
Defective pipeline d600	-	-	-	-	-	-	-	-	0.8	-0.12
Hours	3.8	114	-	-	-	-	2.76	-	2.54	-

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 performance assessment of the manufacturing system.

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 d200	0	0	0	0	1087.66
Pipeline d600	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 reusable 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 reusable 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

Discussion

The Multi-layer Enterprise Input-Output formalisation method aims to create a consistent data architecture to formalise the whole manufacturing system by simultaneously involving information to consider technical, environmental, economic, and value creation aspects. The method helps to share the information about the system among the several internal and external stakeholders of the company (e.g., stakeholders of the supply chains and internal departments such as innovation, production, engineering, and manufacturing). It aims to support the adoption of other methods to assess performance and analyse the system to improve it. The method aims: 1) to avoid partial and hidden information, and inconsistencies among methods focusing on different performance dimensions, and 2) to reduce redundancies in data collection, processing and conditioning activities. In the following, the interpretation of findings is addressed together with theoretical, managerial and practical implications.

Interpretation of findings

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.

The MEIO method improves the findings of the other methods; for example, the MEIO data structure allows the other methods to identify and quantify 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 data structure allows to identify 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.

Theoretical implications

The proposed method contributes to clarify the role of lean principles in the new industrial paradigms of Industry 4.0 and 5.0, as it is still not completely well-defined (Sanders et al. 2017). The positive effects between new technologies and lean methods are mutual and non-exclusive because new technologies improve the effectiveness of lean methods (Sanders, Elangeswaran, and Wulfsberg 2017), and lean approaches support the adoption of new technologies (Tortorella et al. 2020). The method provides a robust and objective formalisation of the activities of a system under several dimensions that can be updated through real-time floor data. Also, it can increase horizontal and vertical data integration by sharing the information of its data structure.

In particular, the proposed method shows that the overall benefits of systemic identification and removal of the eight types of waste through continuous improvement can be extended by also considering environmental and economic points of view. On the other side, the method highlights the positive and negative contributions of essential and non-essential non-value-added activities. It can show to the decision-maker a trade-off situation (e.g., removing non-added-value activities though they reduce environmental impacts) or a clear picture of negative impacts of these activities also in other dimensions. In all the cases, the data-driven approach allows the method to monitor real-time production systems, improving the ability to identify the causes of the deterioration of technical-economic-environmental performance.

The proposed method sheds light on the impact achievable by the positive synergies of data-driven manufacturing paradigm, lean principles, and sustainable manufacturing.

Managerial and practical implications

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 can support decision-makers in planning and controlling complex production systems, especially those focused on 6Rs strategies. The 6Rs strategies can create many loops of by-products, waste, and defectives that are reused and repaired, while others are disassembled or purified and then used as raw material for other processes. These loops make the value-chain approaches complex and scarcely adequate to represent the real systems, while the MEIO method exploits a network approach capable of representing all the resource exchanges. Moreover, the MEIO method can integrate actual data from manufacturing systems 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 to monitor and extend industrial symbiotic networks, in which the waste of a company becomes the raw material of another.

MEIO can also be an easy-to-use formalisation method to allow companies (currently focused only on technical performance) to model their activities by simultaneously considering economic and environmental dimensions to improve their performance analysis, showing them how crucial the other dimensions 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 method does not require extensive resources and knowledge; therefore, it is also indicated for SMEs. It is particularly suitable in those production systems where many internal and external stakeholders manage different aspects, especially in the presence of 6Rs strategies that complicate the system representation. In those systems, the method can significantly increase consistencies among several kinds of analyses performed by different stakeholders and save time and resources in redundant activities. For example, this method can help different companies in designing production networks characterised by an effective innovation content in which stakeholders cooperate to substitute raw materials by mutually exploiting their waste (e.g., industrial symbiosis networks). Also, process and product industries can implement it to assess the multi-dimensional performance of their systems.

However, the proposed method is not recommended in the case of production systems for highly customised products, low repeatability in production processes, and subsequent unpredictability in resource consumption and production.

Conclusion

This paper proposes a new method, the Multi-layer Enterprise Input-Output (MEIO), which is based on the main principles of MFA and a new data structure that combines some characteristics of MSM and EIO. MEIO allows the development of a shared architecture that can support the simultaneous assessment of techno-economic-environmental performance and value creation of manufacturing systems. The method allows to focus on a subset of dimensions, thus reducing redundancies in data collection, processing and conditioning while improving data formalisation.

The MEIO method can support decision-makers in planning new production systems and controlling the current ones through aligned data, also in the presence of many loops such as those of 6Rs strategies. Moreover, MEIO can be crucial for SMEs, which mainly focus only on technical efficiency. Its flexibility and easy-to-use formalisation approach can foster its adoption, making the SMEs aware of the effects of environmental and economic dimensions of their production systems and how they affect the environment.

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 is versatile since it can support other methods through the shared data 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 multivariate functions; in fact, the production and the absorption of a resource can depend on the production and consumption of more than one other. However, the method provides a good approximation of system performance and could be easily replicated and used by any company. Modern production systems involve '*plug and play*' machines and robots able to change their roles according to contingent situations. Thus, methods exploiting a priori knowledge of the system can rapidly become obsolete; further research can be devoted to developing 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.

A preprint and not peer-reviewed version of this paper is available at the EngrXiv database (Castiglione, Pastore, and Alfieri 2021).

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Appendix A

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

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

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

Response to the reviewers

March 3rd, 2022

We are delighted by reviewer 2's positive feedback that suggested accepting the manuscript as-is. Furthermore, we are grateful for further reviewer 1's suggestions that carefully identified some minor lacks representing opportunities to strengthen the manuscript. We provided a point-by-point answer (blue in the following) to all the reviewer's questions and suggestions (black in the following) by also citing the new parts added in the manuscript (red in the marked version of the manuscript).

1. Response to reviewer #1

1. *Thanks for an interesting paper. I see that you have improved with revision to previous reviewer comments. I still have some improvement suggestions.*
   We are glad about the positive feedback, and we appreciate the further suggestions.

2. *Motivation - there also exist green-lean value chain models and approaches based on environmental value stream mapping, waste flow mapping and provider value evaluation that do overcome most of the three limitations presented and: include both environmental and economic value, can include cross-flow and circular flows and take operational effects on value into account. Perhaps hedge the statement "no method considers at the same time technical, economic and environmental dimensions and value creation" and change to "few methods considers at the same time technical, economic and environmental dimensions and value creation (possibly references to one or two that exists).*
   We are grateful for this suggestion. We carefully revised the scientific framework introduced in the manuscript and we removed excessively strong sentences like the one indicated by the reviewer.
   We improved the literature review in two directions: 1) adding the topics suggested by the reviewer; 2) moving the references and the related discussion regarding lean and green-sustainable indicators and lean and agile approaches from the introduction to the literature review. Finally, we improved the introduction by adding the following paragraph to strengthen the research motivation (page 2, line 19 - page 3, line 2):

   > "Therefore, the methods vertically integrate the characteristics of two or more of these four groups by allocating resources for the activities of each group.
   > On the other hand, the scientific literature highlights the need to consider the environmental dimension in the performance assessment to achieve viable and sustainable systems, for example, by integrating green and lean approaches (Zekhnini et al. 2021). Considering simultaneously technical, economic, environmental, and value creation dimensions requires combining tools, methods and KPIs (Ferretti et al. 2017). However, the concurrent application of

several methods creates a possible redundancy in data generation, transmission, collection, conditioning, storage and processing."

3. *Literature - to a large extent appropriate literature is covered except e.g for some methods like environmental value stream mapping, waste flow mapping and provider value evaluation. Although the authors have attempted to add some relevant lean papers, I would recommend a quick further look into the green-lean research field and possibly extension of table 1 with other multilayered green-lean approaches that combines MFCA and VSM with visualisation and evaluation (e.g. waste flow mapping). To mention these similar approaches would strengthen the presentation of the MEIO method and put it into a better group context where further research could investigate when to use which of these tools.*

We appreciated this suggestion and deeply extended the literature review following the reviewer's suggestions. Specifically, we addressed all the suggested topics and also others that are crucial for this scientific framework, i.e.:

a) Environmental stream mapping;
b) Economic and environmental stream mapping;
c) Waste flow mapping;
d) Sustainable flow mapping;
e) Green-lean approaches;
f) Combined VSM-other methods approaches;
g) Provider value evaluation

Specifically, we added the following paragraphs:

P1 for green-lean approaches and indicators (page 6, line 10-21): " Recently, continuous improvement strategies involve both lean principles and green approaches to develop more sustainable conceptual models (Teixeira et al. 2021) and self-assessment models to adopt sustainable best practices (Cherrafi et al. 2021). The lean tools have also been used to improve and develop green indicators (Hartini, Ciptomulyono, and Anityasari 2020), as in the case of the green productivity improved through the green VSM (Prayugo and Zhong 2021), and achieve better results in the Global Reporting Initiative indicators that measure the economic, social, and environmental performance of a company (Lambrechts et al. 2019). Combining lean tools and indicators can be effective both in technical and environmental dimensions (Swarnakar, Singh, and Tiwari 2020), as in the case of the green modified VSM (Zhu, Zhang, and Jiang 2020) and the sustainable-setup-SM (Ebrahimi, Khakpour, and Saghiri 2021)."

P2 for the several extensions of VSM (e.g., Waste flow mapping and Environmental stream mapping) (page 7, line 1 – page 8, line 5): "Several VSM-based methods focus on some environmental aspects; for example, the Waste Flow Mapping analyses the sources of waste (Kurdve et al. 2015); the Environmental SM (Garza-Reyes et al. 2018) combined with the Plan-Do-Check-Act approach, and the Overall Greenness Performance-VSM (Muñoz-Villamizar et al. 2019) foster the continuous improvement in reducing waste and implementing more sustainable practices. Also, VSM-based methods support the transition towards the circular economy; for example, the Green Performance Map focuses the continuous improvement approach on the circular economy for the shop floor (Kurdve and Bellgran 2021), and the Sustainable VSM considers the resources involved in the 6Rs strategies (Faulkner and Badurdeen 2014) in several industrial fields (Brown, Amundson, & Badurdeen 2014). VSM and VSM-based methods are generally employed within the lean approach of the continuous improvement based on the discrete steps of Plan-Do-Check-Act, even when the 6Rs strategies are considered (Hedlund et al. 2020)."

P3 for showing the case of dynamic analyses with VSM (page 8, line 5-8): " Therefore, they are rarely used for dynamic and real-time approaches, as in the case of the combined use of VSM and Discrete Event Simulation in the Economic and Environmental VSM (Alvandi et al. 2016)"

P4 for clearly delimiting crucial aspects regarding the literature gap (page 8, line 9-12): "[…] concurrently with their techno-economic-environmental and value creation dimensions and the 6Rs strategies in a dynamic fashion. Moreover, the outcomes of its application depend on the choice of the flow unit used in the analysis (Shou et al. 2017)."

P5 for the extension of VSM-based methods to networks (page 8, line 12-15): " The Multi-Layer SM (MSM) extends the VSM to integrate the assessment of the value creation of production systems and their resource efficiency (Holgado et al. 2018). These characteristics make the MSM useful for analysing reverse logistics supply chains (Ahmed and Zhang 2021)."

P6 for lean and agile approaches (page 8, line 16-22): "Lean and agile principles are often combined when some factors external to the company are considered in the analyses, such as raw material purchasing and product demand. At the intercompany level, leagile (an integrated lean and agile use) approaches focus on identifying decoupling points to maximise technical efficiency, adapt to customer demand, and reduce costs (Shahin et al. 2016). At the intracompany level, lean and agile approaches support quality improvement and internal cost reduction (Shahin and Rezaei 2018)."

P7 for provider value evaluation (page 9, line 1-4): " The investigation of value, economic and environmental performance in product-service systems are generally addressed with other approaches such as the provider value analysis (Matschewsky, Sakao, and Lindahl 2015) that investigate product performance during its entire life cycle (Matschewsky, Lindahl, and Sakao 2020)."

P8 to extend the set of VSM-other methods (page 10, line 7-11): "Several approaches integrate VSM and other methods to extend their effectiveness to other performance dimensions and their adaptability in other fields; for example, the combined VSM-MFCA allows environmental and economic assessment of company performance (Thanki and Thakkar 2016), and the VSM-LCA approach extends the VSM static approach by including life cycle environmental performance (Salvador et al. 2021)."

P9, to improve the identified gap (page 11, line 1-3; page 11, line 7-10):
"• adopting several methods may lead to redundancies in data collection, transmission, processing, and conditioning activities leading to partial and inconsistent information and hidden risks and opportunities;
• these approaches struggle to properly exploit data to benefit from the I4.0 paradigm and consider all the involved resources in the process network by including simultaneously technical, economic, environmental, and value creation dimensions and their quantities for dynamic analyses and production monitoring. "

Finally, we did not extend table 1 to other methods based on VSM. In fact, table 1 only contains the main classes of the reviewed methods and not their combinations or their derived versions. A deep and detailed discussion has been added in the manuscript to present the several methods adequately.

4. *Method - please present which tool-design-methodology that has been used and describe in detail the research approach deployed to develop, test and analyse the usefulness of the MEIO-tool..*
   Thanks for the comment. We added the following paragraph to the introduction (page 4, line 11-22): "The research methodology is based on what is reported in the portal of research methods (Anne Håkansson, 2013). The research method used in this paper belongs to the class of applied research methods, and it has an abductive approach involving deductive and inductive phases. The deductive phase consisted in identifying the literature gaps by desk research. The aim was to investigate, in both cross-sectional and longitudinal fashion, the industrial production literature about the principal methods used to analyse production systems and assess their technical, environmental, and economic dimensions and their value creation. Then, the research design exploited such gaps to drive the development of the new formalisation method. The final part of the research design used an inductive approach by proposing a numerical example to show the implementation of the method in a realistic system. The results drove the discussion on the contribution of the proposed method to the literature review."

5. *Discussion - discuss in what situations it is most advantageous to use the tool.*
   We appreciated this comment. We added the situations in which the method is encouraged and those in which it is discouraged. Specifically, in the discussion section we added the following two paragraphs:

   P1 (page 34, line 2-12): "The Multi-layer Enterprise Input-Output formalisation method aims to create a consistent data architecture to formalise the whole manufacturing system by simultaneously involving information to consider technical, environmental, economic, and value creation aspects. The method helps to share the information about the system among the several internal and external stakeholders of the company (e.g., stakeholders of the supply chains and internal departments such as innovation, production, engineering, and manufacturing). It aims to support the adoption of other methods to assess performance and analyse the system to improve it. The method aims: 1) to avoid partial and hidden information, and inconsistencies among methods focusing on different performance dimensions, and 2) to reduce redundancies in data collection, processing and conditioning activities."

   P2 (page 37, line 5-18): "This method does not require extensive resources and knowledge; therefore, it is also indicated for SMEs. It is particularly suitable in those production systems where many internal and external stakeholders manage different aspects, especially in the presence of 6Rs strategies that complicate the system representation. In those systems, the method can significantly increase consistencies among several kinds of analyses performed by different stakeholders and save time and resources in redundant activities. For example, this method can help different companies in designing production networks characterised by an effective innovation content in which stakeholders cooperate to substitute raw materials by mutually exploiting their waste (e.g., industrial symbiosis networks). Also, process and product industries can implement it to assess the multi-dimensional performance of their systems.

However, the proposed method is not recommended in the case of production systems for highly customised products, low repeatability in production processes, and subsequent unpredictability in resource consumption and production."

2. Response to the reviewer #2

1. *Recommendation: Accept as-is or minor revisions - no further review. Comments: this new version of the paper effectivelly overcomes all my previous remarks. In my opinion it can be accepted as-is.*
   We appreciate the positive feedback on our paper.