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A quantitative framework for Industry 4.0 enabled Circular Economy

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Abstract

Sustainability and digital transformation represent two of the main trends of the last decade. More in detail, Industry 4.0 (I4.0) and Circular Economy (CE) are two key concepts that are characterizing the present and that will shape the future. From the extant literature review emerges that, although academics identify a possible synergy between these topics, a concrete integrated framework able to achieve CE at systemic level is still missing. The objective of this research is to put in relation the I4.0 and CE paradigms to understand the link between the two topics and envisage a new framework focused on circularity among supply chains. Therefore, a systematic literature review on CE, I4.0 and on their mutual relationship have been conducted to investigate which are the synergies and how the new I4.0 technologies support the implementation of CE at supply chains network level. Hence, a framework in which I4.0 technologies support the adoption of Reduce, Redesign, Recycling and Remanufacturing strategies has been developed. Indeed, starting from the 6Rs' model (Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture), the focus has been shifted towards these 4Rs since they have been considered the most affected by I4.0. Regarding the use of I4.0 technologies, Cloud Manufacturing (MaaS) and Additive Manufacturing have been deemed the most enabling technologies. Indeed, they allow to respectively aggregate resources and reduce wastes. The framework is supported by a quantitative analysis of economic and environmental impacts that results in the definition of a Multi-Objective Integer Linear Programming (MOILP). The framework works in closing the loop by acting as strategic node able to link different supply chains. It has been developed focusing on discrete manufacturing and replicable in different sectors. Finally, the model identified has been supported by some pilot assessments through semi-structured interviews.

Keywords: Circular Economy; Industry 4.0; Closed-Loop; Sustainable Manufacturing; MOILP; Supply Chain

1. Introduction

The circular economy (CE) paradigm has reached increasing attention among academia as a mean to promote sustainability [1]. Today, the most famous definition of CE has been provided by the Ellen MacArthur foundation where it is defined as a "*system restorative and regenerative by design, which aims to maintain products, components and materials at their highest utility and value*" [2]. In general, CE contrasts the TAKE-MAKE-DISPOSE paradigm of the Linear Economy, trying to decouple economic growth from environmental losses [2]. Ellen MacArthur foundation has distinguished two loops, the biological and the technical one. In the biological loop, materials follow the natural cycle, re-entering in the biosphere. The technical cycle, instead, deals with non-biodegradable components [2]. In this paper, the authors focused the attention mainly on the technical cycle, going to consider how the Industry 4.0 (I4.0) technologies are contributing to reach efficiency implementing the 6R practices included in CE framework.

I4.0 describes a model of the "smart" factory of the future where computer-driven systems completely connected, control the physical processes, create a virtual copy of the physical world and make decentralized decisions based on self-organization mechanism. Despite the overall awareness that I4.0 may support CE implementation, a practical suggestion for integrating new technologies with CE principles is still missing. In particular, a quantitative approach able to assess the real impact turns out to be crucial since the Manufacturing Industries, not only need to focus on the impact over

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environmental performances but also have the necessity to reach satisfactory economic ones. Hence, the multitude of objectives to be fulfilled have pushed the authors to choose a Multi-Objective Integer Linear Programming (MOILP) approach to develop the quantitative part of the framework. Hence, the authors have focused on defining a Business Model (BM) based on I4.0 technologies that could be able to ensure the achievement of CE.

2. Research Context

2.1 Circular Economy

To implement the CE in practice systems, the paradigm has to be translated into concrete actions for the circulation of materials flows within the system. This purpose has led to the identification of some industrial circular practices. [3], in its definition of "Sustainable Manufacturing" proposes the so-called 6Rs model, where the traditional 3R model based on Reduce, Reuse, Recycle practices has been enriched with three additional actions namely Recover, Redesign and Remanufacture.

Recover regards mainly energy and water recovery. In general, this "R" represents the process of collecting products at the end of the "use" stage, disassembling and cleaning them for utilization in subsequent lifecycles. *Redesign* involves the act of redesign products thinking about using materials recovered from previous products, and about facilitating the creation of a sustainable lifecycle. *Remanufacturing* involves the re-processing of existing products for restoration to their original state or to a new form, without losing functionality. In addition to the 6Rs approach, also new paradigms enabled by the advent of new technologies are consistently supporting the spread of CE. One of the most relevant examples in this sense is given by the change in the concept of value proposition given by the introduction of Product-Service Systems (PSS) [4].

A sustainable transition to CE is expected to bring benefits in environmental, economic and social terms. [5] esteemed a yearly growth in the European economy about 0.6 trillion € till 2030 given by primary-resource benefit. A higher collaboration between companies and the setting of a more systemic view will be reached: the waste from one process can become energy for another. Synergies and new operational effective solutions will be identified. Looking at the social side, CE is expected to bring new jobs by boosting an increased consumption of sustainable products. On the other hand, regarding the barriers and the main open challenges, CE paradigm will require big changes in industrial practices and patterns of consumption. One of the main deterrents is that societies are locked-in to resource intensive infrastructure and development models [6]. Moreover, high upfront cost, investments and risks need to be faced [7].

Finally, information sharing along the Supply Chains (SCs) can raise questions about information security and competitiveness, practical arrangements will be needed for the shared intellectual property arising from multi-partner activities[6]. In fact, the achievement of CE is mainly a matter of interconnecting different actors along the SCs. Hence, a model able to take into account multiple perspectives and objectives turns out to become crucial for a real adoption of CE values.

2.2 Industry 4.0

Within CE affirmation process, I4.0 revolution represents a push towards this more sustainable direction. Thanks to digitalization, the modern industrial scenario is becoming a place where people and machines coexist in the same environment, guaranteeing a more efficient production [8]. The technologies of reference included in the I4.0 concept are a lot: AI, IoT, Digital Twin, CPS, Robotics, Human-Machine interface, 3D Printing, Cloud Computing and Big Data (BD). These technologies are based on collecting huge quantity of information that acquire meaning thanks to effective processing algorithms and they give the power to improve processes' flexibility and effectiveness.

At present, in general, large enterprises actively pursue I4.0, instead, only a fraction of SMEs is implementing these technologies. Lack of capital, staff qualification and uncertainty in reaching high benefits represent the most common barriers among SMEs. I4.0 will bring changes all along the Value Chain of a company, the big amount of information and the good utilization of it will be useful to reach a more sustainable way of acting. Speaking about this, it is clear that sustainable manufacturing and I4.0 are two related concepts and in the paragraph number 4, the authors went in deep with the exploration of this.

3. Methodology

In the Introduction, an overview on the modalities through which practitioners may undertake a digitalization process in order to enhance CE has been provided. Narrative review and systematic overview have been used to briefly collect and summarise the already known information [9]–[11]. However, a comprehensive knowledge of the link between these two concepts has not been detailed yet. The research question that drove this work was "What is the link between CE and I4.0?". CE and I4.0 have been analysed through a systematic literature review, together with meta-analysis. The reason behind this choice is linked to the definition of the approach [12]. Moreover, systematic literature review allows to identify in an efficient way potential gaps in available academic literature and research. On the basis of the research question, appropriate research keywords have been identified.

- ("Circular Economy" OR "Closed Loop") AND ("Industry 4.0" OR "Smart Manufacturing" OR "Smart Factor*")
- ("Circular Economy" OR "Closed Loop") AND ("Industry 4.0" OR "Smart Manufacturing" OR "Smart Factor*") AND ("Barrier" OR "Barriers")

The keywords used have been structured to identify the highest number of researches focused on the topics. The keywords shown before, have been used in 3 main research databases: Science Direct, Scopus and Web Of Science. Papers have been filtered on the basis of 4 features: English language, research articles, open access and 2011 as the oldest year since "CE" has been coined that year. 90 papers have been selected for setting the body of the literature review. The answer to the first research question is provided in chapter 4.

Subsequently, the second research question has been "How the I4.0 could help the implementation of CE?". For this second part, a framework has been developed at first by analysing the integration along the SCs actors and then at factory level. For each level of detail, the role of I4.0 technologies have described in detail. Subsequently, the framework has been quantified by formalising the objectives of the conjectured firm, its related constraints and the objectives of SC actors. Since multiple goals have been identified and most of the constraints were composed by Boolean variables, the authors relied on a MOILP approach. In fact, such approach is specifically designed to address this kind of problems. The detailed answer to the second research question is provided in chapter 6 and supported by a set of interviews in order to carry out a first pilot assessing.

4. Circular Economy and Industry 4.0

4.1 CE and I4.0 - Introduction

[8] affirmed that I4.0 and CE *"are candidates to be two sides of the same coin"*. There is a link between the development of a circular paradigm and the affirmation of the new technological evolution: on one side, CE is designed to be regenerative by itself, the biological cycle has to come back to the biosphere and the technical cycle must be treated to re-enter in the environment with the minimum impact [13]. On the other hand, the I4.0, due to the increased interconnection of companies and resources, will encourage the introduction of new BMs focused also on environmental and social aspects, working on human and environment well-being [8]. Hence, the implementation of a circular paradigm is strictly related with the new technological development, digitalization can boost the transformation towards more sustainable BM, it can help closing the material loops by providing information on the availability, location and condition of products.

Moreover, it can help in achieving waste minimizations and transaction costs [14]. Smart and connected products allow producers monitoring and optimizing products' performances; also, predictive maintenance will be possible, increasing products reliability and the possibility of extending products lifetime.

Thanks to data and algorithms, service tasks and travels routes are optimized, the SC will be more synchronized, the energy consumption will be optimized in respect of the environment. In this sense, two technologies can be considered as enablers to ensure this: IoT and BD [14]. Within CE context, IoT can use information generated by sensors to connect stakeholders across the SCs, they could act as dynamic feedback control loops. Interconnected SCs enable to extend the product lifecycle management beyond the producers' boundaries [15]. On the other hand, BD analytics is seen as an effective approach for giving meaning to the large amount of information recorded by IoT, to enable better decision making [16].

Among all the I4.0 technologies available at present, also Cloud Manufacturing (CM) and Additive Manufacturing (AM) turns out to be highly promising for a concrete implementation of CE in the manufacturing context.

In order to clarify the synergies of combining I4.0 technologies with CE framework, the authors summarized the findings previously written in Table 1.

Table 1. Factors of connections between CE and I4.0

CE and I4.0	IoT	Big Data	Cloud	AM
Process Optimization	X	X	X	
Efficient Resources Usage	X	X	X	X
Higher Labour Productivity	X		X	
Higher Product Quality	X	X	X	X
Lower Time to Market		X	X	X
Supply Chain Interconnection	X	X	X	
Supply and Demand Matching	X	X	X	X
Improved Inventory Management	X	X		X
Assets Lifecycle Extension	X	X		X
Product Lifecycle Extension	X	X		X
Reduce Environmental Emissions	X	X	X	X
Energy Consumption Optimization	X	X	X	
Productive Cost Reduction			X	X
Waste Reduction	X			X
Remanufacturing Support	X			X
Improved Production Flexibility			X	X

4.2 CE and I4.0 - Cloud and CE

Cloud computing and cloud manufacturing are considered by companies as an effective solution to get the work done at low cost and with less effort. Cloud technology not only reduces costs but it also provides positive environmental externalities since resources are shared among several companies and used efficiently [17]. Companies that convert their business in favour of cloud computing will be able to remarkably reduce energy consumption and carbon emissions level, servers and data centres should be replaced by virtualized ones, computational power can by hired from cloud infrastructures [18]. [18] identified 4 key drivers of Cloud Computing's environmental footprint reduction, namely: Dynamic Provision, Multi-Tenancy, Server Utilization and Data centre efficiency. In fact, thanks to cloud dynamic allocation the capacity is managed more diligently reducing inefficiencies. Moreover, the cloud providers serve simultaneously multiple companies on the same server infrastructure, the same instances are shared between multiple organizations reducing the environmental impact. Similarly to the multi-tenancy feature, the higher utilization rate of server infrastructure would lead to higher performance levels and utilization. Finally, data centres are optimized for power efficiency, their infrastructure and equipment is typically innovative and environmental friendly as much as possible [18].

4.3 CE and I4.0 - Additive Manufacturing (AM) and CE

Because of its high efficiency and effectiveness, AM has to be cited as one of the key enablers in the transition towards a circular framework. AM technologies typically follow a customized single part production principle, thus overcoming the conventional design guidelines. With this technology, the concept of *economy-of-one* becomes possible against the concept of *economy-of-scale* [19]. This technology creates intricate parts more efficiently, it conserves energy, resources and emissions. The precise addition of material also minimizes waste for a reduced environmental footprint [20]. 3D printing can offer companies new opportunities to produce spare parts closer to the end-user, in this way also the physical goods transportation can be reduced as well as the related emissions. Then, AM is supporting the effective implementation of the remanufacturing practice. In addition, this approach generally requires less amount of resources for production, the intensity of physical flows is reduced and several intermediaries in production chains are eliminated, thus shrinking the SC.

Finally, AM offers maximum usage of materials because of the ability to reuse raw materials like powder and resin that have not been sintered during the productive process [21].

5. Gap identification and Development of the framework

From the literature analysed, it emerges that CE and I4.0 represent a big opportunity for manufacturing in business value creation and in the transition towards a more sustainable industrial way of acting. A lot of concrete examples are present in the current literature, but they do not provide a concrete support in the transition towards more sustainable BM. The authors identified this lack of information as the literature gap to be filled, therefore in this contribution it is proposed a detailed and concrete theoretical BM that uses I4.0 technologies to reach CE goals. In particular, the framework deals with a specific BM but it has been proposed keeping a perspective replicable in many other contexts. It is based on an objective function and a list of constraints to be respected. The variables considered could be kept as a driving tools for different type of companies and several business situations.

Despite, with the advent of the fourth industrial revolution, the distinction between service sector and good-producing sector is increasingly becoming blurred through new concepts such as the PSS [22]. In this work, the authors have focused on those Industries traditionally belonging to the second category. The framework has been designed for manufacturing sector. Due to the vastity of processes in which the model proposed is involved, the authors have opted for focusing on processes involving material flows that occur within the factory. Concerning information and data flows, the focus has been on the phases that take place outside the factory since the exchange of information among different business entities prove to be more critical when adopting I4.0 [23]. Finally, only the most critical areas on the manufacturing industry that would be impacted the most by the solution conjectured have been chosen, namely: Planning and Control, Production, Inventory Management, SC management and coordination, Suppliers and Customer Management. Cloud configuration, namely Manufacturing as a Service (MaaS), covers a key role in the development of the framework as it represents the cornerstone on which the model interacts with all the actors involved. The Cloud Provider (CP) acts as node linking among SCs that otherwise would not interact in any form. This choice is due to the higher number of models already available in literature and business addressing the issue of CE even for the consumer market and also because of the goal of CM itself. In fact, by offering production resources and so capacity, at present, the target for such a service is still oriented to the business rather than the final consumer [24]. The CP proposed has been designed as able to provide 2 different services, disposal of waste and the supply of production capacity (MaaS). In particular, the first service (red arrow in Fig. 1) is meant for the introduction of wastes in the "node".

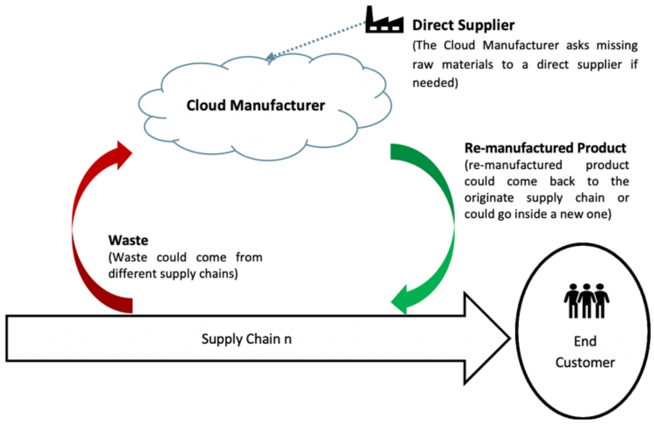

Fig. 1 Representation of the material flows of the model

Shifting the focus on the production processes that occur once the wastes are collected in order to be transformed into new goods to be reintroduced into the loop again, AM becomes the crucial I4.0 enabling technology. The main advantage of AM consists in the possibility to reproduce basically any shape starting from a design in the for of file to be read by the CPS. This allows the factory to be flexible and capable to ensure the customer an outstanding variety of designs, potentially uniqueness of goods and so to lead to almost complete personalization of physical goods at reasonable cost and without the need for partnerships with suppliers that necessarily imply also Relationship Specific Investments, risk of lock-in and lead to an overall rigidity of the SC. As stated above, the firm at the centre of the framework has the crucial role of being the node that links different Value Chains. It is so evident how different industries involved in the production of different products will also generate different kind of wastes. According to the outcomes of the pilot assessment, the variety of waste generated can be defined by 6 main variables:

1. Different raw material in input
2. Different status of the waste
3. Different stages in which the waste is generated
4. Different processes undergone by the good before becoming waste
5. Different designs and size of the waste
6. Waste can be either constituted by 1 single material or the result of different materials assembled together

For this reason, prior to the introduction of the wastes collected into the production process it is necessary a preliminary processing in order to transform this variety of wastes into standardized or homogeneous form of new raw material. Hence, a first distinction between assembled good and homogeneous material has to be made. The first category would require a disassembly phase to separate the components. Subsequently, according to the material to process and the kind of 3D printer used, raw material should be transformed into standard form, namely powder, wires, bars etc. through traditional methodologies such as shredding, melting, moulding etc. [25].

Once the new RM obtained are available in stock, the smart factory conjectured would be able to print, finished goods for its customers by adopting a Pull approach. The only constraint given would be related to the materials to be used. However, since the customer would also be suppliers of the provider, or at least would belong to the SC by which the Cloud provider supplies its RM, the authors deem reasonable to suppose that the risk of not matching material specifications is negligible. This risk is also reduced when considering the characteristic of the provider of interacting with multiple SCs thus increasing the possibility to adapt material specifications of each RM to at least one or few sectors. To conclude, some assembly activities could be implemented in the final phases that take place in the smart factory in order to provide the customer with more complex or high-value products at reasonably higher margin. Fig. 2 shows the internal processes described which are meant to take place within the top cloud in Fig 1

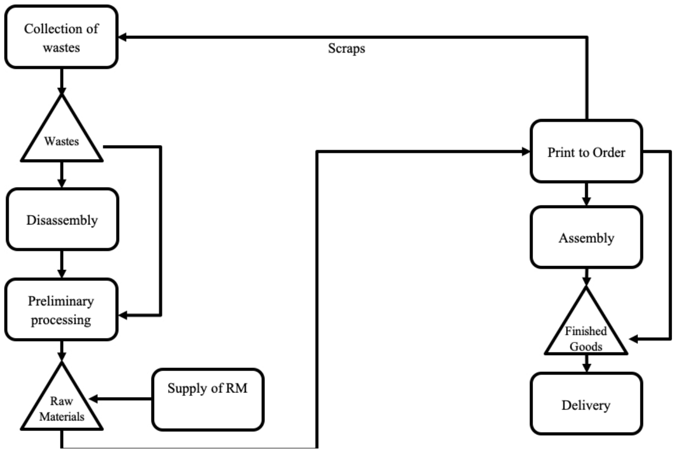

Fig. 2 Main phases of the production process

Once defined the framework in a descriptive form, now it is worth focusing on the surrounding quantitative component. As mentioned above, the choice of relying on a MOILP is due to its peculiar capability to address problems characterised by multiple goals and also by its characteristic of being a method designed to solve problems with zero-one decision variables [26]. Moreover, framework's variables are discrete and well defined, MOILP is usually implemented in these contexts. The figures below show briefly the structure of the formulas developed to assess the model.

Nomenclature

AC_d: available capacity for activity d-th;
AR_b: Cost of Advanced Robot, or similar, b-th;
AR_l: investment in Advanced Robots, or similar, l-th;
$B_i = \begin{cases} 1 & inventory\ of\ waste\ i-th\ is = 0\ (stockout) \\ 0 & inventory\ of\ waste\ i-th\ is > 0 \end{cases}$;
C_{3PL}: Logistics cost of the third party logistics provider
c_i: unitary cost of material i-th.
$c_{d;c}$: production capacity demanded by customer c-th for activity d-th.
$c_{d;j}$: production capacity demanded by customer j-th for activity d-th;
C_{RM}: unitary cost of supplying the CP for the j-th firm;
$C_{RM;i;j}$: Cost of supply of material i-th for firm j-th
CL_A: Cost of labor for assembly activities;
CL_D: cost of labor for disassembly activities;
CMN_k: cost of maintenance or generic asset k-th;
CO_d: setup time needed to fulfill the demand of resource/activity d-th.
CSU_k: set up cost for generic asset k-th;
D: Demand
d_n: unitary cost of n-th alternative disposal
E_k^i: unitary cost of energy for processing waste i-th on generic asset k-th;
e_i^f: f-th unitary externality (benefit or cost) for waste of category i-th.
FC: Fixed costs
FG_z: unitary cost of FG z-th;
M_a: Cost of machinery a-th;
M_h: cost of machinery h-th (excluding investments in AR);
MC_x: Maximum Capacity of Inventory of waste (W), RM or FG
O_A: Other investments linked to assembly activities;
O_D: other investments linked to disassembly activities;
p: Unitary price
p_d: unitary fee for activity d-th;
q_w^W: average inventory level of waste w-th;
q_y^{RM}: average inventory level of RM y-th;
q_z^{FG}: average inventory level of FG z-th.
RM_i: quantity of material i-th purchased;
RM_y: unitary cost of RM y-th;
S_x: Volume of waste w-th, RM y-th or FG z-th;
t_a: time of full amortization of machinery a-th;
t_b: time of full amortization of AR, or similar, b-th;
t_h: time of full amortization of machinery h-th;
t_l: time of full amortization of AR, or similar, l-th;
$\bar{t}_O$: average time of full amortization of other investments linked to assembly/disassembly activities;
VC: Variable costs
W_i: quantity (tons) of waste belonging to category i-th collected by the CP
$W_{i;j}$: quantity of waste i-th provided by firm j-th;
W_w: unitary cost of waste w-th:
W_k^i: quantity of waste i-th to process on generic asset k-th;
i: material i-th; j: firm j-th; k: generic asset;

Name	Formula
Supplier's Feasibility	$C_{RM;i;j} < \min(d_1; \dots; d_n)$
Generic firm's EBIT	$EBIT = p * D - VC * D - FC$
Costs of "new" Raw Material	$CRM = \sum_i B_i * RM_i * c_i$
Costs of Disassembly	$CD = \sum_h \frac{M_h}{t_h} + \sum_l \frac{AR_l}{t_l} + \sum_k \left(\sum_i E_k^i * W_k^i + CMN_k + CSU_k \right) + CL_D + \frac{O_D}{\bar{t}_O}$
Costs of Preliminary Processing	$CPP = \sum_m \frac{M_m}{t_m} + \sum_m \left(\sum_{kw} E_m^w * W_m^w + CMN_m + CSU_m \right) + CL_{PP} + \frac{O_{PP}}{\bar{t}_{PP}}$
Costs of Printing	$CPr = \sum_p B_p * \left(\sum_i E_p^i * D_p^i + \frac{M_p * n_p}{t_p} + CMN_p + CSU_p \right) + CL_{Pr} + \frac{O_{Pr}}{\bar{t}_{Pr}}$
Cost of Assembly	$CA = \sum_a \frac{M_a}{t_a} + CL_A + \sum_b \frac{AR_b}{t_b} + \frac{O_A}{\bar{t}_O}$
Stock Holding Costs	$SHC = \sum_w W_w * q_w^W + \sum_y RM_y * q_y^{RM} + \sum_z FG_z * q_z^{FG}$
Logistics Costs	$LC = \sum C_{3PL}$
Revenues from collection of wastes	$R_W = -\sum_j \sum_i C_{RM;i;j} * W_{i;j}$
Revenues from MaaS	$R_{MaaS} = \sum_d \sum_j p_d * c_{d;j}$
Production Feasibility	$\sum_j c_{d;j} + \sum CO_d \le AC_d \quad \forall d$
Physical Material Waste	$PMW = \sum_i W_i$
Environmental Profit	$EP = \sum_i \sum_f W_i * e_i^f$
Environmental Feasibility	$\sum_f W_i * e_i^f \ge 0 \quad \forall i$
Inventory Feasibility	$\sum_w S_w \le MC_w$
	$\sum_y S_y \le MC_{RM}$
	$\sum_z S_z \le MC_{FG}$

Fig. 3 List of formulas developed in the framework

The quantitative formulation of the framework has been thought as a MOILP. Hence, starting from the determination of the objective function and subsequently the explication of constraints and variables, the conclusive model is shown.

$$(P) \begin{cases} \max R_W + R_{MaaS} - \text{Economic Costs} + EP \\ \max EBIT_k \quad \forall k \end{cases}$$

Constraints:

$$\text{Economic Costs} = NSHOC + CRM + CD + CPP + CPR + CA + SHC + LC$$

$$R_W + R_{MaaS} - (NSHOC + CRM + CD + CPP + CPr + CA + SHC + LC) \ge 0$$

$$\sum_f W_i * e_i^f \ge 0 \quad \forall i$$

$$\sum_j c_{d;j} + \sum CO_d \le AC_d \quad \forall d$$

$$\sum_w S_W \le MC_W$$

$$\sum_y S_y \le MC_{RM}$$

$$\sum_z S_z \le MC_{FG}$$

$$C_{RM;i;j} < \min(d_1; \dots; d_n) \quad \forall i, \forall f$$

$$\Delta ROI_c \ge 0 \quad \forall c$$

$$W_i^j \in \{\text{Printable materials}\} \quad \forall i, \forall j$$

6. Conclusions and Limitations

This research has focused on the technical cycle defined by[2], and on how I4.0 technologies could help in reaching a restorative and regenerative system by design. In particular, answering the research questions, the authors could highlight the potentiality of the integration between the two concepts. It is showed that understanding CE and I4.0 potentialities stay at the basis for maximizing the sustainability value obtainable from business, since environmental goals need powerful instruments to manage their intrinsic high complexity. The authors supported the general awareness about synergies between I4.0 and CE detailing a concrete and quantitative BM. It can be taken as a reference by companies operating in different sectors. Regarding the limits of the model proposed (Fig. 4), the first is the focus on economic and environmental sustainability rather than the whole TBL. The social responsibility of the actors involved has not been considered in the formulation. The second limit is related to the choice of not addressing in detail the thematic of HR Management and Logistics in terms of implications that the model could have as well as detailed analysis of overall dynamics, variables and costs. Regarding the analysis of the framework itself, 2 main limits to the implementation of the framework in a real business context have been identified. The model has been designed under the hypothesis that the material flows of wastes and the demand for production capacity have already reached reasonably high volumes, namely the system is proceeding at operating speed. However, the lack of sufficient volumes in input has been solved with the introduction of a direct supplier. Secondly, the issue of trustworthiness and IP protection has not been solved thus still representing an open challenge of CM. Other limits highlighted are colour limitation of re-worked plastic goods, averagely longer CT of AM compared to traditional moulding processes and trustworthiness. A non-structured validation of the model has been performed by interviewing three manufacturing companies, a multinational firm, an SME and a small enterprise. The validation has covered five areas: collection of wastes, first phase of the internal process, second phase of the internal process, formulas and concept. All these limitations and a structured validation of the model may be valuable ideas for future research.

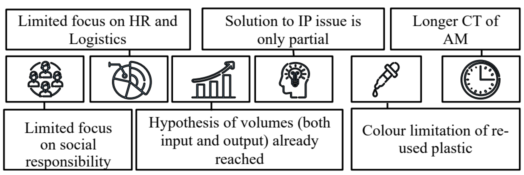

Fig. 4 Limitations of the framework

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