Green and Lean? – Understanding ecological and environmental implications in the light of Industry 4.0

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Abstract. Research on Industry 4.0 has only begun to analyse its environmental and social impacts, while technological and economic analyses dominate the current academic debate. However, merging the current debate for a more sustainable industrial value creation with the developments in the context of Industry 4.0 is vital given its benefits beyond merely economic considerations. In response to the scarcity of extant research, this paper analyses research publications and gives insights using an empirical approach. Qualitative-empirical data from 33 expert interviews within German manufacturing enterprises are used to extend the current state of literature in this field. In particular, company-internal and company-external benefits from an environmental and ecological point of view are uncovered, along with drivers and requirements to approach the potentials. Further, the results are discussed against the background of extant publications in the field. The paper closes with recommendations for managerial practice and suggestions for future research.

1. Introduction
The concept of Industry 4.0 promises numerous opportunities for companies to succeed in value creation and global competition. Based on digital interconnection in horizontal (across the supply chain) and vertical (across functional departments) directions and end-to-end transparency of data (from sourcing to recycling), the initial concept behind Industry 4.0 already shows potential paths towards environmental sustainability, or a circular economy [1]. However, in extant literature on Industry 4.0, many authors solely focus on technical and technological aspects of Industry 4.0 [2]. In recent years, however, economic, environmental and social opportunities have become significantly more important against the backdrop of globalization, changing environmental circumstances, and social pressure. Yet, in the context of Industry 4.0 aspects of environmental and ecological importance have been little regarded, such as recycling aspects and requirements towards a circular economy [1,3,5]. Further, as sustainability dimensions of economic, ecological, and social dimensions, referring to the Triple Bottom Line of sustainability, require to balance the three dimensions against each other and especially consider
interdependencies [2,3]. In response to this research gap, this paper is devoted to the following two research questions:

1) What potentials does Industry 4.0 pose for the environmental or ecological dimension?
2) What interdependencies with economic or social aspects do those potentials have?

2. Background
This paper is based on the literature review that was conducted for the study and that is explained in the method. Due to limited space in this short paper, only a brief summary is given in the following, focusing on a short overview of potentials associated with Industry 4.0 from an environmental and ecological perspective.

Given a scarcity of resources, climate change, and sustainability awareness in society, the importance of ecological aspects expands to the industrial context. Industry 4.0 can help to improve the ecological sustainability of industrial value creation through intelligent processes and thus increase the resource efficiency of companies [7,8]. Reasons for that are manifold but they are mainly caused by the intelligent interconnection of value chains and networks alongside the process transparency. Both processes and products can be optimized in an ecologically sustainable way. For instance, processes and the entire ecological footprint of companies can be monitored, controlled, and managed, using data analyses and simulations based on data exchange across the entire supply chain [7,8]. In the same manner, energy consumption can be optimized through intelligent energy systems [9]. By taking a holistic view and managing the product life cycle, resources can be used optimally [2,10]. This also includes using renewable energies, the reusing and recycling of resources or products as well as retrofitting [11]. The latter refers to the retrofitting, modernization or expansion of existing plants, machines and equipment. Doing so requires significantly lower investments compared to new purchases. Furthermore, Industry 4.0 enables to reduce resource consumption both for resources used during operations (e.g., materials, energy, and water) just like for by-products generated during operations, e.g., waste, emissions such as greenhouse gases, and chemical residues [11,12].

In addition, Industry 4.0 opens up ecological opportunities in transportation and logistics. Superfluous material flows and transportation processes can be avoided with the help of end-to-end data transparency throughout the value chain. In addition, transportation routes and capacity usage can be made more efficient, reducing waiting and storage times, and decreasing incorrect deliveries [3]. Further, reshoring, i.e. the relocation of production sites back to where a product is consumed, is a further opportunity to simplify transportation and logistics, and also in turn, reduce environmental pollution [13]. New technologies, such as additive manufacturing, help to reduce resource consumption, avoid waste, and improve logistics processes, e.g., in spare parts delivery [14].

3. Material and Methods
This paper applies a mixed method approach combining the results of a qualitative empirical study with those of a literature review. The methods are explained in the following.

First, a qualitative, empirical research design was chosen in order to extend the existing research on Industry 4.0 regarding environmental and ecological aspects. Semi-structured interviews with experts from business practice were conducted forming the empirical basis. The shape and form of the interviews ensure a scientific structure, whereas at the same time, the procedure does leave space for deviating, individual questions. Given this openness and flexibility, the semi-structured interviews allow gathering new and unexpected information and grasping the entire context.

Between January and May 2019, 33 semi-structured interviews were conducted with experts from various German industrial companies. The interviews lasted between 25 and 60 minutes and were conducted in German, the mother tongue of the interviewer and the interviewee alike. All experts are selected for their knowledge, experience, and awareness of Industry 4.0 opportunities. For confidential reasons, the names of the companies and the interviewees were anonymized in the present work. The sample companies stem from the following manufacturing industry sectors: Automotive industry,
mechanical and plant engineering, electrical and electronics engineering, and information and
communication technologies.

The interviews were recorded, transcribed, and then examined applying a qualitative content analysis. We followed an inductive approach, this means the categories are not created before viewing data, but they are derived from the data material, i.e. directly from the transcripts. The aim of this procedure is to bundle and summarise the collected data without distorting the interviewees’ statements and intentions [15]. In a first step, the interviewees’ statements were precisely recorded in the category formation and their statements are paraphrased. In a second step, these categories were then synthesized into superordinate categories. Doing so generalizes the statements and raises them to a more abstract level. Hereafter, the categories are coded consolidating homogeneous categories into subcodes. In a last step, related subcodes are summarized and transferred into topcodes.

Second, a literature review is conducted in order to grasp the current state of research and to uncover similarities and differences compared to our qualitative empirical results. The analysis bases on three steps (1) preparation, (2) selection and classification, and (3) analysis, as is common in research practice [16]. First, we defined search terms (e.g., Industry 4.0, IIoT, sustainability, ecology), determined the time horizon (2011–present), selected databases (ABI/Inform, EBSCO, Science Direct, Scopus), and selected publication types (peer-reviewed, published high-quality academic journals). Second, the selected articles are classified and categorized. In a last step, we compared, contrasted, critically evaluated, and discussed the articles against the backdrop of our empirical results. The entire process is summarized in Figure 1. The following section presents the findings and discusses them respectively.

| 1. Preparation | 2. Selection & Classification | 3. Analysis |
|----------------|-------------------------------|------------|
| (1) Defining search terms | (5) Selecting articles | (7) Analyzing selected articles |
| (2) Determining time horizon | (6) Classifying articles | |
| (3) Selecting databases | | |
| (4) Selecting publication types | | |

**Figure 1.** Approach for literature review.

### 4. Results

Table 1 presents the results of the coding process and indicates the topcodes and subcodes developed from the empirical data. It also includes references that confirm the results. In general, most potentials can be attributed to higher data transparency and data sharing across the supply chain and across product lifecycles, optimized products and production, predictive capabilities, optimized logistics processes, and eased management of processes. Hereby, multiple occurrences per interviewee are possible, the number in brackets refers to the number of mentions out of 33 interviews.

**Table 1.** Data structure.

| Topcode | Subcode | Description and enablers | References |
|---------|---------|--------------------------|------------|
| **Reduction of resource consumption** | Reduction of production input resources (11) | Load balancing and data sharing across the supply chain, early recognition of errors. | [4,14,11,17] |
| **Reduction of waste generation** (22) | Reduction of waste and emissions (11) | More efficient processes can be established through self-optimizing and interconnected production. | |
| | Reduction of travel, paper and documentation (8) | Communication and documentation can be transferred to digital means or become automated. | |
5. Discussion
In terms of the environmental benefits of Industry 4.0, our empirical analysis has shown that increasing resource efficiency is highly relevant, based on the efficient design of processes and products throughout the product lifecycle, and recycling of products. In the existing literature, these aspects are also listed and supplemented by the chance of retrofitting [11,18]. Furthermore, the reduction of resource consumption, e.g., the reduction of materials, CO2 emissions, and energy was identified as a significant ecological opportunity both in empirical analysis and in existing literature. The experts emphasized the reduction of paper consumption due to digital processes in their companies.

There is research in the literature on the extent to which additive manufacturing contributes to reducing resource consumption [13]. However, this aspect is not confirmed in the empirical results as it was not mentioned by any of the interviewed experts. Furthermore, the empirical analysis found the reduction of transportation and logistics processes to be an opportunity, which is also theorized by some authors in the literature [2,10]. The interviews and literature emphasize the reduction of material flows and transportation processes, which reduces waiting and storage times just like incorrect deliveries [3]. The experts consider that an orientation towards ecological goals as relevant, for example through the development and expansion of an environmental and energy management system. Another opportunity is the need for a holistic management across the entire product lifecycle [2].

As far as interlinkages between the dimensions are concerned, one of the most notable interdependencies results from the effects of energy efficiency on cost efficiency potentials. Since electrical energy accounts for a large part of the costs in industrial value creation, Industry 4.0 offers several potentials. With smart energy distribution, improved process efficiency, and improved design
efficiency, the eco-effective production of the future can also make a significant contribution to the economic dimension [2]. For example, intelligent energy systems are capable of predicting a company’s energy consumption adjusting it to the energy production. Through intelligently planning and scheduling energy peaks, companies can make use of times of cheap energy costs and in doing so, strategically adapt production speed to the energy supply [3]. In contrast, some authors argue that Industry 4.0 leads to higher energy consumption, for instance, as digital infrastructure and data centres consume a great amount of energy [10]. Furthermore, creating new technologies and setting up machines related to Industry 4.0 requires a great deal of additional resources [3]. Comparable interdependencies can be found between reducing logistics processes and waste reduction, which can be combined to generate both, economic and ecological benefits. More environmental-friendly processes can also lead to social benefits at the same time, such as hazardous or physically challenging tasks in which humans can be assisted by technical solutions [2,3,10].

For the development towards a circular economy, especially two barriers can be identified. First, the integration of developing countries, which are responsible for sourcing and recycling activities in many industrial processes. However, companies from these countries often do not have the means and technology to allow data transparency across the supply chain, and across the entire lifecycle of products [20]. Comparably, small and medium-sized enterprises are vital contributors to global value chains, but do not have the level of standardization or resources to provide data transparency required for Industry 4.0 [18,19].

6. Conclusion
By integrating the empirical insights gained from the cases of 33 German industrial companies with extant literature, this paper provides an overview of potentials related to ecological or environmental aspects within the Triple Bottom Line of sustainability. Further, the paper shows interdependencies with other dimensions, such as the economic and the social dimensions. This allows to shape future research in the field of Industry 4.0, and to design managerial strategies aligning the dimensions of the Triple Bottom Line. In particular, the understanding of how data transparency and data sharing across the supply chain and across the lifecycle of products does generate economic and ecological benefits is vital to handle the struggles of technical interfaces and standardization.

The research results of the present work include some limitations given their qualitative character. The empirical analysis was limited to 33 German industrial companies of different industry sectors and company sizes. Although the research results of the empirical analysis were stem from semi-structured interviews to guarantee a high degree of reliability, robustness, comparability and to allow replicability, they should not be generalized to other situations or circumstances without further consideration. In addition, experts from non-governmental organizations, research institutes, industry associations and politics could also be interviewed in the course of further research. Other recommendations include focusing on supply chains and business ecosystems, and approaches that statistically quantify sustainability aspects of Industry 4.0. This could help to balance the three dimensions against each other, also relating to their perceived importance, or interdependences.

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