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Role of smart technologies for implementing industry 4.0 environment in product lifetime extension towards circular economy: A qualitative research[☆]

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ABSTRACT

Since sustainability has grown in prominence over the past two decades, the impetus for improving the lifetime of durable and semi-durable manufactured goods has never been stronger. In order to decrease the level of natural resources extraction, as well as the increasing amounts of residuals and solid waste, product lifetime extension (PLE) strategies, such as improved design, maintenance, redistribution, access, and recovery, show great potential, especially if paired with smart technologies in the Industry 4.0 (I4.0) environment. Much research has investigated the contribution of I4.0 technologies to sustainability and the circular economy. Yet, only a few studies have focused on exploring the contribution of smart technologies to the specific area of PLE. This paper advances knowledge regarding the impact of four specific types of smart technologies on PLE strategies: Additive Manufacturing, the Internet of Things, Big Data, and Artificial Intelligence. This study consists of exploratory qualitative research to explore the mechanism underlying the implementation of these I4.0 technologies in PLE for a circular economy. Qualitative data is collected through twenty semi-directed, in-depth interviews with business leaders and executives involved in product development and research and development (R&D) in Quebec, Canada. An analytical approach parented to grounded theory and consisting of open, axial, and selective coding led to identifying four emerging themes explaining how focal smart technologies contribute to PLE. These include (1) empowerment and acceleration of R&D (improvement of prototypes, prototype validation), (2) smarter production (tooling assistance, manufacturing assistance), (3) automation of managerial and operational processes (automation of management, automation of production), and (4) help with decision-making (anticipation, identification, and solving of problems). These findings have broad relevance for sustainability theory and practice by highlighting the specific mechanisms through which technology contributes to product sustainability.

1. Introduction

One area to foster sustainability has long been recognized as product lifetime extension (PLE) (Bakker et al., 2014), which is a

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critical component of the circular economy because PLE favors “circular products that go round” [1–3], “augmented products” [4], or “circular products” [5,6]. Put differently, if a reduced product lifespan generates accelerated material (and energy) flows and more waste [7], PLE decelerates material flows and associated waste. This “Long View” [8] on products would thus also contribute to fostering the circular economy by optimizing the productivity of existing resources (i.e., objects), be they inputs (i.e., pieces, components, machinery, equipment) or outputs (i.e., end product sold to clients).

Yet, despite the claims that Industry 4.0 (I4.0) contributes to sustainability [e.g., [9–12]], little research has investigated how the technological advances of the fourth industrial revolution contribute to PLE. More precisely, the empirical study of technology 4.0’s connection to PLE is necessary and contributes crucially to the literature because current research in the area remains conceptual and lacks empirics [3] or is grounded in specific sectors or contexts [e.g., [13]]. For example [14], explored smart product-service systems in the healthcare industry. Furthermore, earlier studies focused on the connection between sustainability and particular technologies, such as large-scale data analytics [15] or 3D printing [16,17] in isolation or investigated the broader concepts of synergies between I4.0 and circular economy [e.g., [18]], I4.0 and sustainability [19], I4.0 and environmental management [e.g., [20]], or the sustainable digital transformation [21], with only partial or uncomplete narrowing down to the opportunities for increased product lifetime. Hence, applicability to PLE remains insufficiently covered in the literature. In addition, the institutional environment is shifting, and several countries and governments posit I4.0 technologies as crucial enablers of progress and sustainability, such as in Japan with the concept of a “Super Smart Society/Society 5.0” [22], but also in Europe with the European Commission’s research and innovation plans [11,12], among others.

Thus, by focusing on a subset of four technologies of I4.0, including additive manufacturing, big data analytics, IoT, and AI, which have already been conceptually studied in relation to PLE [see 3,4 for a review], this research seeks to examine empirically how smart technologies benefit organizational users to enable PLE and, more broadly, the circular economy. Relying also on previous studies classifying PLE business models (PLEBM) [e.g., [1,23–26]], this study identifies three core strategies for PLE, namely improved product design, maintenance, and recovery, and shows how I4.0 technologies contribute to these strategies in order to extend product lifetimes. Therefore, the overall study objective is:

ORO) To investigate the mechanisms underlying Industry 4.0 technologies’ contribution to PLE.

The specific objective of this study is:

SRO) To examine how the four core technologies of Industry 4.0 (i.e., additive manufacturing, big data analytics, IoT, and AI) contribute to product lifetime extension through improved product design, maintenance, and recovery strategies.

More formally, the research seeks to respond to the following research questions:

RQ1) To what extent do Industry 4.0 technologies extend the lifetime of manufactured goods?

RQ2) What is the process underlying the assistance of industry 4.0 technologies to organizational users in enabling them to extend the lifetime of the physical goods they manufacture?

In order to answer those research questions, this study consists of qualitative field research in the province of Quebec, Canada, where the government is currently implementing a roadmap for digital transformation with its *Digital economy action plan* [27]. A total of 20 semi-directed interviews were conducted with managers of Quebecer manufacturing companies that use I4.0 technologies in their operations. The emerging themes from the qualitative analysis answer the two research questions and fulfill the research objectives by suggesting that I4.0 technologies contribute to PLE via four features: (1) empowerment and acceleration of R&D (improvement of prototypes, prototype validation), (2) smarter production (tooling assistance, manufacturing assistance), (3) automation of managerial and operational processes (automation of management, automation of production), and (4) help with decision-making (anticipation, identification, and solving of problems).

These key findings provide numerous theoretical and practical contributions. Theoretically, the research responds to several calls for empirical research in business [3] and engineering [28] to better understand how I4.0 contributes to sustainability via PLE. For the first time, this study provides an empirical and detailed account of how different smart technologies contribute to specific PLE strategies. It informs scholars and managers alike on the main benefits of those technologies. For scholars, this study contributes to extant research on empirics examining the link between I4.0 technologies and PLE [e.g., [13]] without focusing on a specific sector or industry but considering the topic of (semi-)durable goods manufacturing generically. Furthermore, the study is not limited to particular technologies (e.g., large-scale data analytics [15] or 3D printing [17,29] but covers a broader spectrum of what can be considered core technologies of I4.0, notably Internet of Things (IoT), Big Data, Additive Manufacturing, and Artificial Intelligence [29]. Although narrowing down the focus to PLE, the study also contributes to the broader field of the circular economy [e.g., [18]] and the contribution of I4.0 to sustainability [19] and the triple bottom line [30]. For managers, in particular, this gives them an overview of the major improvements that smart technologies might have before investing in them. Interestingly, the technology contributes both to sustainability through PLE but also to desirable business and managerial outcomes through optimization and support for decision-making. These results align with previous research highlighting the increasing synergies between sustainability and optimization [e.g., [31,32]]. This study shows more precisely how these synergies occur at the manufacturing level to prolong product longevity.

The remainder of the article is structured as follows: The next part introduces the theoretical framework of the product lifetime extension business model (PLEBM), which comprises the PLE strategies considered in this study. Section 3 outlines in more detail the methods used in the study. Section 4 presents the analysis results, while Section 5 presents the study’s implications for theory and practice.

2. Theoretical framework

2.1. Product lifetime extension strategies

Product lifetime (PL) is defined as "the duration of the period that starts at the moment a product is released for use after manufacture and ends at the moment a product becomes obsolete beyond recovery at product level" [[1], p. 519]. According to Van Nes and Cramer [33], product lifetime extension (PLE) thus refers to the means used to extend that duration. PLE excludes end-of-life (EOL) treatments such as recycling [1], destruction for reutilization, composting, or biodegradation. From a managerial viewpoint, PLE has deployed through a variety of business processes generically called product lifetime extension business models (PLEBM) and which aim at improving product design (*nature* strategies) [1,23] or increasing the lifetime of the product during post-production phases (*nurture* strategies) [26]. In PLEBM studies, there are five overarching PLE activities [24,25], namely:

1. **Improved product design**: improvement of product and production processes as well as improved design for repair [[26], p. 3];
2. **Access**: use-oriented "service scape," including leasing, renting, mutualizing, and pooling to temporarily transfer a product from an individual who does not want or need it to another individual who wants or needs it [[26], p. 3]. It also refers to Stahel's [34] notion of performance economy;
3. **Maintenance**: product-oriented "service scape" including maintenance, advice, training, and consultancy contracts [[26], p. 3];
4. **Redistribution**: product transfer activities from one individual to another through various activities such as donation, swapping, and second-hand purchase [[26], p. 3];
5. **Recovery**: restoring a given product to an initial functioning state through product repair or remanufacturing, refurbishing, repackaging, or reconditioning [[26], p. 3].

These five strategies are various ways to extend product lifetime for improved circularity and sustainability. Yet, access and redistribution strategies are less relevant in this study because they involve the circulation of end products between peers or from firms to consumers. In contrast, the scope of this study is limited to the investigation of PLE strategies at the production level within organizations. Therefore, we shall focus on investigating how I4.0 strategies contribute to improved product design, maintenance, and recovery.

2.2. Industry 4.0 technologies

Although enabling technologies of I4.0 are relatively diverse, including Edge Computing, Artificial Intelligence, Cobots, 6G and beyond, Blockchain, the Internet of Every Thing, or Big Data Analytics, we shall focus on a few key technologies.

More specifically, we follow Ertz et al. [3] in selecting the Digital Twin as a Service (DTaaS) framework as an "architecture reference model" [[35], p. 1] to identify the critical constitutive technologies of I4.0. Initially, the framework intends to exploit Digital Twin's capabilities for industrial transformation. However, it also applies to broad industries and sectors, including services to fuel a Digital Twin as a Service paradigm [36]. More importantly, it provides a holistic reference architecture model which stipulates a preliminary relationship between crucial technologies such as AM, BD, IoT, cloud computing, augmented reality, and AI for digital transformation purposes [35]. Although the framework also includes other technologies, such as cloud computing or augmented reality, we follow past literature [3] to focus on those technologies with presumably the most intuitive relationship with PLE, namely AM, IoT, BD, and AI.

As of now, the in-depth examination of I4.0 technologies has evolved independently from the study of modalities of PLE opportunities [e.g., 37,38]. Consequently, there is a dearth of knowledge on the potential synergies between these two domains, despite the criticality of such knowledge for infusing new product marketing and sustainable societies. Therefore, the article investigates to what extent new technologies (commonly termed I4.0) may contribute to extending product lifetimes.

3. Methods

3.1. Methodological approach

Considering the few studies dealing with the impact of I4.0 technologies on the durability of objects, this research is exploratory and descriptive since it seeks to understand a phenomenon and reveal all of its particularities [39]. Furthermore, we focus on small and medium-sized enterprises (SMEs) because not only do they constitute the vast bulk of jobs and account for the majority of economic activity in most countries, but since they are smaller, they often lack the full-fledged resources required to roll out complete digital transformation [21]. As such, SMEs constitute a very relevant and conservative study case because they represent the average business network of a nation, and their perspective is thus more easily transferable across different contexts and settings [21]. Therefore, an exploratory qualitative methodology is chosen to study SMEs using 4.0 technologies in developing or producing their products.

3.2. Study participants and sampling

The participants in this study were business leaders (i.e., management) and employees of manufacturing companies involved in the production process of Quebecer manufacturing companies. Data collection occurred between December 8, 2020, and March 2, 2021.

Given the exploratory and qualitative nature of the study, interview participants were recruited using two non-random sampling methods. First, convenience sampling [39] was used since the research team used a combination of their professional network, knowledge of the industrial environment as well as specific sampling frames, including specialized directories such as the ICRIQ, i.e., Quebec's company repository, to identify and select firms. In addition, convenience sampling was constrained by the purposeful sampling method [41], which was used to select firms and identify the respondents within each selected firm who might provide the most relevant information [42]. In fact, since the study focuses on PLE, we limited the scope to investigating firms producing non-consumable and non-perishable products. Within each company, we sought to recruit at least two respondents and targeted those individuals holding positions related to I4.0 technologies, product development, production, or management, such as CEOs, product managers, R&D managers, and production managers. We recruited at least two or more respondents in each firm except in a smaller firm, where the CEO was the most knowledgeable informant for our topic. The varying number of respondents per firm is attributable to two factors. First, since we focus on SMEs, the selected organizations are of varying sizes, with differing numbers of qualified personnel to respond adequately to specific and technical questions. For example, in the case of an organization that does not have a CTO (chief technology officer) or a technical director, we rely on another person who knows the most about new technologies, albeit this is not their core expertise (e.g., manager, CEO). Second, as the subject is quite specific and requires good expertise, it is sometimes rare that a single person is able to answer all the questions. Some information may thus be available from more than one employee. We followed the organization in the choice of its respondents to answer the questions in the best way, and in some cases, this required several respondents to have complete insights on a question. Eventually, 20 respondents, presented in Table 1, participated in the research.

3.3. Theoretical saturation and sample size

Qualitative research prioritizes depth and quality over representativeness and quantity, so we followed the principle of theoretical saturation to finalize the fieldwork and constitute the final sample size of the research. More specifically, following Glaser and Strauss' [43] recommendations, the interviews were finalized when all the data from new interviews no longer provided us with additional information compared to what we had already identified through previous interviews. Saturation was reached at the twentieth respondent, so we ended the data collection process at this point.

3.4. Interview guide

An interview guide was developed by the research team and included all the relevant information about the terms and conditions for taking part in the study. Afterward, informants were invited to present themselves and the company they represent. This made it possible to know more about the company and its activities and better understand the respondents through their careers, roles, and tasks in the organization. Secondly, respondents were asked about their understanding and perception of I4.0 and how their company was part of it. Finally, four technologies specific to I4.0 were further explored. Thus, Additive Manufacturing, the Internet of Things,

Table 1
Profile of the informants.

	Name	Gender	Job title	Firm industry	Firm size	Firm Revenue	Firm Market
1	Adele	Female	Production manager	Textile Manufacturing	120	8 M	International
2	Andrew	Male	Mechanical engineer & Co-owner	Medical Equipment Manufacturing	10	2–3 M	Canada
3	Anne	Female	Marketing & Communication manager	Industrial Sewing	25	Undisclosed	Canada
4	April	Female	Production planner	Medical Equipment Manufacturing	10	2–3 M	Canada
5	Benjamin	Male	CEO	Industrial Production	425	115 M	International
6	Bruce	Male	CEO & Co-owner	Medical Equipment Manufacturing	10	2–3 M	Canada
7	Charles	Male	R&D Coordinator	Industrial Production	425	115 M	International
8	Gary	Male	Mechanical designer	Manufacturing	200	50 M	North-America
9	Jake	Male	Production manager	Manufacturing	200	50 M	North-America
10	James	Male	Dir., Products	Manufacturing	200	50 M	North-America
11	Joseph	Male	CEO	Manufacturing	8	500k	North-America
12	Leslie	Female	CEO	Industrial Sewing	25	Undisclosed	Canada
13	Michael	Male	VP, Operations	Industrial Production	425	115 M	International
14	Philip	Male	CEO	Manufacturing	200	50 M	North-America
15	Raymond	Male	Engineer	Engineering	120	1,5 M	Provincial
16	Ron	Male	Dir., Operations	Manufacturing	200	50 M	North-America
17	Ryan	Male	Dir., Quality	Manufacturing	200	50 M	North-America
18	Sara	Female	Marketing & Communication manager	Textile Manufacturing	120	8 M	International
19	Stephen	Male	Dir., R&D	Industrial Manufacturing	200	46 M	North-America
20	Tom	Male	Dir., Marketing	Manufacturing	200	50 M	North-America

Note: The names provided in the table are aliases in order to ensure the non-disclosure of participants' real identities.

Big Data, and Artificial Intelligence were discussed in more depth to understand their use in the firm, especially their impact on product durability.

3.5. Data collection

The interviews were conducted online, lasted between 45 min and 60 min, and focused mainly on the organizations' use of I4.0 technologies and their impact on the sustainability of their products. The online mode of data collection was favored, given the pandemic context and the difficulty of conducting interviews face-to-face. The interviews used probes and exploratory questions (e.g., can you explain further? Or can you give an example?) to encourage respondents to provide more detail [44].

3.6. Ethical considerations

The study project was approved by the ethics committee of the authors' institution (certificate no. 2021-634). All 20 in-depth interviews have been conducted with participants' informed consent. The discussion guide started with information about the research procedure, information confidentiality, anonymity, study objectives, data storage, and dissemination modalities. Informants also provided their consent for being recorded and were allowed to stop the interview whenever they wanted. The interviewees were not compensated.

3.7. Analytical procedure

After being transcribed verbatim, the qualitative data were pre-analyzed to get a sense of the data and were then subjected to content analysis. In order to analyze data, we used Corbin and Strauss' [45] grounded theory method of analyzing qualitative data with the Nvivo software. First, an open coding phase consisted in performing several rounds of readings on the verbatim to extract the primary codes [46]. Each text segment was broken up and labeled with one (or several) code(s) to consistently contrast and compare similar elements in the data [47]. Second, axial coding followed to elaborate connections between codes and group codes into categories [48]. This step resulted in creating several categories supported by a set of relevant supporting codes. Finally, selective coding connected all the similar categories obtained through axial coding into one core theme [45]. Appendix A shows an excerpt of how the codes were grouped into categories and the latter into emerging themes. The quotes provided in the appendix are also different from those cited in the text (see Section 4) for improved validity and credibility of the results [49]. A more visual representation of the results is provided in Fig. 1.

This process resulted in the emergence of four overarching themes (i.e., empowerment and acceleration of R&D; smarter production; automation of managerial and operational processes; and help with decision-making), each being comprised of one to two categories, and the categories encompassing each between two to three primary codes (see Fig. 1). The detailed results and discussion of their interrelationships as well as their contribution to the three PLE strategies under study are presented in the next section.

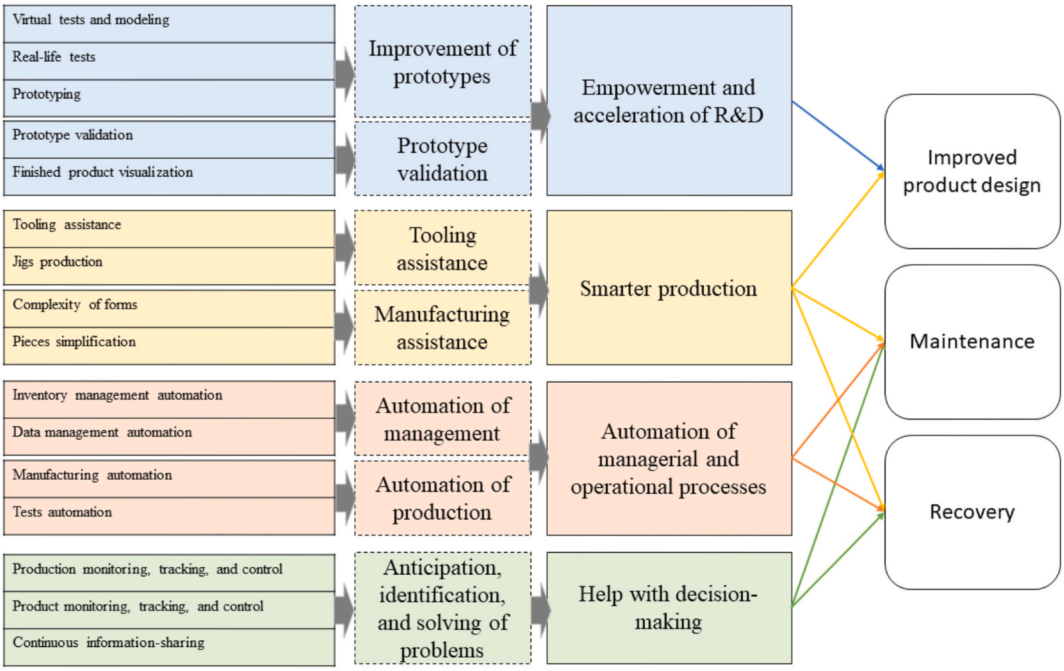

Fig. 1. Contribution of Industry 4.0 technologies to product lifetime extension.

4. Results

The analysis results are illustrated by smart technologies' impact on PLE, and the inductive model is shown in Fig. 1. The remainder of this section explains each theme by its constitutive categories and corresponding codes.

4.1. Empowerment and acceleration of R&D

I4.0 technologies empower firms to conduct Research and Development (R&D) activities by repatriating them internally, which speeds up the development process. More specifically, I4.0 technologies allow (a) the improvement of prototypes and (b) prototype validation.

4.1.1. Improvement of prototypes

Our results show that the prototype improvement occurs via three processes.

Virtual tests and modeling. Also known as "simulation testing," virtual tests and modeling examine specific prototypes without producing any physical object. Moreover, thanks to the help of technology, *"we can simulate what we want today"* (Benjamin, CEO). And as this simulation *"almost resembles reality"* (Adèle, production manager), several companies test several concepts with different physical parameters, increasing their likelihood of developing a better quality product via improved design.

> "For a [company product], among other things, we had a request to have a weak point in the assembly so that if a vehicle hits the pole, the pole breaks a certain way so as not to injure people on the sidewalk and the vehicle, etc. That was done first by simulation, the points, to see how they would behave by applying a force, and then we went to the laboratory to do the equivalent of a crash test dummy." (James, Product Manager)

Real-life tests. After simulation testing, technologies such as additive manufacturing (3D printing) make it easy and quick to test concepts in real-life conditions. The object is printed to be tested for "realistic tests" or "full-scale tests," which are superior to purely digital test settings where the object cannot be physically manipulated. And, since *"there is enough information in 3D to justify your decision"* (Joseph, CEO), companies use it to help them in their product development process. This is illustrated by James (product manager) by explaining that *"lately we have been making lids, so we used the 3D printer to make a new lid, then we tested if it was easy for a user to take and hand over the gun"*. During the development process, companies also carry out all kinds of tests, sometimes in the laboratory, to improve or validate their ideas, which will have an impact on the lifetime of the product since it will be of better quality with improved upstream design.

> "When we do the tests, we test in the laboratory under extreme conditions. We try to bring the products to extreme conditions to see the weaknesses. So, it allows improvement, it will enable to correct design faults. It is obvious that all these tests that we do in the laboratory allow us to improve the lifetime of the product". (Benjamin, CEO)

Prototyping. This is the activity most mentioned by respondents in order to explain the improvement of concepts and help with the validation of concepts. Several companies use technologies such as 3D printing (additive manufacturing) to develop prototypes, whether for *"having a part evaluated"* (April, production planner), *"evaluating the reaction of the market"* (Joseph, CEO), or assessing the feasibility of larger *"volume production"* (Jake, Production Supervisor) or simply test the product.

> "We have a 3D printer, so we use it a lot for prototyping, to do validations, to accelerate research and development curves so, instead of having it manufactured in real materials, we can easily produce prototypes that allow validation for the average user." (James, Product Manager)

This will improve the durability of the products since, as mentioned by some informants:

> "Per printer, we will have a better prototype which will lead to the industrial production of a better product." (Michael, Vice President of Operations)

Being able to manufacture prototypes will also allow companies to save time in R&D in addition to savings in development since *"printing a prototype and then testing it or trying it or to see it versus touring it allows for correcting or avoiding errors before going to the final process"* (Benjamin, CEO).

4.1.2. Prototype validation

Prototype validation. Our results show that prototype validation is fastened by I4.0 technologies that provide a visualization of the finished product. In fact, validation is accelerated thanks to technologies, particularly 3D printing, which allows *"a shortcut in research and development"* (Joseph, CEO) while allowing for concept improvements since more time can be devoted to development.

> "In fact, the less time we waste either waiting or doing validations, the more time we have thinking about better concepts. It's a bit funny like that, but sometimes, the advantage at the time it wasn't the pandemic, and the whole research and development team was at our offices, someone was making an impression then, and it was very easy to get feedback, to have feedback from teammates in real-time. We would try it out and iterate fairly quickly, so instead of having everyone wait four weeks to try and

> comment because everyone is on different projects or mandates, everyone is on the same page at the same time, and it makes better concepts in the end." (Gary, mechanical designer)

Finished product visualization. The validation of concepts is also accelerated and facilitated by the fact that 3D printing makes it possible to visualize the finished product even before it goes into production because:

> "Having the prototype in hand gives a better overview of how the product could look like once in industrial production." (Michael, vice-president of operations)

This will also make it possible to *"evolve the design or the concept"* (Charles, R&D coordinator), thus allowing the continuous improvement of a product with better quality.

4.2. Smarter production

In addition to "empowerment and acceleration of R&D," new technologies provide "smarter production" via tooling and manufacturing assistance.

4.2.1. Tooling assistance

Tooling assistance. Participating companies explained that they use technologies such as additive manufacturing to create valuable tools in the production phase, such as *"small fixing gigs, supports, racks"* (Stephen, R&D director), for example, allowing them to save money.

> "A recent example that I have is that we had inserts in the back cover of one of our terminals whose threads were breaking. Then, we developed a tool with additive manufacturing to allow the service teams to be able to remove the inserts without having to remove the bollard completely because we had a high rate of returns from installers who, instead of manual screwing, used percussion tools, therefore power tools, then what that did was that it broke the threads of the screws. So, with additive manufacturing, we quickly came up with a solution to allow the insert to be removed and replaced without having to reverse the terminal completely. Then, we are really at the stage of training at the level of our service teams and allowing them to go and do this repair in the field. That's a use that we managed to probably speed up the repair solution; having done that by traditional methods would have stretched the process a lot." (Ryan, Quality Manager)

Jigs production. Companies also use additive manufacturing to produce jigs to help them with manufacturing by providing them with more precision and, therefore, better quality, as well as a specific time saving due to the speed of execution allowed by templates and their printing, which is *"much shorter"* (Raymond, engineer), than traditional production.

> "She serves at different levels. In fact, it is used for production engineering. The main thing it was used for and is still used for is that we have to put a varnish on our electronic terminals. They call it "comb for all coating," and we have a machine that spreads it, which, in a way that is automated, in fact, is like a small robotic arm that will spread with the right program depending on the chosen board that will extend that and, electronic boards must not … There are certain places that we must mask so that they do not receive varnish because we are not able, if we want, with the nozzle, to avoid this place there, but you have to be sure not to put any varnish. Normally, what would be done is that we would put a kind of masking, sticky paper, on the components that should not receive any varnish. So that's manual, then we have to mask, we put on the varnish, we bake the varnish then after that, we have to remove the masks. Well, with the 3D printer, what we did was we printed templates, and we put our masking on top. We printed a masking template on top, so we just clipped, and when the nozzle passes, well, it passes over, then our board does not receive the varnish. It avoids a lot of manipulations of masking and unmasking. That's why we created all the different templates for our types of boards, then we use it for that, then at some point the cache comes, the template comes full of varnish, we clean it then at some point given it has an end-of-life. It's not big plastic, so we still reprint it regularly. This is one of the main uses." (Ron, Director of Manufacturing Operations)

4.2.2. Manufacturing assistance

Our results show that I4.0 technologies assist the manufacturing of objects because they enable to shape more complex forms, ultimately simplifying product constitution and spurring user-friendliness.

Complexity of forms. First, additive manufacturing makes it possible to create more complex parts than those produced traditionally. Indeed, 3D modeling can:

> "make it easier to do more complex things, more aesthetic perhaps more easily, with the tools that are optimized in the software." (Charles, R&D coordinator).

This result aligns with Ertz et al. [3], who identified "shape and form complexity" as a major contribution of I4.0 technologies.

Pieces simplification. We complement those findings by emphasizing that being able to manufacture more complex parts will ultimately lead to products that are *"easier to make, simpler to assemble, and simpler to use"* (Andrew, mechanical engineer). Such a process may also ultimately result in a product of better quality because *"fewer parts to put together, the less chance there is of breakage"* (Andrew, mechanical engineer). This is facilitated, among other things, by the precision of the parts produced, *"the refinement, the more precise functions of more durable products, a better knowledge of the weak points."* (Andrew, mechanical engineer).

> "The printed part is going to be much more precise, closer to reality than to the production part. The objective is to make a product more complex and as simple as possible. It's a bit funny to say, but the simpler it is, the more work there is on the product to make it simple." (Bruce, CEO)

Similarly to prototype development and validation, the high degree of freedom in design and shape complexity of 3D printing [3] plays a predominant role in tooling assistance by producing small materials, which help improve the overall production process. In addition, due to the increased precision of AM, commonly termed "mass personalization" [50], the technology is a stepping stone for manufacturing assistance by enabling the faster production of more complex parts and components that are more refined and precise. Consequently, products tend to be easier to make, assemble, and use, contributing to the "disassemble" function of the design for disassembly (DfD) strategy in the conception phase [51]. Furthermore, since 3D printing adds layers of materials to create a product, those goods comprise less to no alloys, making them easier to disassemble, such as for maintenance (repair) or recovery (reconditioning) PLE strategies.

4.3. Automation of managerial and operational processes

Our results show that new technologies, especially the Internet of Things and Big Data, contribute to management and production by automating them.

4.3.1. Automation of management

The results of our study show that technologies such as the Internet of Things and big data have an impact on management automation, mainly through inventory and data management automation.

Inventory management automation. First, technologies help companies manage their inventories at the production level, particularly to *"validate inventory levels, turnover rates"* (Ron, director of manufacturing operations) or even to monitor production.

> "There may be an IoT thing I forgot to tell you too. It's the tools that manufacture the parts, basically, all the management of the inventory of these tools is managed by the system, our CIM [Computer-Integrated Manufacturing] software, so when we go to take out a tool, the tool has been identified to a code on it, then it's this identifier, for the cutting tools that will manufacture the part and the measuring tools, the system will also track them. It's really a unique identifier, it's not, again, it's not geolocation, it's really a precise ID that is given so we'll be able to follow the life of a tool through this identifier, we will be able to follow the use of a measuring instrument in relation to this identifier there too. So, there are a few examples like this of things that are used that we will track in the process." (Stephen, R&D Director)

One company reported using the Internet of Things to track the maintenance of their products and the needed parts and tools.

> "For example, our service team will monitor, with the former customer, they will monitor the terminals, and that allows us to say, fine, okay, we have a DC terminal that is in trouble in such a place, and we can know what type of material they are going to need, what consumption that could have at the material level. So, it helps us plan the consumption and restocking of the parts they would need. So, through the service and the status of the terminals, we can have an idea of the impact on our inventories and then on our purchases. Because we are the ones who still buy the spare parts for the service team." (Ron, Director of Manufacturing Operations)

Data management automation. Second, the companies under study explained that the data management carried out by Artificial Intelligence would allow them to be *"much faster than any human"* (Tom, marketing director). Moreover, since with *"management by data, we improvise a lot less, we can predict the future a little more"* (Ryan, quality director), companies use them to control processes, inventory, production, or repairs.

> "Obviously, on the quality of the product necessarily if we use data to control the processes. With this data, it makes it possible to make compliant products that are good in order not to produce scrap and, above all, to ensure that you don't deliver scrap either. By not having a system like that, well, it's easy to fail and then to think to make quality while we don't make it for real. After that, because we're automating the flow of operations, let's admit supply, preparation, stuff like that, the processes are optimized so that, in the end, it reduces the cost of these products too. That for sure is a very competitive advantage for [Company Name], either to have increased profitability or otherwise to have more competitive prices." (Stephen, R&D Director)

4.3.2. Automation of production

Our results indicate that technologies help companies to automate their production. This is facilitated by manufacturing automation as well as test automation.

Manufacturing automation. Technologies have enabled companies to automate their production, whether with the help of specialized machines such as laser cutters allowing them to *"save time"* and obtain *"a perfect cut"* (Leslie, CEO) or even thanks to *"robots that pick and place"* (Stephen, R&D director) on production lines. These technologies will make it possible to minimize human error at the manufacturing level, thus generating more efficiency, consistency, speed, and precision.

> "I would say, in our way of doing things too, it's a lot compared to avoiding, automating most of the steps to avoid errors and also ensure good quality of our production. Something constant too. It's a lot around the yield, obviously, to stabilize the yield." (Jake, production supervisor)

Tests automation. One of the companies studied mentioned having automated its test benches, and to make this possible, they implemented the principle of *"design for automation"* (Philip, CEO), allowing fast and efficient testing.

> "What this will allow us to do is that on a production line where I have four employees who work, I will have one of the tasks which will be automated, so we will just be able to take the terminal, put it on the test bench, and press "start tests." While the test time is being done, that means from 4 to 7 minutes, during these 7 minutes of the test there, the employee who is normally in front of the terminal, who clicks and follows the test procedure, this employee there will simply be able to assemble the next terminal. So, instead of having three stations that take 7 minutes of assembly and then a test station that takes 7 minutes, I will have four stations that will separate the 21 minutes of assembly, so we will reduce it. Doing that will allow me to make more terminals in a day with the same number of employees and the same square foot at a lower cost because I will have fewer direct labor hours to charge to my product." (Ron, Director of Manufacturing Operations)

4.4. Help with decision-making

Finally, our results also show that 4.0 technologies, such as the Internet of Things and Artificial intelligence, in particular, contribute to product maintenance and recovery because companies use these technologies as decision support systems through anticipating, identifying, and solving problems. Indeed, these technologies allow the surveillance, monitoring, and control of production and end products through continuous information sharing.

Production monitoring, tracking, and control. Technologies allow companies to perform real-time production monitoring at the part and machine levels. Thus, a batch of parts can be monitored to ensure compliance and quality, as long as it is in the *"part production flow,"* for example because the parts are not individually identified but in batches (Stephen, R&D Director). Production monitoring is also done in real-time thanks to the connectivity and interconnectivity of the machines making it possible to *"see from the bill of manufacturing equipment, to the end of the order where the product is delivered"* (Michael, vice-president of operations) in real-time. Also, the connectivity of the machines allows the real-time identification and resolution of production problems while retaining the data. In addition, *"the optimization of manufacturing processes leads to costs reduction."* (Stephen, R&D Director)

> "Well, the most notable thing I've seen at the 4.0 level is the kind of internal virtual social network. […] There are flat screens almost everywhere in the factory where you can see in red, in green, the workstations that are having problems or are in normal capacity. Let's say that these are more visual tools in the factory. Well, I can see it, it doesn't affect what I do, but when I walk around the factory, I see these tools that are there. Well, I think it's a good deal, as I just talked about the Poka tool, as far as maintenance is concerned, it's every time maintenance goes to fix a problem on a machine, they can document their intervention and then avoid starting from scratch when there is a similar problem that will come back later, and then someone else from maintenance will come back. So bar codes, QR codes on each piece of equipment that the maintenance person gets to a piece of equipment, there's a problem, he can scan that bar code there and see a bit of a history of what has been done on the piece of equipment. I think that in terms of maintenance, it has a huge advantage. Documentation, speed of access to information, and efficiency in resolving problems that have already arisen. Knowledge is not lost through this." (Charles, R&D coordinator)

The impact on product quality is direct in the sense that the automation of production makes it possible to minimize the risk of error since it allows *"to have a process that is 100% compliant every time."* (Stephen, R&D Director)

Product monitoring, tracking, and control. In addition to production, the Internet of Things allows companies to monitor the status of their products, identify and fix problems since they can *"detect them, interact and fetch usage information"* (Ryan, quality manager), which allows them to collect data to anticipate future issues. These data can be *"the number of cycles, error messages"* (Andrew, mechanical engineer) as well as the type of use, their duration, and even the users' profile. All this collected data allows them to identify recurring problems and warning signs to anticipate them.

> "Since they are connected, we can see their state, if there is anything abnormal, we can see it on the network, at the same time, it allows us to have data precisely to improve our product all the time. Also, be proactive in seeing what may be coming, certain problems, unlike before, if you have less information, sometimes they are harder to analyze, and then you often see the problems when they arise. While currently, we can see that by having a status of the terminal connected, normally, we are able to correct the problems before it blows us in the face. And then, we can constantly improve the product in this way." (Jake, production supervisor)

Continuous information-sharing. Monitoring, tracking, and controlling production and product are possible thanks to Big Data, but above all, to the Internet of Things, which allows continuous and real-time information sharing. Thus, at the production level, *"there are systems that have been put in place […] at the level of productivity management […] to monitor productivity"* (Charles, R&D coordinator) and, therefore, follow in real-time what happens on the production line.

> "For us, what does 4.0 mean? It's the interconnectivity of our equipment, it's real-time, it's real-time information. So, if you visit our factories, of course, on each workstation, on each piece of equipment, there are screens, and we can see in real-time

> everything that is happening, both in terms of productivity, the declaration of the production, and defects. Everything is in real-time, and all the devices are connected to an ERP system, so there is no more input and no loss of time. We see the information day by day." (Benjamin, CEO)

This also makes it possible to report problems in real-time, and this continuous information *"allows decisions to be made and course corrections to be made."* (Benjamin, CEO). Concerning the product, a certain saving of time is made possible because the connectivity makes it possible to obtain *"the data continuously, in real-time, and to make it possible to accelerate the cycles of improvement of the life cycles of the product"* (Tom, marketing director), as well as the possibility of offering immediate troubleshooting thanks to the alerts issued.

> "We have a monitoring center that will ensure the health of the terminals, so to which we can report various data, various alerts, and alarms to realize the state of the terminals and also to support someone calling who says, I'm in front of the terminal, it doesn't work." (James, Product Manager**)**

Therefore, I4.0 technologies exert multidimensional effects on production/product, monitoring, and control, and thus maintenance and recovery, largely thanks to massive volumes of big data generated by the Internet of Things.

In conclusion, through a series of diversified mechanisms, I4.0 technologies contribute to PLE. These elements will be discussed more thoroughly in terms of theoretical and practical implications in the remainder of the paper.

5. Discussion

5.1. Theoretical implications

The main output of this study is the identification of the concrete impacts that I4.0 technologies have on objects, especially for PLE. It contributes significantly to topical research, which has remained predominantly conceptual to this date [3]. Our study shows that PLE is optimized thanks to many contributions of I4.0 technologies at different stages of the production process, i.e., at the stage of design, production, and maintenance. This impact of the industry on PLE confirms that I4.0 contributes to sustainability [9,11,12].

With regard to production activities related to PLE, the study confirms and expands on prior findings, which were limited to specific sectors (e.g., healthcare [26]), scope (e.g., focus on design [1,23]) or methodological approach (e.g., conceptualization[3]). Furthermore, the empirical findings of the study demonstrate how I4.0 technologies contribute not only to improved product design but also to product maintenance and recovery across a broad range of industries manufacturing durables.

In sum, the study thus fulfills the overall (specific) research objective by highlighting the contribution of a subset of I4.0 technologies (additive manufacturing, big data analytics, IoT, and artificial intelligence) to PLE (improved product design, maintenance, and recovery) since the study results suggest that those technologies enable: (1) empowerment and acceleration of R&D (improvement of prototypes, prototype validation), (2) smarter production (tooling assistance, manufacturing assistance), (3) automation of managerial and operational processes (automation of management, automation of production), and (4) help with decision-making (anticipation, identification, and solving of problems). These results answer RQ1) about the extent to which I4.0 technologies extend the lifetime of manufactured goods. In light of the results, it is fair to state that I4.0 assists in PLE throughout the product lifecycle and especially during R&D, production, and even during usage and disposal. In answer to RQ2) about the process underlying the assistance of smart technologies in PLE, the results further suggest that the four features contribute differently to PLE strategies. While the R&D empowerment and acceleration feature is more directly related to improved product design, the automation of managerial/operational processes as well as decision-making assistance, impact both the maintenance and recovery of (semi-)durable manufactured products. In contrast, the smarter production feature resulting from increased tooling and manufacturing assistance influences the three focal PLE strategies (i.e., improved product design, maintenance, and recovery) altogether.

5.1.1. Contribution to improved design

Mesa et al.'s [52] review emphasized the cruciality of product design for durability. This study shows a notable contribution of I4.0 technologies to PLE via improved product design, principally levied by additive manufacturing/3D printing. Past research emphasized how that technology has a strong effect on PLE and contributes to improving product performance [2,53,54] since it leads to better quality, continuous improvement allowing hyper customization and personalization [50]. Therefore, this technology is at the heart of what I4.0 brings to the sustainability of objects and the transition to a sustainable industry [11,12]. In fact, the features of a high degree of design freedom and shape complexity, as well as customization and personalization that are specific to AM [3], contribute to improving product performance by designing more durable and reliable products [2,53,54].

The results specify that 3D printing contribution to improved product design occurs through empowerment and acceleration of R&D activities as well as smarter production. It is first through the improvement of prototypes that enhanced durability and reliability occur. In contrast to the resource-intensive conventional manufacturing, three-dimensional printing – which allows hyper customization and personalization [50] - increases the opportunities to conduct virtual tests and modeling (before manufacturing a prototype), do real-life tests, and prototyping. Second, it is through the implementation of a smarter production that the contribution of 3D printing to improved product design further occurs. Third, the results confirmed that additive manufacturing provides a "high degree of freedom and high shape complexity, customization and personalization as well as localization" [3, p. 129] which improves both product compatibility [55] and durability [2]. Specifically, the results further explain that it is through the provision of tooling assistance in the form of producing additional tools such as gigs, supports, or racks, but also through producing jigs that the design of a product can be significantly improved.

5.1.2. Contribution to maintenance and recovery

While maintenance refers to activities occurring during a product lifetime and recovery refers to those occurring at the end-of-life stage, they will be grouped together because they were often referred to simultaneously in the results. First, smarter production levied by 3D printing, primarily through manufacturing assistance, contributes not only to improved design but also to maintenance and recovery. In fact, respondents indicated how making a simpler product of quality that is easy to use, repair and recover requires additional effort. Because 3D printing allows for higher shapes and forms complexity, organizations are thus able to increase the preciseness and accuracy of their pieces, components, and overall products to increase their usability but also their reparation and recovery. This finding provides more detail to past research findings specifying that 3D printing creates easier products to assemble and disassemble [51], allowing better maintenance and recovery.

Yet, the most relevant technologies to maintenance and recovery appear to involve Big Data Analytics, Artificial intelligence, and the Internet of Things. Past research emphasized how Big Data and AI facilitate maintenance through problem anticipation and predictive maintenance [50]. Moreover, IoT also facilitates maintenance by enabling remote monitoring and control as well as updates and repairs. Thus, I4.0 allows superior value creation through machine-machine and machine-human interactions [50,56]. Our results validate those conclusions but delve deeper into the process underlying them. On the one hand, the Internet of Things and Big Data contribute to management and production by automating them. Management automation occurs via inventory management automation as well as data management automation, whereas production automation results from manufacturing automation and tests automation (i.e., automating quality management processes). On the other hand, the Internet of Things and artificial intelligence form the substrate of decision support systems since they assist with decision-making via anticipating, identifying, and solving problems. These are possible thanks to the production/product monitoring, tracking, and control underpinned by continuous information-sharing. Albeit the contribution of I4.0 technologies to d assist decision-making is somewhat less marked for recovery, according to the findings, it certainly is for maintenance.

5.2. Managerial implications

Managers of manufacturing companies wishing to integrate I4.0 technologies into their production process could benefit from this study, first, by integrating technologies such as modeling or additive manufacturing into design activities that will allow visualizing, testing, and improving the concepts under development, by printing them with 3D technologies, for example, to continuously improve them and obtain an improved product design at the end. Secondly, by integrating 4.0 technology into maintenance activities, managers will be able to identify problems and perform predictive maintenance by collecting and processing data from their products. In addition, IoT will provide the ability to update and repair products remotely. Thirdly, companies could also improve their recovery activities thanks to 4.0 technologies. As for maintenance activities, repair activities will be facilitated on the one hand by IoT, Big Data, and AI and, on the other hand, by the initial object design made to facilitate recovery. Ultimately, these activities will allow companies to offer better quality and designed products with a longer life span. Finally, beyond the links established between these technologies and PLE, our results also show that companies make other gains, whether it is the acceleration of R&D, economic gains, or minimization of human error, with several impacts, such as efficiency, accuracy, and speed. Implementing one or more of these technologies in manufacturing companies would therefore allow them to be more competitive while contributing to sustainability and the circular economy.

6. Research limitations and avenues for future research

While the study provided an in-depth exploration of the activities of the companies and especially a thorough investigation of three companies, in particular, the number of respondents and companies analyzed is the main limitation of our study. Additional research might conduct similar explorations by increasing the number of respondents as well as the number of parent companies. In addition, although we focused on the main I4.0 technologies whose impact on sustainability had already been discussed [3], this study does not consider other technologies that would impact PLE. Additional research could provide a more exhaustive examination of established and conceptualized relationships between the features of I4.0 technologies and opportunities for PLE.

As this exploratory study draws the first empirical relationships between I4.0 technologies and PLE, it would be interesting to validate those qualitative results quantitatively using a hypothetico-deductive approach and a cross-sectional or longitudinal research methodology on larger samples. Furthermore, additional qualitative inquiries are also needed to replicate findings exploratively or validate findings in other regions and areas. Besides, considering that each technology covered in this study has its own specificities and impacts on PLE, it would also be relevant for future quantitative empirics to focus on one technology, particularly to better assess the relationships between technology and PLE. Finally, to concretely illustrate the improvements in terms of sustainability brought by I4.0 technologies, a comparative case study of the same type of product developed with and without I4.0 support could also be relevant.

7. Conclusion

In conclusion, it is essential to underscore that as sustainability gains prominence, the issues of extending the lifetime of (semi-) durable product lifetime in order to decrease virgin resources extraction and curb the production of residual and solid waste will only grow in importance. Meanwhile, developing smart technologies offers interesting synergistic possibilities to improve product circularity. This exploratory qualitative study of 20 semi-directed, in-depth interviews with business managers shows how a subset of smart technologies (i.e., Internet of Things, Big Data Analytics, Artificial Intelligence, and Additive Manufacturing) may contribute to specific product lifetime extension strategies. The emerging study results suggest that those four technologies enable: (1) empowerment and acceleration of R&D (improvement of prototypes, prototype validation), (2) smarter production (tooling assistance, manufacturing assistance), (3) automation of managerial and operational processes (automation of management, automation of production), and (4) help with decision-making (anticipation, identification, and solving of problems). Additionally, R&D empowerment and acceleration strictly relate to improved product design, whereas automation of managerial/operational processes as well as decision-making assistance, impact both the maintenance and recovery of (semi-)durable manufactured products. Interestingly, smarter production resulting from increased tooling and manufacturing assistance contributes simultaneously to improved product design, maintenance, and recovery. The results have important implications for research in the field and practice.

Ethics statement

The study design was assessed by the ethics committee of the University of Quebec at Chicoutimi (UQAC), and was approved by the board with an ethical approval (#CÉR-2021-634). The authors confirm that the study complies with all regulations. Informed consent has been provided by the respondents since they were informed about the purpose of the study and its voluntary nature.

Author contribution statement

Myriam Ertz: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Florian Gasteau: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data will be made available upon request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Additional quotations by subtopic

EMPOWERMENT AND ACCELERATION OF R&D

Improvement of prototypes

Virtual tests and modeling

"It's with the computer and then the software, by finite elements most of the time. We will find the solution by trial and error because it will be faster with that. I'll put more force or less force, I'll put more thickness there or less thickness there, etc. Once our part is as we want and has the right results in the analysis, we will calculate it in theory. For example, make a calculation on a sheet of paper, the real engineering calculation we have to do." **Raymond, engineer**

"We use Solidworks for manufacturing, for product design, and it's a software program, so we can also do the analysis by finished element in the background. So, there is a way to test products without actually manufacturing them. We can know where it will break first if we put a load on the product, let's say 400 pounds at one end or a shock, whether it's for a product that's going to go in the ambulance, for example, where it's going to bend if a 50G shock happens. All of that, there's a way to find that information virtually." **Bruce, CEO & Co-owner**

Real-life tests

"Well, yes, it speeds up because we are able to take real components that are manufactured by the factory here, ok, and put a prototype that comes from the printer attached to that, and then you are able to see the complete product afterward. With real components, ok manufactured and prototyping that comes from 3D." **Michael, VP operations**

Prototyping

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EMPOWERMENT AND ACCELERATION OF R&D

Improvement of prototypes

Virtual tests and modeling

"It's certain that if we printed all the parts we made before with the 3D printer, it would allow us to see things that we wouldn't have seen on the computer. For example, the interference that would occur when putting bolts in." **Raymond, engineer**

"Before we had a 3D printer, we could have wooden parts made. We were trying to test our concepts and principles, and it's certain that it's more laborious and less precise. Whereas when we can print our part, which will eventually be made in metal, but we make our prototype to validate the concept with plastic, it is much more precise. We can see where there may be potential problems, so there is less risk of errors between the prototype or the concept and reality. We are closer to reality with a 3D printer." **Bruce, CEO & Co-owner**

"We can validate many more principles with the 3D printer, and it will be more aesthetic. It's closer to reality, as I say. It's more accurate as a prototype manufacture." **Bruce, CEO & Co-owner**

Before, we could validate principles with wood, but then we would have the part manufactured in steel with the delays and the price that comes with it, then we would validate. This is the next step: For the first principles, we validated them with steel parts instead of validating them with parts that we could make ourselves. We can do it overnight, while before, we validated them by having them made by a machinist. It could take two or three weeks to get it, whereas now the part is printed overnight, so we save a lot of time." **Bruce, CEO & Co-owner**

Prototype validation

Prototype validation

"Well, taking for granted that sustainability is something that is important to us, it's a requirement, the best thing to validate the requirement is to make sure as soon as possible that it will meet the requirements. We were talking about prototyping and use. For me, the gain is mainly in time. Because we can machine a wooden part, we can order it from a supplier, but we will save time. I don't know to what extent it will have an impact on durability in our case because we work a lot more with metal parts, aluminum among others, but it's certain that durability is an important element for us, no matter which way we go, we'll get there. The gain, for me, in additive manufacturing is much more one of speed. So, we can get to something faster that will help us validate our requirements, and then it comes with the final product. I see it much more like that, a gain in efficiency and, therefore, in the speed of execution since we don't print metal there. If we were printing metal, I would say that we could more easily validate the durability of the product, but this is not the kind of technology we use to validate. Then we would do corrosion tests in an environmental chamber with chemicals. For the durability of our products, additive manufacturing is not where the greatest value is added. In my opinion, it's much more in improving the efficiency of the execution of what we have to do." **Ryan, Dir., Quality**

"I think it's the speed in prototyping. When you think about the 3D printer, it allows us to test concepts faster and easier. That, I think, saves us time." **Bruce, CEO & Co-owner**

"We already have a 3D printing device for several years. It specifically serves us in our research and development department where we print all our prototypes during product development to improve, to develop our products even faster."**Benjamin, CEO**

"If we only dedicate ourselves to concept validations, it reduces the time enormously, the run over time to have a concept in our hands to do the validation. For example, it would take four weeks for folded sheets that we would send for external prototyping. But if we are able to have a concept and print it within a day, it's less waste of time and, for the company, less loss of money at that level. So the concepts and the validation of the concepts are done much more quickly. We have an in-house printer, but also, when the parts are too big, there are specific companies that only do 3D printing with several technologies. There are a lot of technologies related to that, and they offer a service that, within a week, we have, it's still a turnkey service; we receive larger parts for validation. Another example I have is castings. These are molds that would cost several tens of thousands of dollars, and we always have to validate that our concept is correct before making the first casting. We can also machine in a big block of aluminum which costs thousands of dollars, or we can just have 3D printing to do validation in-house, which reduces costs by an astronomical amount there." **Gary, mechanical designer**

"We can easily draw a concept, send it to the printer, and then have it in our hands in one or two days to validate and evolve it to improve the design or the concept. It helps us a lot in terms of time to market or in terms of speed of development because before, for each concept I wanted to validate, I had to have the part or parts quoted externally from one or two, or three suppliers to get a good price. Then placing the order, all that—even at the organizational level, doing a purchase requisition and issuing a PO. After that, the job would go into the job queue at the supplier. It wasn't necessarily done right away. After that, for it to be done, shipped, received, and forwarded to my office, it could easily take a week before I had my part. So, 7 or 8 days before I get my piece to validate a concept, during the time it takes, I can have other ideas, and my concept will already evolve. Sometimes, when I receive the part, it is already out of date, I have already evolved the concept in the meantime. So that's a big bonus now that we have the tool in-house."**Charles, R&D coordinator**

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EMPOWERMENT AND ACCELERATION OF R&D

Improvement of prototypes

Virtual tests and modeling

Finished product visualization

"Lately, we've been doing lids, so we used the 3D printer to make a new lid and test it to see if it was easy for a user to pick up and put back the gun. Was the visual look in line with the identity of the product line as well." **James, Dir., Products**

"It speeds up the decision process, and then by having the prototype in hand, it gives you a better idea of what the product might look like once in industrial production." **Michael, VP operations**

SMARTER PRODUCTION

Tooling assistance

Tooling assistance

"For the moment, the printers we have are essentially for plastic and are therefore used much more for prototyping or for tools for our teams than for the composition of products." **Ryan, Dir., Quality**

"We also use it for production when we need to make a small template for the workstations for different tasks that are done by the people who do the assembly of the products, it's super practical to print templates for production. […] It's just for prototyping and tooling if we want for production." **Andrew, mechanical engineer and co-owner**

Jigs production

"We also make assembly templates, and when we have to make several parts, one part in several copies, we will make an assembly template with this cutting machine. It takes much less time to make the template, and then we make our parts from the template." **Raymond, engineer**

"There is a step called coating. In our case here, 3D printing has allowed us to reduce the manufacturing time of our products. Before we put this coating on the electronic circuit to protect it, we had to spend a lot of time to be able just to protect the areas on which we didn't need to put a coating. Then 3D printing, what it did, is that it was able to make jigs, setups in fact, which allowed masking these areas without the human need to do it manually. He just needs to put it in some kind of template." **Jake, production manager**

Manufacturing assistance

Complexity of forms

"Well, yes, yes, for sure, there is more complexity. They can make much more complex parts and are also more accurate. It's less, how can I say this, the margin of error." **Jake, production manager**

"But now that we have one and the cost is amortized, it's less expensive to draw the part directly when we do the drawing, the complex shapes and so on in the cutting, there is less manufacturing to do." **Raymond, engineer**

Pieces simplification

"Refinement, more precise functions, more durable products, a better knowledge of the weak points of the products. Also, the challenge is to come up with something simple to develop a simple product; when I say simple, it's at all levels: simple to manufacture, assemble, and use. It requires a lot of effort, and all this data helps us. We still have a lot of work to do, but all these tools there help us develop a product that is as simple as possible to use for everyone." **Andrew, mechanical engineer and co-owner**

AUTOMATION OF MANAGERIAL AND OPERATIONAL PROCESSES

Automation of management

Inventory management automation

"In the first quarter of 2016, we implemented the ERP software. The reason why we implemented it is that we had some growth in sales, we added a lot of products, so a lot of parts to manage, and we had a very, very basic accounting system and a lot of Excel sheets on the side for different things for inventory management, production lot management, time management and all that so we wanted to integrate all that into one software. That's when we decided to implement an ERP." **Andrew, mechanical engineer and co-owner**

"4.0 is also about getting information from our customers. Every week, we get information from our main customers on what they have sold, what they have sold in which region, and which products, more specifically. We also see their inventories, which are updated in our systems every week. This allows us to better plan our production, to better plan our sales forecasts. So, we also work closely with our customers at that level." **Benjamin, CEO**

Data management automation

"With data-driven management, you improvise a lot less, you can predict the future a little bit more." **Ryan, Dir., Quality**

"You know, the quality of the products is directly related to the 4.0 technology we use. That is, the fact that the system dictates what to do, controls the processes, and controls the tasks, it's directly related. It just allows us to have a process that is 100% compliant every time." **Stephen, Dir., R&D**

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EMPOWERMENT AND ACCELERATION OF R&D

Improvement of prototypes

Virtual tests and modeling

Automation of production

Manufacturing automation

“When we put on a zipper, we want our steam to stick, come in on the right side, come in on the left side. The same thing with all the cuts until the bottom of the garment. Applying velcro is done in a robotized way. You start the machine, and it will do its operation, and it stops when it’s finished. Someone is operating the machine, but it’s easily done robotically. There are a lot of things in terms of inspection, cutting, laser cutting, and those things. Before, when we did a placement to cut, we did it on the computer. We had to print a piece of paper and put it on the table. Now, it stays in the computer, and the machine cuts anyway.” **Adele, production manager**

Tests automation

For most of our new products, we’ve always designated them for servicing, for manufacturing. One thing we’ve started to bring in our latest product is design for automation. So we automate the test benches. It’s the bottleneck of most of our production lines. It’s going to take us to another level, but before we do that, we design the products to be tested in an automated way in the right way. It’s a culture change, it’s a change in the way we develop projects, but when it’s a 24-month project for a certain product, it makes all the difference if it’s been designed accordingly. So I’d say these are the first mind stones in that direction.” **Philip, CEO**

“Basically, it’s like an automated arm that will come in and cycle the cable in and out of the terminal. We had bought a small piece of equipment for automation, and every thousand cycles, there was a stop, and then we had to go and look at the wear of the parts. Instead of doing it manually, we’re doing it automatically to come in and wear out the parts to see the functionality after several thousand cycles of life.” **Gary, mechanical designer**

HELP WITH DECISION-MAKING

Anticipation, identification, and solving of problems

Production monitoring, tracking, and control

“Everything is interconnected, everything called manufacturing with the Oracle central information system, everything is interconnected. It’s done from A to Z. On my cell phone, I can see exactly from anywhere on the planet the efficiency of each sector in real time, 24 h a day. It’s a need that we configured ourselves for our internal needs, but it’s coming from objects, it’s definitely going into the Internet of Things family.” **Michael, VP operations**

Product monitoring, tracking, and control

“Our products are designed to be connected, so at all times, it gives us a view of the status, what’s going on. It also allows us to create this interconnected network between our products to offer a whole. It becomes a complete network, and that’s achieved through the connectivity that allows us to make the link between the client and the product. We also have a monitoring center that will ensure the health of the products, so we can report various data, alerts, and alarms to know their status and also support someone who calls and says: I’m in front, and it does not work”. We can get a series of data that will allow us to understand and assist that person. The next step for us is to create automatisms with this. So, to detect patterns of failure or patterns that generate future breakdowns. So, make sure to offer predictive maintenance by sending people before it breaks, and then make sure to offer continuous service. We currently have the reading points installed relatively well, we capture the data, and we report it. Now it’s about successfully putting a layer of intelligence in there to predict and accelerate service.” **James, Dir., products**

“In fact, since the objects are connected, it also allows us to make remote updates. So when we detect an improvement, whether it’s based on a bug or a new feature that we want to develop, we can send them in batches, as we say, and update all of our products. It becomes transparent for the owner and the customer; this way, we keep our equipment up to date with the best version we know of, which normally offers the best service. It’s not just patching, it’s also increasing the capacity in terms of functionality as long as the physical hardware that is installed allows it.” **James, Dir., products**

“Right now, if we have problems, we’re able to detect them. We’re able to interact, we’re able to go and get usage information to try to understand the context, how to reproduce the problems, and all that. But of course, the next step will be to evaluate: okay, we know that the terminal has been used so many times, and you know, this is an industry that is not yet very mature. So it’s still difficult to say: we’ve used it 10,000 times, we know that a certain component probably needs to be changed preventively because after a certain number of charges, it’s going to get worse and worse, or we can see that the power delivered decreases over time. So, it’s information in some cases that we have or don’t have, but we don’t do many preventive things with it yet.” **Ryan, Dir., Quality**

“All our connected devices, you have all the history, the operation, you also have the fact that the user can communicate with the bollards. There’s a network that’s there, that sees our bollards in real time what state they’re in. There is an intelligence behind that which allows us to have usage data. We are also able to have the network’s operating status. We are able to see if the terminals are

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EMPOWERMENT AND ACCELERATION OF R&D
Improvement of prototypes
Virtual tests and modeling
functional or broken, what is happening, and how many vehicles are connected. We're able to have a living history of that right now." **Jake, production manager**
"We can get data from the control box by connecting to the computer. We can find out what happened. Okay, there was a 650-pound load that was applied. Our product we ask not to exceed 350 pounds for example. What happened is that the customer, at such and such a time, put so much load for so long, it exceeded the cycles, it exceeded the capacities that we were recommending, so we're going to be able to justify and then protect ourselves from that." **Bruce, CEO & co-owner**
Continuous information sharing
"4.0 also allows us, on each of these workstations, as soon as there is a stop, all the touch screens are called up, so the user can immediately report what the problem is. These problems are also analyzed. If we see that a piece of equipment is continually failing, we will correct it, we will change that piece of equipment. If it is a lack of material, we will check why there is a lack of material on the workstation. The information is there, it is continuous. It allows us to make decisions and to correct the situation." **Benjamin, CEO**
"For example, our more commercial DC charging stations that do fast charging, our previous version had maybe five sensors if I remember correctly, and the current version is between 20 and 30. This means that there are many more signals transmitted to our web software. So in real-time, we can see the anomalies in the terminals. Sometimes it's just flags or maintenance stuff, or if it's not, the terminal is stopped, and a technician has to go there right away. So there are different types of alarms attached to different types of readers, I mean values read by the sensors." **Gary, mechanical designer**

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