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SUSTAINABILITY STRATEGIES, INVESTMENTS IN INDUSTRY 4.0 AND CIRCULAR ECONOMY RESULTS

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ABSTRACT

Environmental sustainability has increased its relevance within business strategies and innovation in particular while circular economy (CE) is receiving growing attention as a new paradigm of production and value creation. Low attention has been given to explore the relationship between digital transformation of business processes *via* industry 4.0 technologies and CE strategies. On the one hand, digital manufacturing supports efficient use and control of resources. On the other hand, such technologies improve product life cycle management (through IoT or big data) and new business models (product-as-a-service). The paper explores the relationship between environmental sustainability strategies, technological investments in industry 4.0 and green outcomes, based on unique data gathered through an original 2017 survey on a sample of more than 1,100 Italian firms. Results show the positive relationship between green drivers and green outcomes for firms adopting industry 4.0 technologies, both in terms of eco-efficiency and circularity. Investing in digital manufacturing, smart products, and higher variety of 4.0s technologies characterize adopters with green outcomes. Having a clear green strategy, ICT propensity, domestic production, and low customer dependency are factors positively related with green outcomes for adopters.

Keywords: digital manufacturing, industry 4.0, circular economy, sustainability, eco-efficiency

SUSTAINABILITY STRATEGIES, INVESTMENTS IN INDUSTRY 4.0 AND CIRCULAR ECONOMY RESULTS

INTRODUCTION

Investing in environmental sustainability has become a priority for a growing number of firms. Attention toward a better use of resources and positive environmental outcomes of business activities has spread across firms of different size as well as across industries with relevant implications for innovation, value chain organization, and competitiveness in general (Bansal & Roth, 2000; Nidumolu, Prahalad, & Rangaswami, 2009; Porter & Kramer, 2006; Wagner & Schaltegger, 2004).

Within the theoretical debate on the sustainability issue, recent studies have started to discuss about circular economy (CE) as a new sustainable paradigm (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Webster and MacArthur, 2017). According to those authors, CE is specifically characterized by focusing on better use of resources pushing the entire economic system to adopt a circular approach (waste as a resource) instead of a linear one. By closing the loop (Krikke & Blanc, 2004; Yeo, Pepin, & Yang, 2017), firms can enhance value creation by multiplying input generation, extending product life cycle, and avoiding leakages. The CE approach is directly connected to new business models, where firms do not offer simply products, but product-service-systems (Tukker, 2015).

The CE scenario stresses the relevance of manufacturing processes and how they are organized within the firm and across the value chain with suppliers (Bonilla, Almeida, Giannetti, & Huisingh, 2010). By focusing on how products have to be made in a CE perspective, firms can redesign their sourcing strategy as well as their innovation processes to cope with a more sustainable use of resources. Firms can reduce waste through eco-design but also through a more appropriate control over their production leakages. Waste can become a new input for the firm itself, but also for other firms, enlarging the use of waste-as-a-resource in other industries through innovation opportunities. Besides manufacturing, CE-oriented firms are also interested in monitoring product use within the consumption sphere to further enhance product lifecycle or waste recovery ((Bakker, Wang, Huisman, & Den Hollander, 2014). In this scenario, customers' involvement is increasing, where consumers are aligned with firm's environmental goals and are often eager to actively participate to product innovation.

The new emerging technological scenario labeled "industry 4.0" (Reinhard, Jesper, & Stefan, 2016) can offer additional strategic tools to firms achieving sustainability goals. There are new digital technologies available that are transforming manufacturing processes (from robots to additive manufacturing), its organization (i.e. big data) and products (Internet of Things - IoT). Such technologies increase firms' capabilities to deeply monitor input selection and use during the production process, to track input acquisition from suppliers or product use at the customer level. In this context, few scholars are debating about the positively link between sustainability strategies and the new digital paradigm (Chen et al., 2015; Kohtala & Hyysalo, 2015), within a larger emphasis provided by international institutions (Ellen MacArthur Foundation, 2016) or consulting firms (Lacy, 2015). Further knowledge has to be developed in order to capture how those two "revolutions" – CE on the one side and digital manufacturing on the other side – are related.

The paper investigates the relationship between investments in industry 4.0 technologies and environmental sustainability strategies, by comparing firms based on their degree of explicit sustainability-oriented strategies and the environmental outcomes eventually achieved. Our study is based on an original dataset related to primary data collection carried out by the authors between

May and December 2017 on a sample of more than 1,100 Italian firms. Results show the positive relationship between green drivers and green outcomes related to investments in industry 4.0. Moreover, adopters with green outcomes have a different business profile compared to non-green firms. Final theoretical and managerial implications are provided.

THEORETICAL FRAMEWORK

Environmental strategies and circular economy

Literature on environmental strategies has explored how firms oriented to achieve environmental goals through their business activities under multiple perspectives.

A first area of interest refers to innovation. Sustainability-oriented firms redesign their innovation approach in order to take into account the environmental consequences of their production, by focusing on a better or diverse input selection and use or by investing in order to reduce product impacts at the end of its life (i.e through product modularity) (Jay & Gerard, 2015). Eco-innovation is characterized by open innovation dynamics (Cainelli, De Marchi, & Grandinetti, 2015), where specific actors such as KIBS can have a crucial role in supporting innovation trajectories and sustain firm's capabilities related to green goals. Suppliers are also key partners in environmental sustainability strategies. On the one hand, specialized suppliers provide key knowledge to the firm in terms of selected material or components, in addition to positive green practices such as just-in-time solutions and the like. On the other hand, green supply chain management strategies allow the firm enhancing suppliers' capabilities through knowledge transfer or mentoring practices in order to achieve superior environmental performance within the whole value chain (De Marchi, Di Maria, & Ponte, 2013; Frey, Iraldo, & Testa, 2013; Srivastava, 2007).

In the relationship with the market and specifically with final customers, environmental-oriented firms may invest to provide full information about internal green practices and investments at the product or process level, in terms of green marketing strategies – also within CSR practices oriented to all the stakeholders (Acquier, Valiorgue, & Daudigeos, 2015; Chan, He, & Wang, 2012; Porter & Kramer, 2006). The attention toward the environment can lead to a deep transformation of the firm's offering whenever the firm adopts new business models to couple economic and environmental sustainability (Lacy & Rutqvist, 2015).

Within this theoretical scenario, new recent contributions focused on CE have been developed to propose a new economic paradigm substituting the linear mechanism of "make, use, dispose" with a closed-loop approach in the use of resources ("reduction, reuse, recycle"). According to this emerging framework (Geissdoerfer et al., 2017; Ghisellini, Cialani, & Ulgiati, 2016) the entire value chain of the firm - from suppliers to final customers – as well as the whole business (and natural) ecosystem can benefit from an integrated approach on the production, selection, and use of resources as inputs as well as outputs (products). According to the Ellen Mac Arthur Foundation CE is an industrial system that is restorative by design, in the sense that it preserves and enhances natural capital, optimizes resource yields and minimizes system risks by managing finite stocks and renewable flows (Webster & MacArthur, 2017).

As described by (Ghisellini et al., 2016) there are multiple actors involved beyond the single company, where also consumers play an active role with their actions during the use of the product and at its end of life - in addition to the meso (i.e. eco-industrial parks) and macro (i.e. cities or regions) level. CE challenges innovation processes of environmental-oriented firms in the direction of lower use of resources or waste-based inputs. In this direction, it extends the supply base beyond the established suppliers, to involve also new ones based on potential new inputs coming from waste or reuse practices (Lacy & Rutqvist, 2015; Webster & MacArthur, 2017). Moreover, CE emphasizes efficient manufacturing processes in terms of leakage avoidance but also shortening supply chains (i.e. distributed manufacturing processes). The shift towards CE can offer positive rewards from environmental and economic points of view.

Industry 4.0 and sustainability

In this scenario recent technological trends with the rise of new digital technologies impacting on production and use can offer important tools for firms adopting CE strategies. A broad set of new digital technologies – from 3D printing to robotics, from Internet of Things (IoT) to artificial intelligence – are reshaping business activities, innovation dynamics, business models, as well as business ecosystems (OECD, 2017). According to some authors (Roblek, Meško, & Krapež, 2016) a new industrial revolution is emerging, changing the role of customers – that can become *makers* (Anderson, 2012) - also reversing the order in the value chain between manufacturer and customer in product idea generation and manufacturing (*direct digital manufacturing*) (Chen et al., 2015).

Industry 4.0 technologies may support environmental sustainability from multiple perspectives in terms of the value chain (inputs, process, product management) (Stock & Seliger, 2016). The discussed technological scenario supports firm' strategic approach specifically oriented to corporate social responsibility ((Porter & Kramer, 2006) or corporate sustainable development ((Bansal, 2005; Bansal & Roth, 2000), under the perspective of lower use of resources as inputs, reduced waste generation or pollution consequences during production or consumption (Chen et al., 2015; Yeo et al., 2017).

Few recent studies have depicted how direct digital manufacturing – and specifically 3D printing – can sustain a shift toward the new emerging CE paradigm. Direct digital manufacturing opens opportunities for *distributed* manufacturing processes, reducing the distance between supply, production, and use as well as increasing the level of product customization without losing efficiency (Weller, Kleer, & Piller, 2015). Also operations become more efficient (Sanders, Sanders, Elangeswaran, & Wulfsberg, 2016), in addition to lean and more agile supply chains (Nyman & Sarlin, 2014).

Moreover, from the CE perspective, the rise of powerful information management based on big data, artificial intelligence, and IoT solutions increase firm's control over internal as well as external processes and relationships with actors of the value chain, partners in the business ecosystems, and consumers (Adner, 2006; Huberty, 2015). Firms can exploit information about product use to enhance product lifecycle, improve durability or increase value generation based on new services (Porter & Heppelmann, 2014). In fact, new digital technologies allow firms reshaping their offering through new business models based on servitization (product-as-a-service) (Coreynen, Matthyssens, & Van Bockhaven, 2017).

Despite these analyses, it is not fully explored both theoretically and empirically the link between the green strategic motivation of the firm – in the context of CE – and investment in industry 4.0 and the consequences in terms of achievement of better environmental results. Based on the above-mentioned theoretical premises, we are interested in investigating if, and under what circumstances, the adoption of industry 4.0 technological solutions can lead to improved environmental outcomes, also considering for the environmental orientation of firms. Also, we are interested in understanding what are the characteristics of the companies that implement circular economy strategies *via* the introduction of industry 4.0 technologies. To best of our knowledge, no research has been developed so far in this direction, in particular measuring empirically the connection between sustainability strategies and industry 4.0 technologies and related green (and CE) results.

METHODS

The study focuses on the firms of Made in Italy sectors located in the North of Italy. The choice is due to the relevance they have for the Italian Gross Domestic Product (GDP) and for the national competitiveness in the international markets. The universe consisted of 8,022 manufacturing firms drawn from AIDA database selected in the industry considered (namely automotive, rubber and plastics, electronic appliances, lightning, furniture, eyewear, jewelry, and sport equipment) and with a turnover higher than 1 Ml Euro (in industries characterized by the presence of industrial districts[1] firms with a turnover lower than 1 Ml Euro have been also considered).

Based on a structured questionnaire submitted through CAWI methodology to entrepreneurs, Chief Operation Officers or managers in charge for manufacturing and technological processes, firms have been contacted and 1,146 firms (14.3% of the universe) answered to the survey. The questionnaire assessed the adoption of the following technologies: (1) Robotics, (2) Additive manufacturing, (3) Laser cutting, (4) Big data and cloud, (5) Scanner 3D, (6) Augmented reality and (7) IoT and Intelligent products. These technologies are those that more than others fit the strategic needs of the manufacturing firms both in B2C and in B2B markets (Sanders et al., 2016). The subsequent questions aimed assessing the motives underlining the adoption and the no-adoption of the technologies mentioned before. For the adopting firms, the questionnaire continued assessing (a) the output of the production process (products for final customers vs. products for business clients), (b) the activity of the value chain where the firm focused the investment in the new technologies and (c) the results obtained. Tables 1 and 2 show descriptive statistics on the firms interviewed.

Insert table 1 here

[1] Lightning, eyewear, jewelry, and sport equipment.

Insert table 2 here

In the following we propose a dual analysis. In order to investigate the relationship between industry 4.0 technologies (from now on 4.0s) adoption and sustainability, and more in particular CE, outcomes, we implement multivariate analyses of variance (chi-square test and t-tests). Then, to investigate the features of the firms that did achieved sustainability results following 4.0s we run logit regressions.

Thought the questionnaire was not built only to address the link between 4.0s adoption and sustainability strategies, it collects several useful information to assess the relevance of sustainability issues for the companies as well as the sustainability effects of the technology adoption. In particular, the question asking the motivation of the adoption of 4.0s was used to build the variable GREEN DRIVER. The companies were asked to rate, on a scale from 1 (null) to 5 (very much), the importance of 11 items as motivations to invest in 4.0s: i) efficiency of internal processes, ii) increase product variety, iii) opening new market opportunities, iv) maintain production in Italy, v) reshoring, vi) maintain international competitiveness, vii) imitation of competitors, viii) increase customer service, ix) to respond to request by large buyers, x) to adapt to an industry standard and xi) environmental sustainability. The dummy GREEN DRIVER takes values 1 if the company reported that environmental sustainability was a very (4) or very much (5) relevant motivation for the introduction of 4.0s. Also, companies were specifically asked to rate, again in a scale from 1 to 5, if the introduction of 4.0s drove any environmental sustainability impact, considering for each of the following aspects:

i. Reduction of production waste;
ii. Reduction of inputs used (including energy, materials,…);
iii. Reduction of process-related environmental-impacts (e.g., on air, water,…);
iv. Adoption of more sustainable inputs (e.g., recycled or recyclable materials,…);
v. Upstream (with suppliers) or downstream (with customers) traceability;
vi. Use of firm's waste in the production process;
vii. Use of waste coming from other sectors/firms as inputs;
viii. Move toward greener suppliers.

The variable GREEN OUTCOME is a dummy taking value 1 if the company reports that the adoption of 4.0s resulted in a strong (4) or very strong (5) reduction in any of the 8 elements reported. CIRCULAR equals 1 if companies reported a strong or very strong reduction in any of the elements of the above list ranging from iv) to viii). In a similar vein, the remaining elements - ranging from i) to iii) - are used to build the dummy ECO-EFFICIENCY, which is also reporting on important reductions of environmental burdens but being more oriented toward eco-efficiency strategies than to the implementation of a CE[2] (Geissdoerfer et al., 2017). As reported in Table 4, that will be discussed in the following, the two strategies might overlap: the dummy GREEN NON CIRCULAR captures firms that have reported high environmental benefits as emerging from the variable ECO-EFFICIENCY but not any in the items included in CIRCULAR.

[2] Please note that we have purposefully adopted a conservative approach to identify companies engaging in sustainability strategies (the variables GREEN OUTCOME, CIRCULAR, ECO-EFFICIENCY), as we selected just companies that reported a high (4) or very high (5) environmental benefits following industry 4.0 adoption.

RESULTS AND DISCUSSION

In the following, we report results of the multivariate analysis of variance to investigate the relationship between industry 4.0 technologies adoption and the reduction of environmental burden of firms' activity, with special reference to the CE.

Sustainability Strategies and Outcomes

Table 3 reports descriptive statistics regarding firms that introduced 4.0s to achieve sustainability results (GREEN DRIVER) and those that achieved sustainability results because of the introduction of 4.0 (GREEN OUTCOME).

Insert table 3 here

One firm out of 4 (25.8%), of those included in our sample, reported that sustainability concerns have been among the key drivers supporting their investment in industry 4.0 technologies. This result stresses how such technologies can support explicit environmental sustainability strategies carried out by firms, where digital transformation of business activities and processes is perceived as a means for sustainability. Interestingly, the share of companies that achieved important environmental benefits following 4.0s adoption is almost double: 48.5% of the sample. While just one fourth of the companies had a clear sustainability strategy before introducing 4.0 technologies, a much larger share did recognize such an opportunity following their introduction. This is an important result since it suggests that environmental benefits can be considered a sort of 'by-product' of the investment in 4.0s, where such technologies enable firms to gain also from an environmental point of view through technological investments motivated by other reasons (the main one is related to better customer service). Moreover, it could push these firms to further pursue green strategies with a more pro-active behavior (Bianchi & Noci, 1998). Table 3 also reports the co-occurrence of GREEN OUTCOME and GREEN DRIVER: while the share of companies that failed to reach their sustainability goal is quite small (5.3%), 28.0% of the companies considered did realized a important environmental benefit that was not initially planned, or, better that was not the principal driver for the introduction of 4.0s. The results of the Pearson chi-square test suggest that we can reject the hypothesis H0, that is a significant relation between the two dummies considered does not exist.

Environmental sustainability outcomes can be very diverse. Using the classification proposed in the previous paragraph, in Table 4 we analyze the co-occurrences sustainability outcomes related to two different approaches: the first, CIRCULAR, focusing on a better use of resources to reduce environmental burden and attribute value to waste through a new paradigm of production (and consumption); the second, ECO-EFFICIENCY, being rather related to approaches aiming at reducing environmental burdens by reducing environmental costs too, improving efficiency internal to the firm. Without giving a judgment of value among the two in terms of which is the most relevant in tackling relevant environmental issues, from a management perspective it is clear that the first one might entail higher complexity, as it requires to rethink both the product and the processes and, often, the business model too (as discussed in the theoretical section).

Insert table 4 here

Our data show that 32.1% of the interviewed firms that adopted 4.0s achieved important results concerning circularity following this investment, a slightly lower share than those that reported eco-efficiency ones (36.6%). Interestingly, 1 firm out of 5 (20.9%) achieved results related to both strategies, showing how firms can obtain the complete spectrum of environmental outcomes supported by digital investments. Again, the test performed suggests that hypothesis H0, that a significant relation between the two dummies considered does not exist, can be rejected. In the following, we name GREEN NON CIRCULAR those firms that reported eco-efficiency outcomes but not circular one, being the 15.7% of the sample (21 firms).

Investments in 4.0 and sustainability outcomes

4.0s is a broad definition including many technologies, diverse in terms of the investment required, their maturity, the value chain activity in which they can be applied, the outcome that they can provide. Therefore, we are interested to understanding which of the technologies considered are better supportive of sustainability results and in particular to CE ones. The descriptive statistics reported in Table 5 are supportive of this effort, reporting the number of companies adopting the seven types of 4.0s listed, considering for the sustainability impact achieved thanks to the adoption of 4.0s. Robotics, laser cutting and big data are by far the most adopted technologies in the sample (adopted by more than 40% of the companies interviewed), whereas 3D scanners and augmented reality are the least diffused.

The comparison of the diffusion of such technologies considering for the environmental impacts achieved thanks to 4.0s adoption provides novel and interesting insights[3]. As supported by the Pearson chi-square tests, firms that did and did not report environmental benefits out of the 4.0s adoption (GREEN OUTCOMES and NON GREEN) differ significantly for the adoption of robotics and of augmented reality technologies, which are double for green firms (64.1% vs. 32.9% and 20.3% vs. 7.1%). The most adopted technology for NON GREEN is the laser cutting (adopted by 51.4% of the companies), whereas it is robotics for GREEN OUTCOMES firms (64.1%). On

[3] Caveat: sample size is small and the adoption of certain technologies, such as additive manufacturing, is still so few widespread that a cautionary approach to the analysis is needed.

average, firms that reported environmental benefits are adopting higher number of technologies (2.67 vs. 1.96 out of 7), a figure driven by the adoption of CIRCULAR firms (3.05, see Table 6). In fact, CIRCULAR firms show the highest share of 4.0s among the type of firms considered, except for IoT which is higher for companies focused just on improving their efficiency and reduce process emissions (GREEN NON CIRCULAR). Comparing green firms, CIRCULAR ones differ from GREEN NON CIRCULAR mostly for the adoption of 3D scanners (adopted by 30.2% of firms in this category vs. 0%) and of Big data technologies (58.1% vs. 28.6%).

Insert table 5 here

While firms entailing green outcomes out of 4.0s introduction adopt a wider array of technologies than non green ones, their investment is not significantly higher, if measured as incidence on firm turnover (INVESTMENT IN 4.0S, Table 6). Interestingly, as emerges from Table 6, they differ significantly in terms of the stage of the value chain for which 4.0s have been adopted. Firms that reduced environmental impacts after the introduction of 4.0s are more likely to have adopted them in the production process (83% of the firms in the first group, vs. 68% of the second). Applications of 4.0s to the New Product Development activities are lower, and quite similar across the two groups. Hence, it is not in the innovation phase that the digitalization of activities (i.e. NPD based on additive manufacturing or augmented reality) that enhance sustainability, contrary to what one would expect. On the contrary, it is in the manufacturing process the key of sustainability – both in terms of eco-efficiency and CE. Digital manufacturing based on robots (or supported by other digital technologies) leads to clear and extensive green outcomes.

Insert table 6 here

Other interesting information has been achieved by leveraging a questions asking about potential impact of 4.0s application on the product, in particular regarding the possibility to improve the product thanks to the provision of additional services (PRODUCT SERVITIZATION) and the possibility to better control the product during its use (PRODUCT TRACEABILITY). Results suggest that firms that achieve green benefits are associated with higher probability to achieve both results. In particular, traceability seems a very strong element of green firms, being adopted by almost half the firms in this category (42.0%). None of these elements differentiate between CIRCULAR and GREEN NON CIRCULAR firms: while all the means of all variables considered are higher when it comes to firms achieving circularity, differences in variance are not statistically significant.

Industry 4.0 and the profile of green adopters

At this point we are interested in understanding who are the firms that successfully improve their environmental performance thanks to the adoption of industry 4.0 technologies and what structural characteristics are more likely to be associated to higher sustainability outcomes. To this purpose we run two logit regression analyses. The first uses GREEN OUTCOMES as the dependent variable, therefore measuring the impact of the independent variables with respect to the probability for a company to achieve environmental benefits thanks to the adoption of 4.0s (both eco-efficiency and CE). The second uses CIRCULAR as the dependent variable, therefore measuring the impact of the independent variables with respect to the probability for a company to implement circular economy strategy thanks to the adoption of 4.0s (as respect to companies that did not achieve any environmental benefits or at least one benefit that we associated to CE).

Table 7 reports descriptive statistics of the variables considered in the analysis, being:

- SIZE, measured as the natural logarithm of the number of employees;
- ICT PROPENSITY, a proxy of firms propensity toward new technologies measured as a count variable, ranging from 0 to 9 if the firm has adopted from none to all of the following ICT related technologies: i) website; ii) social media (facebook, twitter,…), iii) e-commerce, iv) Customer Relationship Management (CRM), v) Supply Chain Management (SCM), vi) Enterprise Resource Planning (ERP), vii) Material Requirement Planning (MRP), viii) CAD/CAM, xi) Numerical Control Machineries (CNC);
- SHARE OF FOREIGN PRODUCTION, ranging from 0 to 100 and reporting the relative size (in value) of the production capacity located abroad with respect to Italy (either through foreign subsidiaries or foreign suppliers);
- CUSTOMIZED PRODUCTS, a dummy valuing 1 if more than half of the production of the company regards products fully customized;
- CUSTOMER DEPENDENCY, a variable ranging from 0 to 100 reporting the percentage of the turnover from the top customer;
- LOW-TECH INDUSTRIES, a dummy equals one if firms belong to low-tech industries being: i) Furnishings, ii) jewelry, iii) sportswear, iv) eyewear, v) clothing, vi) textile, vii) Leather/footwear

As reported in Table 7, firms achieving green outcomes out of 4.0s adoption (GREEN OUTCOMES) are on average larger than the other 4.0s adopters (NON GREEN), even though this result is not statistically significant as it is driven by influential observations (the three firms having more than 350 employees are part of this group). Green firms are characterized by a higher propensity toward the adoption of ICT technologies (ICT PROPENSITY). This result is related to the degree of investments in 4.0s, where prior experience or internal competences in managing digital tools may support a wider adoption of newest technologies such as 4.0s ones. Green firms are more likely to produce in Italy rather abroad (on average, they produce abroad just 4.08% of their production (in value), with respect to the 12.3% characterizing 4.0s adopted that did not achieve environmental benefits). Finally they are less likely to be dependent from large customers: the turnover from the top customer counts for 24.48% of their overall turnover, as respect to the 32.6% of the other firms considered. No significant differences are detected between GREEN NON CIRCULAR and CIRCULAR as far as the level of product customization or industry is considered.

Insert table 7 here

Table 8 reports the results of the logit regressions aiming at investigating the characteristics of the firms adopting 4.0s for sustainability outcomes (using GREEN OUTCOMES as the dependent variable) and, more in particular for circularity outcomes (using CIRCULAR as the dependent variable). Both regressions passed the test of fitness of god (Pearson or Hosmer-Lemeshow goodness-of-fit test) – the first model reports a Pearson chi2(95) of 99.49 with a p-value of 0.3561, the second a Pearson chi2(95) of 98.12, with p-value 0.3927 – and test for model specification (link test).

Insert table 8 here

Results suggest that larger firms are not more likely to achieve sustainability outcomes out of 4.0s adoption than smaller firms. SIZE do play a role, despite significant just at the 10% level, when we restrict out attention just to circular outcomes (CIRCULAR), which might be explained with the fact that to implement CE more capabilities and competences are needed because of the complexity it entails. Similarly, industry characteristics are not significantly explaining the differential impact of industry 4.0s, in terms of benefits on the environment. Rather, strategy-related elements do play a role. First, it is important the presence of a sustainability strategy within the firm. Indeed, the coefficient of GREEN DRIVER, measuring if the introduction of the technologies was purposefully aimed at reducing environmental impact, which we use as a proxy for firm's green proactiveness, is positive and significant in both models. Similarly, choices related to the location of the activities (SHARE OF FOREIGN PRODUCTION) do play a role, though significant just at the 5% level. The more firms are producing abroad, the less they are likely to introduce 4.0s resulting in environmental benefits. Interestingly, this result is not confirmed when using CIRCULAR as dependent variable: the relevance of the location of production activities is likely to be relevant mostly for firms interested at pursuing eco-efficiency strategies. Another interesting result regards the dependence of the firm from their main customers: the more a company is 'captivated' by one, large, customer, the less likely to introduce 4.0s to reduce environmental issues. This results is even more significant when considering CIRCULAR as the dependent variable: as they might entail higher uncertainty and being more complex, such types of benefits might be more effectively pursued by companies that can spread the risk over a large variety of customers and that are free in setting their own innovation agenda. The degree of customization of the products realized (PERSONALIZED PRODUCTS) does not seems to be significantly related to environmental benefit achieved thanks to 4.0s introduction.

CONCLUSION

Our study provides original results concerning the relationship between investments in industry 4.0 technologies and environmental strategies and results. As per our knowledge, it is among the first empirical analyses offering quantitative results on this issue, by exploring the link between business digitalization and sustainability with details about green impacts, technologies adopted, and investments in different value chain activities. Our evidence offers deeper understanding of how technological investment can sustain green achievements in the current debate on circular economy.

First, by providing empirical evidence, we maintain that 4.0s allow firms with clear environmental strategies pursuing their goals, being able to achieve positive green outcomes. In this respect, our research contributes to support the debate among scholars and practitioners about the positive connection between digitalization of business activities and processes and the environment. In addition, we provide proof of the fact that such technological investment may allow also firms with no direct (or explicit) green orientation – at least for what 4.0s are concerned – toward their investments in 4.0s in obtaining green outcomes. This emerging process of discovery of environmental benefits could foster those groups of adopters in elaborating green strategies in the future, based on the results already achieved *via* technological investments (Mintzberg & Waters, 1985). In this perspective, the new paradigm related to the fourth industrial revolution can strengthen the attention toward the environment also of firms that did not necessarily address this issue previously. We should also consider that adopters not driven by sustainability may not necessarily be aware of the environmental impacts driven by their technological investments, for instance because of weak measurement systems or green practices at the firm level, which could lead them (and us) to underestimate the real level of green outcome achieved.

Second, 4.0s support the achievement of a large variety of green outcomes, being more focused on eco-efficiency or related to more complex CE results. From this point of view, our research sheds further light on how firms can effectively implement CE strategies and can obtain strong environmental benefits both within the firm and in the value chain – from suppliers to customers. CE is emerging as a new imperative for firms (and for the society as a whole) (Webster & MacArthur, 2017). By investing in new digital solutions firms can gain beyond the reduction of resources, also benefiting in terms of enhanced product lifecycle management or product innovation improvement.

Third, in relation to the previous argument, firms achieving circularity are those that invest more in technologies – investing in a wide array of typologies of technologies. Except for IoT, firms with CE outcomes have systematically higher percentage of adoption for the types of technologies considered, as compared to the other firms. It is not a matter of size, but of strategies – as stated above – and of internal competences of the firms. In general, green adopters are more advanced in terms of other ICT solutions than non green firms, thus showing, on the one hand, prior experience in managing technological projects and implementing technological solutions within the organization or with suppliers or customers and, on the other hand, pro-active orientation toward technological innovation.

Fourth, our results show also important insights for what concerns the domains in which 4.0s technologies can support green outcomes. Operations confirm to be a key area in which those technologies may lead the firms in achieving positive environmental results (Sanders et al., 2016). Attention on how to better improve production through digitalization manufacturing can play a remarkable role for environmental sustainability (e.g., supporting important energy and material savings or reducing waste). At the same time, the geography of production matters. Being close to where manufacturing occurs and control manufacturing processes – both internally or through appropriate supply chain management strategies – allows obtaining green outcomes with respect to adopters with higher share of foreign production. This is consistent with studies discussing about the advantages of short supply chains environmentally wise when it comes to complex or innovative products or processes (De Marchi, Di Maria, & Ponte, 2013), but also suggesting that, through digital technologies and digital manufacturing, firms can improve their manufacturing processes (and productivity) maintaining value-added production in advanced (high-cost) countries by also obtaining green results; a win-win-win outcome for the economic, social and environmental domain. On the contrary, investment in 4.0 technologies for new product development and innovation seems to be not relevant for sustainability. Despite few studies exist supporting the opportunity to improve sustainability based on digital fabrication in relation to design (Agustí-Juan & Habert, 2017) our research does not seems to provide evidence in this respect.

Digital technologies can support modification to the product that might improve sustainability as well, from marketing and customer relationship management perspectives. Product servitization and traceability – also in relation to IoT investment strategies (Manyika et al., 2015) – are two important characteristics of emerging business models related to circularity. Our research shows that, in general, investing in this direction for product enhancement can support green outcomes – a result that is not necessarily limited to firms with circular outcomes but also to firms oriented toward the achievement of eco-efficiency results.

From a theoretical point of view, an important contribution of our study is related to the fact that the main difference emerges between firms with green and non-green outcomes based on investments in 4.0s – where circularity refers to a specific, more detailed distinction within the green domain. In this respect, CE embraces and enlarges the eco-efficiency strategy, where the reduction of inputs and reduced use of resources is one of the pillars of CE. Further attention should be given to explore how single technologies in the various steps of the value chains might provide support concerning CE outcomes, as what stands behind the industry 4.0 label is a set of very diverse technologies. From a managerial point of view, our study provides managers with support about the positive consequences in terms of sustainability of investing in 4.0s, where specifically digital investments driven by green strategies is effectively providing green results. Firms with CE outcomes are also more technologically advanced – both under the 4.0s and ICT perspectives – showing the innovativeness of those firms and the internal capabilities and competences they may have with respect to firms with non-green results.

Future research should also focus on better disentangling the relationship between industry 4.0 investments and sustainability by taking into account the corporate environmental sustainability strategy. One of the main limitations of our study is, in fact, that our analysis focuses only adopters of 4.0s technologies. Another limitation is the fact that we explore green strategies and green outcomes in the context of industry 4.0 by considering the ongoing research on CE, which it is rooted in a broad set of theoretical contributions (Geissdoerfer et al., 2017). Further elaboration of our study will be devoted to better include our analysis in the theoretical frameworks of the firm behavior (Barney, Ketchen, & Wright, 2011; Teece, 2007). Additional research should also consider more deeply how to measure the impact of 4.0s to green outcomes and specifically for circularity.

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TABLES

TABLE 1

Descriptive statistics of the sample

Sample			
Firms interviewed		1,149	
Firm’ size (EU revenue class)			
Under million (<1mln)		14.8%	
Micro firms (1mln<€<2mln)		29.1%	
Small firms (2mln<€<10mln)		41.3%	
Medium firms (10mln<€<50mln)		12.8%	
Big firms (>50mln)		2%	
Industry			
Rubber and plastic goods		5.4%	
Electrical Motors and parts		23.1%	
Electric lighting		6.3%	
Motor vehicles and trailers		10%	
Furniture		5.5%	
Jewells		12.4%	
Glasses and lenses		4.5%	
Sport goods		4.5%	
Clothing		9.9%	
Textile		7.3%	
Leather/Footwear		11.1%	
Technologies adoption	**Total**	**B2B**	**B2C**
Firms adopting at least one of the digital technologies listed in the questionnaire	197 (17.15%) (% of the sample)	118 (59.9%) (% of adopters)	79 (40.1%) (% of adopters)

TABLE 2

Characteristics of 4.0s adopters

Turnover (average 2016)	14,745 Ml Euro (min 5 – max 321,167)
Employees (average 2016)	56.8 total 35 in operations 4.5 in R&D 2.4 in marketing
% Export on turnover (average 2016)	47.5% (first export market: 28.1%)
R&D expenditure (% on turnover)	6.3%
Production output	47.4% bespoke products 34.3% standard products 18,3% customizable products
Production location (value)	63.3% Region 29.1% Italy 7.6% Abroad
Supplier location (% on total number of suppliers)	35.8% Region 46.8% Italy 17.4% Abroad

TABLE 3
Sustainability motivations and outcomes of industry 4.0 technologies adoption

		Green driver		
		No	**Yes**	**Total**
Green outcomes	**No**	61	7	68
		46.2%	5.3%	51.5%
	Yes	37	27	64
		28.0%	20.5%	48.5%
	Total	98	34	132
		74.2%	25.8%	100%

Note: Chi-square statistics for statistical significance: Pearson chi2(1) = 17.5371, Pr = 0.000

TABLE 4
Sustainability outcomes achieved thanks to adoption of industry 4.0 technologies

		Eco-efficiency		
		No	**Yes**	**Total**
Circular	**No**	70	21	91
		52.2%	15.7%	67.9%
	Yes	15	28	43
		11.2%	20.9%	32.1%
	Total	85	49	134
		63.4%	36.6%	100%

Note: Chi-square statistics for statistical significance: Pearson chi2(1) =22.2491, Pr = 0.000

TABLE 5
Industry 4.0 technologies adoption and sustainability outcomes

	Non green	Green outcomes	Sig.	*of which* Green non circular	*of which* Circular	Sig.	Total
Robotics	23	41	**	12	29		86
	32.90%	64.10%		57.10%	67.40%		43.70%
Additive manufacturing	23	22		5	17		65
	32.90%	34.40%		23.80%	39.50%		33.00%
Laser cutting	36	31		7	24		87
	51.40%	48.40%		33.30%	55.80%		44.20%
Big data	26	31		6	25	*	81
	37.10%	48.40%		28.60%	58.10%		41.10%
Scanner 3D	8	13		0	13	**	30
	11.40%	20.30%		0.00%	30.20%		15.20%
Augmented reality	5	13	*	3	10		27
	7.10%	20.30%		14.30%	23.30%		13.70%
IoT	16	20		7	13		47
	22.90%	31.30%		33.30%	30.20%		23.90%
Total	70	64		21	43		197
	100%	100%		100%	100%		100%

Note: The 4th column report statistically significant differences between NON GREEN and GREEN OUTCOME, the 7th between GREEN NON CIRCULAR and CIRCULAR, based on Pearson Chi-squared statistics, considering for confidence levels: ** $p<0.01$, * $p<0.05$

TABLE 6
Descriptive statistics considering for different sustainability outcomes

	Non green	**Green outcomes**	**Sig.**	***of which*** **Green Non circular**	**Circular**	**Sig.**
4.0s adopted (0-7)	1.96	2.67	**	1.9	3.05	**
Investment in 4.0s (%, 0-100)	9.24	12.73		13.84	12.22	
4.0s in production (D)	0.68	0.83	*	0.9	0.79	
4.0s in NPD (D)	0.47	0.45		0.33	0.51	
Product servitization (D)	0.13	0.36	**	0.33	0.29	
Product traceability (D)	0.13	0.42	**	0.37	0.49	
Num. companies	70	64		21	43	

Legend: D means Dummy. Note: The 4th column report statistically significant differences between NON GREEN and GREEN OUTCOME, the 7th between GREEN NON CIRCULAR and CIRCULAR, based on Pearson Chi-squared (between qualitative variables) and t-test (between qualitative and quantitative variables) statistics, considering for confidence levels: ** p<0.01, * p<0.05

TABLE 7
Descriptive statistics considering for different sustainability outcomes

	Non green	Green outcomes	Sig.	*of which* Green non circular	*of which* Circular	Sig.
Size (ln employees)	3.24	3.41		3.06	3.58	
Num. Employees (0-935)	41.21	66.77		28.1	85.65	
Green driver (D)	0.1	0.42	**	0.43	0.42	
ICT propensity (0-9)	3.33	4.14	*	3.68	4.36	
Share of foreign production (%, 0-100)	12.3	4.08	*	3.67	4.29	
Customized products (D)	0.41	0.53		0.67	0.47	
Customer dependency (%, 0-100)	32.6	24.48	*	29.05	22.35	
Low-tech industries (D)	0.6	0.64		0.67	0.63	
Num. companies	70	64		21	43	

Legend: D means Dummy. Note: The 4th column report statistically significant differences between NON GREEN and GREEN OUTCOME, the 7th between GREEN NON CIRCULAR and CIRCULAR, based on Pearson Chi-squared (between qualitative variables) and t-test (between qualitative and quantitative variables) statistics, considering for confidence levels: ** $p<0.01$, * $p<0.05$

TABLE 8
Results of logit regression analyses: investigating the characteristics of the firms adopting industry 4.0 technologies for sustainability outcomes

	Green outcomes		Circular	
	Coef.	**S.E.**	**Coef.**	**S.E.**
Size	0.165	-0.229	0.414+	-0.22
Green driver	2.277**	-0.647	1.198*	-0.504
ICT propensity	0.338*	-0.166	0.256	-0.158
Share of foreign production	-0.036*	-0.017	-0.02	-0.015
Customized products	0.761	-0.484	0.15	-0.477
Customer dependency	-0.022+	-0.013	-0.022*	-0.011
Low-tech industries	-0.311	-0.476	-0.246	-0.477
Constant	-1.477	-0.956	-2.509*	-1.04
Pseudo R2	0.1565		0.1229	
Observations	123		123	

Robust standard errors in parentheses.
** $p<0.01$, * $p<0.05$, $^{+}$ $p<0.1$