Understanding Sociomaterial Transformations in Industry 4.0: An Action Research Study

Completed Research Paper

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Abstract

We propose a lifecycle model for sociomaterial transformation in the emergent fourth industrial revolution (industry 4.0). Canonical action research is our mode of inquiry, conducted in a traditional ceramic company over a period of eighteen months. The findings suggest that the claimed revolution requires the introduction of combined changes in the social and the material, creating new product lifecycles that emerge from the fusion and co-evolution of different materialities. For practice, our study provides concrete examples and accessible guidelines for industry 4.0 roadmaps in traditional industries. For theory, we (1) explain the sociomaterial nature of industry 4.0 transformation, (2) suggest that sociomateriality is an appropriate theory for design and action, and (3) stress the potential of sociomateriality to strengthen the use of action research in information systems.

Keywords: Sociomateriality, industry 4.0, digital transformation, lifecycle assessment, action research

Introduction

Big shifts loom for industry managers. The emerging fourth industrial revolution (aka industry 4.0 or I4.0) will bring significant technological changes involving robotics, simulation, data science, augmented reality, 3D printing and other enablers of digital transformation (Lasi et al. 2014; Weill and Woerner 2015). The pace and the depth of transformations will determine if and how industries will remain competitive, reshaping work practices, business models, corporate strategies, and their relation with entire society, for example, in job creation and destruction, efficiency of energy consumption and reduction of environmental impacts (Majchrzak et al. 2016; Schwab 2015).

Industry 4.0 is defined as a profound transformation in the production systems that not only merge technologies but also blur the boundaries between (1) physical, digital, and biologic domains, (2) products and services, (3) business processes and organizations, and (4) professional and personal lives (Chatterjee et al. 2017; Soldatos et al. 2016; Yoo 2010a). Cyber-physical systems are at the core of this global movement, where the "*physical and the digital level merge*" (Lasi et al. 2014). It requires the investment in new technologies to allow horizontal, vertical, and end-to-end integration in the supply chains (Brettel and Friederichsen 2014). I4.0 is now a top priority for multinational companies, consulting companies, and the IT industry that is investing in innovative platforms to manage production, namely, manufacturing execution systems (MES). However, digitalization and cyber-physical systems are still in an immature state in industry, especially in traditional sectors of the economy (Xu et al. 2018).

Digital transformation is shaping new relations between human and non-human elements in organizations, as it happens with the digital twins (Glaessgen and Stargel 2012). Defined as digital replicas of physical objects, they are gaining popularity in industry 4.0 contexts, for their possibility to sense and interact with the environment using sophisticated simulation algorithms. As stated by Orlikowski and Scott (2008), "*technology is an integral part of the fact of work and its performance in the world*". However, the lifecycle of increasingly intertwined forms of materiality (Østerlie et al. 2012; Whyte 2013; Yoo et al. 2012) is understudied in industry transformations. The digital twins are one of the paradigmatic examples of a digital materiality focus but how do the physical and the digital co-evolve over time? Are digital twins a limited perspective of one form of materiality simply mirroring the other, missing the entire range of opportunities emerging from the dynamics of sociomateriality (Contractor et al. 2011)? These open issues, crucial to industry 4.0, can be investigated using the lens of sociomateriality; a theory that attempts to understand the entanglement of people, organizations, and technology (Orlikowski and Scott 2008). It also provides the frame of reference for this paper, which presents the results of an eighteen-month canonical action research (CAR) study (Susman and Evered 1978) with four complete CAR cycles addressing the challenges of I4.0 in a traditional household ceramic factory.

Motivation of the Study

Our research started in a small ceramic company created twenty-eight years ago. Until the mid-nineties, their production was entirely built to order, and only recently did they consider it to be strategic enough to explore their own portfolio of product designs. They employ fifty-four persons and have an annual revenue of USD2.5m, exporting most of their production to the Unites States and Scandinavia. Figure 1 illustrates the production of household ceramic.

Figure 1. The Context of Ceramic Production - Multiple Molds and Product Models

Household ceramics are produced with molds (leftmost image) and follow a traditional process of conformation, drying, surface treatment, firing, glazing, finishing, and packaging. There are hundreds of different products under production and the layout of these factories is typically chaotic (image in the middle). Most of the production records are paper-based, molds occupy a significant area of the plant and the product portfolio is heavily dependent on the success of product design in international markets. The top customers of the company are multinational distribution companies. More recently, they have established partnerships to create innovative products that include a mixture of ceramics and cork.

The impact of digital transformation is particularly relevant for small and medium sized enterprises (SMEs) consisting of high levels of manual labor. This is the case of European ceramic companies that export most of their production and must be prepared to compete at a global scale. According to the European Commission (2018), this sector is mainly made up of SMEs, representing a value of 28 billion Euros in Europe and over 338.000 direct jobs.

The main challenge of our case company is to meet new consumer demands (that results in increased product complexity and model variations), address short product lifecycles and differentiate itself from its competitors. To help address this, we planned a sector-specific roadmap to comprehensively change the organization. Our objective for impacting practice was to "*radically reconfigure the design and production*" (Yoo 2010b) in this company. Our objective for contribution to theory was to explore merging physical and digital layers (Lasi et al. 2014; Yoo et al. 2012) offering an opportunity to study *what are some unique reasons that the sociomaterial perspective becomes more crucial in I4.0*.

The remainder of our paper is organized as follows: next, we present background literature on sociomateriality and its importance for studying and guiding complex organizational transformations. Then, we present and discuss our option for Susman and Evered (1978)'s canonical action research (CAR). In the following section, our four cycles of CAR are presented according to the dual interest of the problem solving and research proposed by McKay and Marshall (2001), adopting Orlikowski and Scott (2008)'s sociomateriality as our focal theory (Davison et al. 2012). We then discuss the study's implications for practice, for theory, for the needed reinvigoration of action research in our field (Avison et al. 2018), and evaluate our CAR according to the principles provided by Davison et al. (2004) to ensure rigor and validity in this form of inquiry. We conclude this paper by presenting the study's limitations and the opportunities for future research.

Theoretical background

The Potential of Sociomateriality for Changing Organizations

Sociomateriality has been attracting IS researchers since 2007. Its *strong* variant posits that reality only exists in the intra-actions between entities, while its *weak* version concentrates on the stability of arrangements of materials, not rejecting its preexisting forms, attributes and capabilities (Jones 2014). According to this theory, humans and objects are indivisible, although it is possible to consider their differentiation for analytical purposes (Gaskin et al. 2014). Therefore, the mutually dependent ensemble of human and non-human actors can be studied according to different perspectives (Cecez-Kecmanovic et al. 2014; Leonardi and Barley 2010).

It is possible to consider changes in digital and physical materialities. According to Yoo et al. (2012) "*physical materiality refers to artifacts that can be seen and touched, that are generally hard to change, and that connote a sense of place and time* (...) *Digital materiality, in contrast, refers to what the software that is incorporated into an artifact can do by manipulating digital representations*". For example, Østerlie et al. (2012) state that it is important to study different materialities that not only represent the physical world – as it happens, for example, with 3D models of physical assets – but also form part of the physical creation process. The work of Whyte (2013) expands this perspective showing "*how a proposed physical artifact shapes and is shaped by work with digital representations*".

It can be argued that the sociomaterial is inborn to IS studies that address the social and material (e.g. IT) transformations in complex organizational settings. The lens of sociomateriality is contributing to the debate on the foundations of IS and much has already been discussed about the importance of entanglement, disentanglement, and imbrications (Kautz and Jensen 2013). Nevertheless, the dominant forms of inquiry in sociomaterial publications are interpretive case studies and ethnographic studies, with interviews as the key source of data, with the social taking precedence and where "*the technologies, nevertheless, are often fairly mute, typically only represented by human spokespersons*" (Cecez-Kecmanovic et al. 2014). Therefore, relevant research in this area would fit predominately in the Type I – theory for analyzing and Type II – theory for explaining (Gregor 2006), lacking sociomaterial studies to address the need of prediction, design, and action in organizations.

Some authors have suggested that more researchers and practitioners need to apply the sociomateriality lens in design, for example, trough the metaphor of imbrications (Hylving 2017; Leonardi and Rodriguez-Lluesma 2013). Moreover, "*designers should create a practice that enables possibilities for experiences rather than trying to predefine and control a design so it fits a plan*" (Hylving 2017). The entanglement of digital materiality and design practice is well represented in the work of Samdanis and Lee (2017). Their case study of Frank O. Gehry focuses on the digital remediation in architecture to explore conceptual, organizational, and physical spaces (defined as white spaces). They argue that additional research is needed to understand "*the ways in which firms strategically develop technologies (...) in order to facilitate co-creation and open innovation* (...) *to include users*". Sociomateriality is a promising theory to understand and guide the digital transformation supported by I4.0 – involving multiple technologies – and new product lifecycle models (Yoo et al. 2012).

Sociomaterial Transformations in Industry 4.0

Industry 4.0 blurs the boundaries of organizations. New configurations of sociomaterial networks can be created (Contractor et al. 2011), which are temporary, dynamic reconfigurations of the social and material realms, as ongoing negotiations of figures with temporary "*stabilities of sociomaterial assemblages*" (Mazmanian et al. 2014). On one hand, changes that occur in sociomaterial practices can occur over a long period of time, requiring methods suitable to capture its similarities and differences according to the context (Gaskin et al. 2014). On the other hand, materiality, practice, and biography of objects (e.g. technologies) as the center of our analysis also have a dynamic nature, shaping/being shaped by the culture, organizations, and people that use them (O'Raghallaigh et al. 2017). In their recent framework proposal for technological objects O'Raghallaigh et al. (2017) consider that "*while the material aspects of objects may remain static, the biographies of objects can be rather more chaotic*", [...and] *live a number of simultaneous lives which can run concurrently as they partake in different practices simultaneously*".

The dominance of social and material agencies in the sociomateriality practices, objects, and quasi-objects (Gaskin et al. 2014; Hylving 2017; O'Raghallaigh et al. 2017) present changes that need to be studied over time (Weissenfels et al. 2016). For example, Paavola and Miettinen (2018) suggested that three dimensional models used in construction via Building Information Modeling (BIM) provide forms of virtual materiality functioning as co-created intermediated objects "*of joint problem solving and as a concrete but dynamic means for collaboration both virtually and in face-to-face meetings*". Their perspective is aligned with the role of digital materiality for creation (Østerlie et al. 2012) and both present sociomaterial examples of what Harty and Whyte (2010) named hybrid practices in construction, combining the physical and the digital.

The social aspects of industry 4.0 have been studied by Prifti et al. (2017) who propose a competency model for employees with three dimensions: IS, computer sciences, and engineering. Other authors have studied the technological aspects of modeling, cloud computing, and 3D printing, as detailed in the review presented by Liao et al. (2017). It is also possible to find studies on specific functions, for example, how quality managers see the I4.0 barriers and opportunities (Závadská and Závadský 2018). The case studies presented by Hallin et al. (2017) conclude that a digital factory in the steel sector is one in which machines have the capacity to take care of themselves and the production systems become enacted as practices. The authors also state that the entanglement of social and material will be less localized as the decentralization increases with industry 4.0. Inspired by sociomateriality, Srai et al. (2016) recognize that the production materiality is changing in distributed manufacturing as the use of 3D printing increases and products lifecycle are disperse in different parts of the globe. More recently Oberländer et al. (2018) proposed a taxonomy for business to things interactions in the context of IoT (internet of things), which is a key enabler of industry 4.0. However, existing studies did not yet explore sociomateriality dynamics to understand and guide the I4.0 transformation of product lifecycles.

We subscribe to the view of Scott and Orlikowski (2014) that "*given the current evidence of unprecedented shifts associated with technologies in practice* (...) *it may be more germane to develop ways of thinking and working that allow us to investigate a reality that is dynamic, multiple, and entangled*". This is the case of industry 4.0 where resilience is crucial. The recent study presented by Amir and Kant (2018) introduces the concept of *transformability*, defined as the sociotechnical change in response to shock or disruption. They identify three main aspects that affect system response, namely, the organization of information, the sociomaterial structure, and the existing anticipatory practices of unexpected events. The three aspects are important to assist companies in their industrial transformation. First, it is necessary to deal with an increase in information between humans and machines (and between each of them), in decentralized contexts of production. Second, industry 4.0 aims at introducing changes in production technologies and organizational practices in an integrated way (Hallin et al. 2017). Third, the organization must be able to respond quickly to the demands of the market, for example, with products designed for a specific customer and individualized production (Brettel and Friederichsen 2014), anticipating the market trends and the technological evolution.

The necessity to rethink traditional models of product lifecycles (Yoo 2010b), and the opportunity to address sociomaterial transformations in a real organization directed our choice of research approach.

Methodology

Since our research aimed at the dual goal (McKay and Marshall 2001; Susman and Evered 1978) of solving a concrete organizational problem and contribute to our understanding of sociomaterial transformations in I4.0, action research was the selected research approach. According to Baskerville and Wood-Harper (1996), action research is "*one of the few research approaches that we can legitimately employ to study the effects of specific alterations in systems development methodologies in human organizations*". Amongst its multiple possible forms (Baskerville and Wood-Harper 1998) we have selected one of the most popular and well documented (Davison et al. 2004; Susman and Evered 1978) that is the canonical action research (CAR) characterized by five steps (Susman and Evered 1978):

- *Diagnosing*, identifying, or defining the situation. The participants interpret the phenomenon and formulate working hypothesis to be used in the subsequent phases of the CAR cycle;
- *Action planning*, specifying courses of action to improve the problematic situation;
- *Action taking*, causing change to occur and trying to create improvements;
- *Evaluating* the consequences of the actions, involving a critical analysis of the results;
- *Specifying learning*, documenting and defining the outcomes that will add to the body of knowledge.

Theory has an important role in action research (Davison et al. 2012). For example, the study presented by Malaurent and Avison (2016) selected activity theory as their focal theory and business process management as instrumental theory that complement each other "*with the former helping to understand an organizational problem and the latter helping to remedy it*" (Malaurent and Avison 2016). Our research resorts to sociomateriality theory as the focal theory and adapts lifecycle assessment (LCA) (Heijungs et al. 2011; Melville 2010) as an instrumental theory to assist the case organization and propose a lifecycle model for industry transformations in industry 4.0.

According to an extensively cited author in the sociomaterial literature, the "*practice of knowing and being are not isolable; they are mutually implicated. We don't obtain knowledge by standing outside of the world; we know because we are of the world*" (Barad 2007). Both, the sociomateriality theory and the action research literature consider that knowledge is created through intervention in the real world (Leonardi 2013; McKay and Marshall 2001).

Our research considers four CAR cycles presented according to the dual interest of problem solving and research suggested by McKay and Marshall (2001) and it is assessed for rigor and validity according to the principles of Davison et al. (2004): *Principle of the Researcher–Client Agreement; Principle of the Cyclical Process Model; Principle of Theory; Principle of Change through Action; and Principle of Learning through Reflection*. We have conducted multiple cycles in the same organization, which can improve the possibilities of generalization (Kock et al. 2017). Figure 2 illustrates the research cycles.

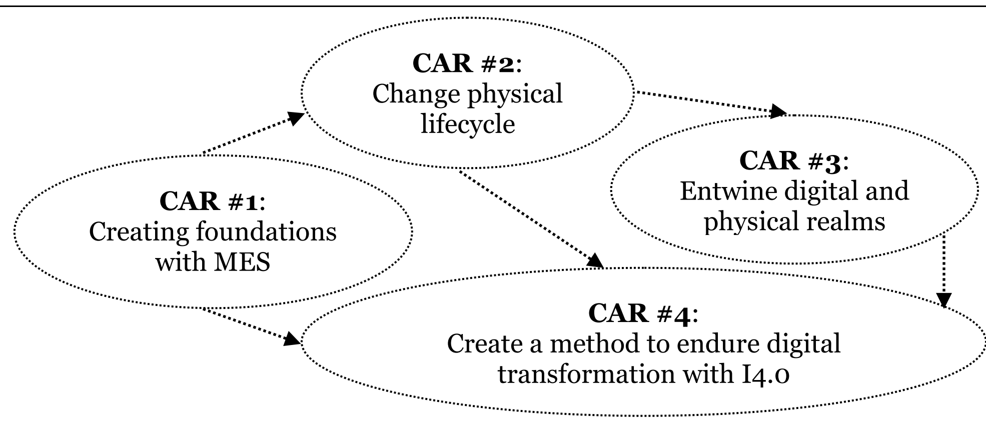

Figure 2. The Sequence of Four Complete CAR Cycles and its Interrelations

The problem to address in the first cycle (September 2016 – September 2017) was the digitalization of production with a cloud-based manufacturing execution system (MES). The lack of basic digital records of production (e.g. products, materials, order management, equipment maintenance) created difficulties to comply to customer demands and improve the product lifecycle with more advanced technologies, for example, additive manufacturing and simulation. Next (2nd cycle: February 2017 – December 2017), we introduced 3D printing in the manufacturing process – one of the key I4.0 technologies. The third cycle (October 2017 – March 2018) explore augmented reality possibilities for ceramic products (twins). Finally, the fourth cycle (February 2017 – March 2018) aimed to create a method to assist the company in their future investments with industry 4.0. Although each cycle had a specific purpose, there were interactions between them, namely, CAR #2 used the MES as a foundation for the introduction of 3D printing in the production process; CAR #3 was only possible due to the creation of 3D models needed for CAR #2; and CAR #4 integrated the insights collected in all the other cycles, in parallel with specific actions to create a guiding model for I4.0 transformation. The next section presents our results.

Results: Lifecycle Approach for Sociomaterial Transformation in Industry 4.0

We'll start our account by describing the actions taken to address the problem solving interest. Next, we detail the contribution for science in the research interest cycle. Although both interests are deeply intertwined and interdependent, its differentiation can contribute to "*maintain rigour and credibility in the knowledge or theory generated through real-life interventions*" (McKay and Marshall 2001).

Problem Solving Interest

Our roadmap for industry 4.0 started with the application of a maturity model to assess the company situation, including the individualization of production, horizontal integration in collaborative networks, and end-to-end digital integration (Brettel and Friederichsen 2014). We also interviewed the company managers and experts of a technological institute, visited similar factories, and studied of the manufacturing lifecycle of ceramic production. Researchers and practitioners identified 3D printing, simulation with augmented reality, cloud, IoT, and mobile as the technologies with most potential for the company. We also identified a lack of digital platforms in our case company to assist manufacturing, difficulties to manage product stock and multiple orders under production, and absence of digital platforms to communicate with external stakeholders (e.g. scenarios of multi-site production).

The first pilot project aimed at solving the lack of information in the manufacturing process, improving stock and order management − material planning, intermediate, and final products. The use of mobile technologies such as tablets and smartphones in the production line was considered appropriate given the company layout (reduced space for new computers), the lack of an IT department, and the cost analysis of the necessary investment. The developed MES includes a module for cloud-based energy management and the use of IoT for equipment monitoring and product traceability. This pilot project allowed the company to improve their manufacturing lifecycle process with real-time information and the possibility to provide a better service to the end customers.

The objective of the second pilot project was to implement additive manufacturing. We enlisted the collaboration from a technology institute to test this process with three main objectives. First, create the company prototypes in different materials. Second, eliminate the ceramic molds and print the final product using ceramic raw materials (individualized production required by I4.0). Third, produce molds with 3D printing – an alternative to printing the products directly. Each option required a meticulous cost-benefit analysis because mold production is still a traditional manual process in ceramics, which could involve changes in job roles, skills to use 3D printers for glaze mold production, factory layout, and product lifecycle. During this project we tested the possibility to eliminate the mold stocks (occupying a significant area of the factory) and print them when necessary. Traditionally, ceramic molds are stored after first use if their conditions are still satisfactory (one mold can be used to produce thousands of products and some orders only require a few). It was evaluated when 3D printing was appropriate and the order history to evaluate the probability of model use in the future − if the probability is low then it was more efficient to destroy the glaze mold (reducing stock) and then print it again when required.

The third pilot project emerged during tests with 3D printing. We found an opportunity to explore the growing number of 3D models (required by the 3D printers) for augmented reality in different phases of the product lifecycle. For example, for quality control during production (confirm product requirements), marketing (simulate product variants – colors, patterns, in trade fairs and showrooms with an augmented reality app), and electronic catalogs (virtual product visualization using QR codes that show the digital model with a smartphone or smart glasses). We also found the necessity to create a “digital warehouse” to manage all the digital assets of the organization and simplified its search, retrieval, and use.

Finally, the fourth pilot project focused on a method to assist the company in their future investments. Industry 4.0 involves a continued transformation; therefore, it requires guidelines and tools to assist managers after the research team leaves the field of intervention. During this phase, we have promoted a workshop with 120 participants of the Portuguese ceramic industry and used a mobile app to gather specific information from the participants in the form of comments and grades about specific enablers of I4.0 (e.g. 3D printing, IoT, cloud-based MES platforms). It became clear that industry 4.0 has sectorial specificities that require a tailored approach to each company, involving the social and multiple forms of materiality. For example, ceramic products – the basis of the industry business, evolves trough a complex interaction of (1) physical transformation supported by digital materialities (e.g. CAD phase), (2) digital transformation assisted by physical materialities (e.g. 3D printed prototypes), (3) social transformation assisted by physical and digital materialities (e.g. layout redesign, new methods), or (4) assisting materialities transformations (e.g. employees training, design process, partnerships with external stakeholders). In fact, the mere concept of “support” that we used to simplify the description is not enough to understand the sociomaterial dynamics of product lifecycle. We found that in some moments, one form of materiality can be temporarily or definitely replaced by other form, as happens when a specific ceramic product is shipped to the customer and its molds are destroyed, continuing the lifecycle in the exclusive form of digital materiality. In this case, the product can evolve through designers’ interaction (e.g. fashion trends) and customer feedback, rematerializing in the future with distinct configurations of social and physical materialities.

Figure 3 illustrates the pilot projects: MES platform (first image on the left, developed in CAR #1), the experiments with electronic catalogs, 3D, cloud, and augmented reality, and the 3D printing system (middle and rightmost image, developed in CAR #2 and CAR #3).

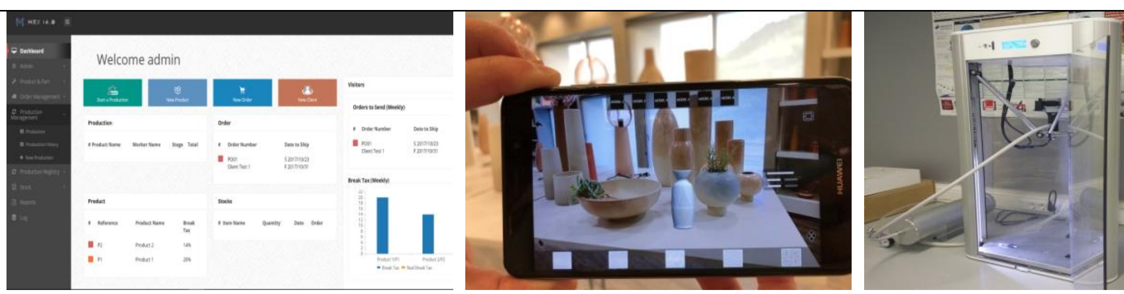

Figure 3. Pilot Projects in the Problem Solving Cycle

Industry 4.0 requires new physical, digital, and social resources. The main physical resources are 3D digital printers, which include plaster and plastics (for prototypes) and ceramic raw materials. Although 3D printing technology is sprouting, the resulting products still require additional processing for parts assembling and defect removal. When the raw material for the 3D printer is ceramic, the result is an intermediate product that needs extra steps to be concluded (e.g. firing, glazing). The entire lifecycle is dependent on the digital resources that appear with the introduction of new technologies, including 3D models of the entire product portfolio, computer aided design (CAD), and MES platforms. The social resources comprise qualified employees, redesigned processes for additive manufacturing and, ultimately, a redesigned business model to allow individual production and end-to-end digital integration.

The lifecycle of ceramics is a situational process of design, transformation, interaction, and co-evolution. Product design is a creative engagement of different stakeholders influenced by market trends, industry constraints (e.g. machinery restrictions), physical and digital tools. To assist the company in this process we found the need to create a digital warehouse of 3D models with metadata to simplify model identification, use, and transformation – during the manufacturing process or in interaction with the end customer. Similarly, the manufacturing process changed to include prototype creation – with the purpose of simulation and test but also as a source for molds development. We also identified the opportunity to take advantage of the 3D models using augmented reality to improve the interaction with external stakeholders using the new combination of physical and digital materialities. To solve this problem, we created an app to assist color and pattern simulations in specific models, available during worldwide household fairs in which our company participates. The practical advantages of this approach are the reduction of physical models in the showrooms, simplifying logistics, the simple creation of electronic catalogs, capturing the attention of the customers and differentiating their offer. The other advantage is to focus the customer in the selection of products according to the existing manufacturing tools and company preferences (e.g. models that reveal lower percentage of defects and rework or that present more possibilities to be integrated for multiple customers at once), lowering the production costs.

According to the company managers, the problem solving cycle was successfully accomplished. First, it contributed to the knowledge about industry 4.0 and the potential of new technologies for their process in particular. Second, it had benefits in layout optimization and real-time information about production. Third, it introduced additive manufacturing and advanced prototyping methods in the organization, with the possibility to shorten the development cycles. Fourth, it identified a form of differentiation in the global market using electronic catalogs and augmented reality to assist in simulation, integrated with the entire lifecycle of the physical product and its digital twin. Fifth, the company obtained a roadmap for their future investments in industry 4.0. We also identified opportunities for future work with big data to identify fashion trends in specific regions of the globe (e.g. colors, popular product models) and assist their designers in launching new product lines. According to the company manager "*we used to manage product lines and now we are interested in managing product generations*".

Research Interest

In parallel with the problem solving interest of each CAR cycle, our research interest was to understand the sociomaterial transformation in industry 4.0. We started our first research cycle with the introduction of a MES to study the changes in the organization. Although necessary to create a digital infrastructure (Venters et al. 2014), this intervention was far from representing a deep transformation to the company practices. In fact, the adoption of MES, IoT and smartphones in the production lines is a mere evolution to them, improving efficiency and real-time information. We learned that it was necessary to create a digital infrastructure to support industry 4.0, but that is just the beginning of the process.

Our second research cycle included additive manufacturing possibilities and the product design with 3D printing. It was possible to address early stages of the product lifecycle and evaluate changes in the work practices, skills, and tools used in the process, namely the possibility to (1) print molds when necessary via their 3D models, (2) print prototypes to assist mold development, or even (3) replace molds with direct printing of the product. The advances were relevant because we tested changes in the process with new physical and digital materialities. Moreover, it was possible to understand the implications in the product design, job change in the product development, and positive impacts in the company layout. According to the company managers, the project could end at this point because they were happy with the results, even if it was not a "revolution". Nevertheless, a new challenge emerged with the proliferation of 3D models and we found an opportunity to go further. The company managers agreed to proceed with an additional research cycle, although not entirely convinced about the benefits that they could get in practice.

Our third research cycle focused on the evolution of the physical product and its digital twin model, the impact of the digital model in the production line and the opportunities to assist the integration of production with external stakeholders (partners, customers, and suppliers). Unlike the typical limitations of digital twins, of merely replicating digital materiality, in our case, the transformation produced several changes in the lifecycle of the ceramic product with implications in the IS and the business model. The transition from a traditional production line to digital production revealed more profound transformations than the mere adoption of industry 4.0 technologies. Only at this stage of the research we faced a significant sociomaterial transformation adopting industry 4.0; one that merges the social, digital, and physical, producing deep transformations in the lifecycle of the company products that were enacted in practice from the interaction with the customers via augmented reality, the characteristics of the physical infrastructure of the factory, the MES, and the machines, and the affordances of the digital twins.

The fourth research cycle occurred simultaneously to the second and third cycles. Although the problem solving interest for this particular company could be fulfilled with a simple roadmap with indications for future steps, our research interest was substantially different and aimed at understanding the differences between a mere evolution and a real transformation in industry 4.0, proposing a sociomaterial lifecycle approach that could assist the industry. According to the lessons learned in the entire project, a lifecycle approach could assist managers in the transformation process. A preliminary exercise with different lifecycle models is presented in Figure 4.

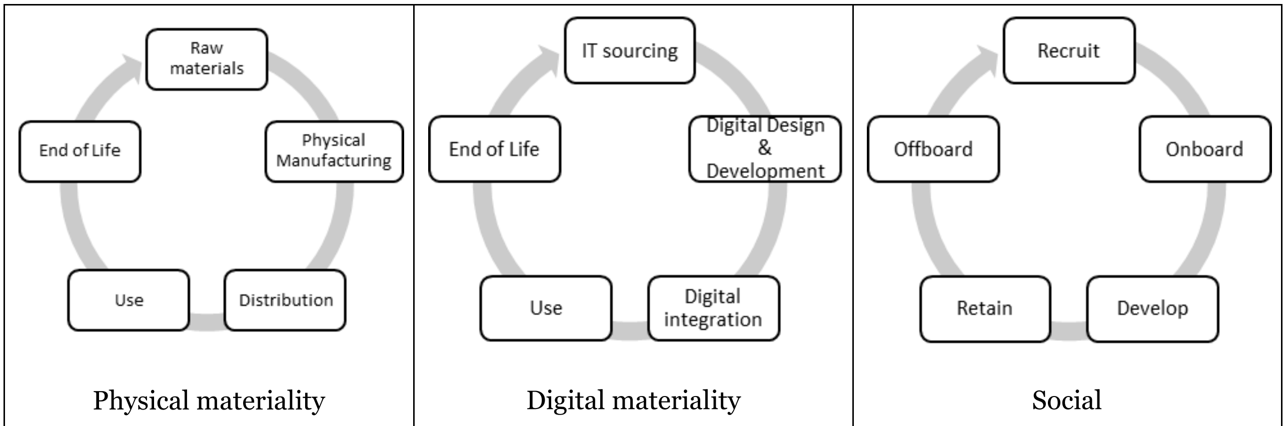

Figure 4. Physical, Digital, and Employee Lifecycles

Figure 4 illustrates why it is not possible to understand the sociomaterial lifecycle according to only one of the components, as we learned since the first cycle of our action research. Physical materiality (first image on the left) is deeply intertwined with digital materiality during design, development, integration, and use of the physical products. For example, in our case company, 3D printing was dependent on the digital models. In another situation, the distribution of the physical product was influenced by using the digital twin (augmented reality simulation). The transformation of one component can impact others, in distinct lifecycle phases (e.g. reducing physical molds via digital replicas that, in turn, require specific training and changes in the manufacturing process). Our findings confirm previous studies suggesting to "*view product architectures as representations that help responding to technological change over time*" (Henfridsson et al. 2014) and explored how "*pervasive technology is interwoven with and is interacting with our more familiar physical materiality*" (Yoo et al. 2012), requiring a new perspective on material agency (Oberländer et al. 2018) in the context of I4.0 transformation of a traditional industry.

Nevertheless, the physical and the digital model can evolve at a different pace (e.g. changes introduced in the model after improvement suggestions made by the customer) and in different contexts (e.g. inside the factory and in use by multiple customers). The social, in this case represented by the employee lifecycle, is not independent of the product development, the digital requirements, and the impact in their work. Moreover, other social aspects that include, for example, organizational changes in the company layout and investments (e.g. 3D printers), are not dissociated from the employees competencies and the product architecture (Yoo 2010b). The lessons learned in the four interrelated cycles allowed us to increase our understanding of the entanglement of social and technical elements in the company setting. It also provided the foundations for the proposal of a sociomaterial transformation lifecycle model presented in Figure 5.

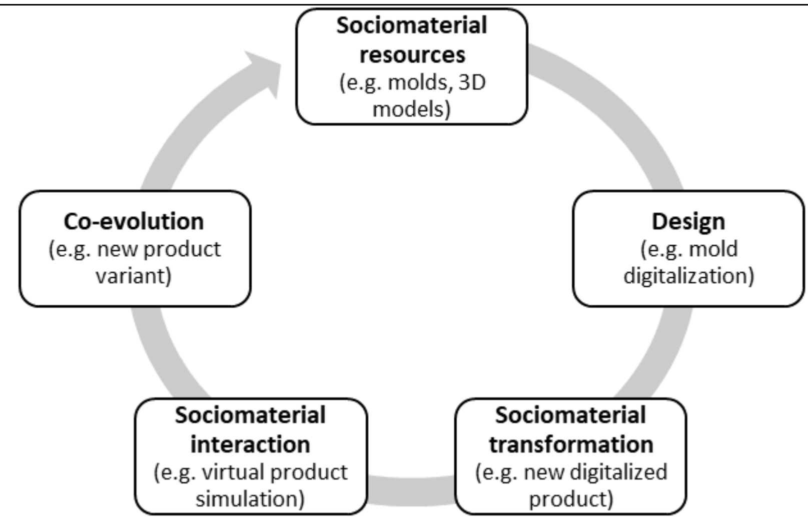

Figure 5. Lifecycle of Sociomaterial Transformation in Industry 4.0

Figure 5 presents an artifact that concretizes learning from our action taking phase (Cole et al. 2005). First, it is necessary to identify and join the synergies of all the organizational resources for the transformation process within the entire product lifecycle. It involves understanding the employees' skills and motivations, preparing company layouts, raw materials acquisition, and IT opportunities. Second, the design phase considers all the – planed and unpredicted actions that create a new sociomaterial configuration (as-is, should-be, to-be). The next state corresponds to the enactment of the physical and digital materialities in the organizational practices, exemplified in our case company by the form of 3D models and the end products. Finally, the interactions that emerge from practice (evolution of the digital and physical twins) will allow sociomaterial elements to co-evolve and produce new generations of routines (Gaskin et al. 2014) and products to the market.

The sociomaterial dynamics produces continuous transformations or "generations" of industrial products, in a cyclic nature. The lifecycle suggests that reality change is partially planned and partially improvised (Bygstad et al. 2010). Although "*we still tend to separate out the social and the material analytically and discursively in our texts*" (Cecez-Kecmanovic et al. 2014), the mangle of practice (Pickering 1993) promotes changes and sociomaterial routines (Gaskin et al. 2014) that cannot be totally understand isolating one of the components. We gathered inspiration in the concept of co-evolution (Benbya and McKelvey 2006) to define this stage of the lifecycle. Although we understand the concept of "revolution" associated with the term, Industry 4.0 is not a single-step process of investment in new technologies or competencies, as we learned in the first CAR cycle and requires additional efforts, as stated by (Yoo et al. 2012) "*firms must spend more time to carefully design, build, and deploy plat- forms and engage in architecting and designing-related standards*". Only the continuous transformation of sociomaterial resources and practices can lead to distinctive advantages in the market, as we found in this company.

Discussion

Implications for Problem Solving

In the fourth industrial revolution, companies benefit from managing the lifecycle of their products as sociomaterial ensembles. Our study shows how a transformational strategy can be biased and limited when focusing on a single element (e.g. digital technology, product) and how the changes become more profound when the roadmap includes sociomaterial transformations. An ideal situation would be a 'cradle-to-cradle' approach to the interrelated lifecycle of physical and digital products, where the end state of a product is involved in the beginning of another. In our case, the end state of each "twin" can be the beginning of a new and different product when compared to the original. The 3D model can be used to create a different physical product and the lifecycle of the physical product can promote changes (e.g.

environmental concerns, fashion trends) in their digital twin. Twins are not synonym of mirrors. Nevertheless, sociomaterial transformations of I4.0 require more effort of coordination between social (e.g. team involvement, training, improvement actions) and material (e.g. investments, simultaneous implementation of different technologies) realms.

The "misalignments" of materiality are also visible when products change due to practical design issues that were not identified in the digital representation, confirming the findings presented by Whyte (2013) in the development of London Heathrow Terminal 5. Moreover, physical and digital materialities can become intermediate objects for the workplace as happens with BIM models (Paavola and Miettinen 2018), not just a mere representation of each other. For example, the 3D models in our case company are useful to simulate changes, interact with the end customer in digital catalogs, and when the physical prototype (which may be produced in a different material such as plastic of glaze) is used to create the molds of the future product replicas. The joint reflection made by researchers and practitioners allowed us to conclude that although the company managers now see digitalization as a deep transformation process and not the mere investments in I4.0 technology, the achievement of distinctive advantages in the market (e.g. the interaction between 3D models used in trade fairs and the production of prototypes) requires a distinct form of managing radical innovation suggested by industry 4.0: "*it will ultimately impact the creation of value by users or customers and can, therefore, transform or disrupt markets and industries*" (Fielt and Gregor 2016).

In this scenario, physical and digital materialities "have their own life" requiring a company strategy that consider sociomateriality as a weapon to compete: removing barriers in product materialities while focusing in product generation lifts. The physical and digital twins may have the same origin, but their evolution creates new social opportunities, as happened in this traditional ceramic company. Moreover, the lack of sociomaterial vision can produce random, undesirable effects in the sociomaterial configurations, for example, deficiencies in employee skills to deal with the process and not taking advantage of potential physical changes in the industrial products that the comprehensive perspective of social and multiple materialities allows.

Implications for Theory

We argue that the fourth industrial revolution is a sociomaterial transformation process and there are three main reasons that justify this claim. First, the mere adoption of new technologies, even the most advanced such as augmented reality and additive manufacturing, will always be simple evolutions of technological elements that may derive (force) minor social changes in the work practice. In this scenario, training actions and minor adaptations in the physical arrangements are necessary. Second, the combination of physical and digital changes, as happened in our second research cycle, allows a higher level of transformation in the company. However, it could have stopped at that moment, not creating new ways of understanding the product, the digital, and the potential organizational changes. We consider that this level of transformation is possible to any company with available capital to invest; however, it is not sufficient for an industrial revolution. According to the findings in our case, to be "revolutionary", it is necessary to introduce changes in the social and the material, creating new product lifecycles that emerge from the fusion of different materialities.

Traditional lifecycle assessment models are not adequate for industry 4.0. Each system (social, digital – informational, and physical) is usually addressed as a separate component in current lifecycle models. For example, LCA for the sustainability of physical products (e.g. IT lifecycle) has been addressed by Stiel and Teuteberg (2013) while Hosseinijou et al. (2014) studied the social lifecycle assessment or S-LCA in the entire lifecycle of material production, use, and disposal. Later, Stiel (2014) proposed a framework to assess the impact of Green IS on physical products, pointing to the need to consider social-technical aspects. In spite of the importance of this research, it does not adopt a sociomaterial stance and are not sufficient to understand the complex ongoing transformations of industry 4.0. To improve this problematic situation, we proposed a comprehensive lifecycle model for sociomaterial transformation.

The first stage of digital transformation in our CAR project was obtained by the introduction of a new technology. The social and physical elements were not significantly affected at this stage. The second stage included social and material (physical and digital) changes with the introduction of new technologies, the changes in the product design, work organization, required skills, digital twin as mirrors of the physical product, and organizational implications (layout). Yet, the transformation was confined to the previous process configuration and we could not find an impact in the company competiveness and product value. The third stage of this research involved the company relation with the market and allowed us to experiment a new level of the digital twin adoption – one that includes entwined lifecycles between the physical and digital materiality. The findings of the third research cycle suggest that, to achieve a deep level of I4.0 transformation, organizations must develop new sociomaterial entanglements. At this level, the lifecycle transformation of the social, the physical, and the digital materiality can only be understood in relation to each other. In this pilot project, the digital twin does not evolve bounded to the physical equivalent; rather achieving specific affordances that shape the organizational routines in market presentations (electronic catalogs using 3D models and augmented reality), product design and simulation, and even replacing physical tools used in the product development (molds).

Our study also advances the theory of sociomateriality. As noted by Gaskin et al. (2014) "*the current dominant empirical inquiry to sociomateriality involves mostly ethnography-based interpretive case studies"*. Interestingly, these authors state that it "*is not sufficient to focus solely on patterns of action, we must also augment this with an understanding of patterns of association between human and material elements of routines (…) Thus, a sociomaterial perspective can seek to leverage more of the use of sequence analytic techniques*". We argue that the "*analytic language, or lexicon, that is consistent with the sociomaterial ontology*" (Gaskin et al. 2014) provides a suitable focus for action research, using sociomateriality lens in Type V theory for design and action (Gregor 2006). Inspired by Cole et al. (2005) advice to include artifact creation in action research to strengthen theoretical contribution, we also found that it is possible and desirable to build artifacts grounded on sociomaterial analysis and action. Moreover, a sociomaterial lens is also able to assist in the creation of new theories for design and action (Gregor 2006), not merely descriptive results of complex phenomena's, as we discuss in the next section.

Particular Implications for Action Research

One of our major challenges in adopting the sociomaterial lens is "*to show what it adds to existing approaches*" (Jones 2014). According to the findings of our literature review, this paper is the first that uses sociomateriality as the focal theory for canonical action research. We acknowledge that the combination of sociomateriality and action research can be seen as a contradiction in our field, positioning the first in the cluster of research-oriented approaches, while the latter much closer to a practice-oriented approach where "*relevance of the contributions to practice that are generated by IS scholars and their externally perceived value are the core concern*" (Avital et al. 2011). Our perspective is that both are important to nurture a thriving IS discipline and can jointly be used in IS research that is rigorous and relevant for theory and practice (McKay and Marshall 2001). For example, the lens of imbrications have inspired recent research in the project management practice and the evolution of shared platforms (Bemgal and Haggerty 2017; Saadatmand et al. 2017). We also agree with the central role of theory in action research (Davison et al. 2012) and argue that sociomateriality lens provide an "*opportunity to reinvigorate AR as an appropriate approach for IS research* [especially, as stated by Doug Vogel, when] *there is the beginning of a shift towards research with more impact which should favor AR* " (Avison et al. 2018). Our study shows how the notions of inseparability and performativity can contribute to reinvigorate action research "*showing not just the entwinement of the social and material, but their mutual constitution, not just how practices are enacted, but how, in doing so, they serve to construct the phenomena they address*" (Jones 2014). The lens of sociomateriality was essential to focus our joint reflection, avoiding the risks of (1) narrowing the discussion in the social changes of CAR and (2) underestimate the equal importance of materiality.

Sociomateriality provided the lens for producing theory and for acting. The discussion and lessons learned (Susman and Evered 1978) were guided by the inevitability of intertwining the social, the technical, and the organizational aspects of digital transformation. During our research we could compare different levels of transformation and concluded that only the sociomaterial level can contribute to develop the fourth industrial revolution. Our problem solving cycle focused joint interventions in the social and in different forms of materiality to assist the organization in their industry 4.0 roadmap. Our joint reflection also concluded that sociomateriality was helpful to discuss the theoretical contribution and avoid the risk of overestimating the practical results of action research, when compared to the scientific contribution.

The definition presented by Finnveden et al. (2009) states that "*Life Cycle Assessment is a tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material* *acquisition, via production and use phases, to waste management*". According to Melville (2010), the "*IS used to enable LCA analysis and LCA analysis of IT hardware—offer rich potential for IS researchers to improve knowledge about sustainability, with implications for scholarly research and management practice*". However, the author also states that "[he does] *not know how and to what extent IS researchers might fruitfully employ LCA*". We present one possible example of employing sociomaterial lifecycle assessment as an instrumental theory for action research.

The dual cycle of action research (McKay and Marshall 2001) provides a valuable framework for reporting action research studies, clarifying the contribution for theory and for practice. When several authors argue that action research is critical to IS due to its close relation to organizational problems (Avison et al. 2018), we contribute to the debate by integrating sociomateriality theory in action research studies, separating the results presentation in its interests of theory building and problem solving.

Evaluating our Action Research

This work addresses a complex sociomaterial context – where it is not possible to know every relevant variable, much less control them individually, posing relevant threats to rigor and validity. For this reason, we have followed the methodological guidance specifically designed to ensure rigor and relevance when using canonical action research (Davison et al. 2004):

Principle of the Researcher–client Agreement

The case organization and the researchers agreed that CAR was a suitable research approach to contribute to science and solve a complex organizational problem in the scope industry 4.0. The ceramic company made an explicit commitment to the project and identified the stakeholders involved. Data collection included interviews, observation, and document collection, safeguarding confidentiality when applicable. The project involved three master students, one Ph.D. student, and two Ph.D. researchers.

Principle of the Cyclical Process Model

The research project followed the five stages of CAR (Susman and Evered 1978) starting with a diagnosis of the company setting. Researchers and company managers developed an action plan and a broad evaluation after action taking. Simultaneously, we considered a differentiation between the problem solving and knowledge interest as proposed by McKay and Marshall (2001). A total of four complete research cycles were conducted during a period of eighteen months.

Principle of Theory

Theory had an essential role in all phases of our research (Davison et al. 2012) that followed a focal sociomateriality theory and adapted an instrumental theory of lifecycle assessment. We confirmed the importance of using a sociomaterial lens for the organizational transformation and for theory building. We compared our findings with the guiding theory, extending the body of knowledge in industry 4.0, sociomateriality theory, and action research.

Principle of Change Through Action

Change occurred in several situations. In the first cycle we have introduced new technologies in the case company, including mobile, cloud, and a MES system, changing the organizational IS. In the sequent cycles we introduced changes in both, the social and the material, manufacturing with 3D printing, and virtual interaction with 3D models. The organization situation was comprehensively evaluated before and after the intervention, ensuring that change was analyzed and documented.

Principle of Learning Through Reflection

We provided progress reports to the company and conducted regular meetings to plan actions and evaluate the results. Learning emerged from a joint reflection during the entire project. At each cycle, we evaluated the findings and the opportunity to proceed to the next stages. We have learned that the (1) fourth industrial revolution is a sociomaterial transformation; (2) sociomateriality can be adopted to guide transformation processes and has benefits in practice-oriented research approaches such as action research. Our results include a lifecycle model for sociomaterial transformation in industry 4.0.

Conclusion

Our study has three main contributions. First, the results of the four complete cycles of CAR have yielded valuable insights to the enduring fourth industrial revolution. To successfully build a genuine industry 4.0 strategy in traditional industries, managers must put into practice a sociomaterial transformation of organizational practices and plan the transformation of different forms of materialities that do not only mirror each other but co-evolve in their interaction. Our research project provides a concrete example with the introduction of mixed technologies that enable industry 4.0 scenarios, namely, augmented reality, cloud, and 3D printing. Based on the results of our case company, we outline a lifecycle for sociomaterial transformation in industry 4.0 that considers the phases of resource preparation, design, transformation, interaction, and co-evolution. We argue that focusing only on independent elements such as the social (e.g. skills, company layout), the physical (e.g. investment in new machines), or the digital (e.g. MES platforms, digital mirrors of the physical products such as 3D models) will simply provide an evolution in the organizational routines and objects, which is a limited perspective of the challenges involved in industry 4.0. Second, our longitudinal field work shows how the lens of sociomateriality can be used to promote transformation in Type V theory for design and action (Gregor 2006), not only to describe and explain phenomena but as a way to produce artifacts that guide action. The way to achieve this goal lead us to the third contribution, which involves using action research with sociomateriality as the focal theory (Davison et al. 2012). As previous research already proved the value of focal theories in CAR (Malaurent and Avison 2016), our study suggests that sociomateriality can strengthen the theoretical robustness of CAR and, simultaneously, guide the problem solving cycle.

Our research has limitations to take into consideration. First, we have restricted our literature review to the scope of industry 4.0 and digital transformation in manufacturing industries, therefore, the proposed lifecycle model can be improved with studies that explore different perspectives of sociomaterial transformations. Second, although our action research evolved in four cycles, it is a single case company; it is advisable to continue the research with different companies and sectors of the economy. Addressing different contexts and technologies can provide exemplars for industrial managers that struggle to find their strategy for a sociomaterial transformation in industry 4.0. Third, although we have proposed a lifecycle model for sociomaterial transformation that adheres to the results of this case company, we only scratched the surface of sociomaterial dynamics. Future research is needed to understand how the entwined physical and digital twins can evolve and provide the necessary resilience for industry transformation, improving transformability – defined as the enhanced organization of information, sociomaterial structure, and anticipatory practices (Amir and Kant 2018). Another possibility is the study of digital traces for industry transformation (Hedman et al. 2013), taking advantage of blockchain technology to ensure product traceability or other properties of digital artifacts such as memorizability (Hedman et al. 2013) to improve physical/digital products with the insights provided by their twin lifecycle (interaction and co-evolution phases of the lifecycle model). Fourth, in spite of the positive feedback gathered from the company managers and other stakeholders, there is a potential risk of the Hawthorn effect (French 1950), which suggests that the results can be affected by the special attention that is received by project participants. We recommend that future research should examine more closely the proposed lifecycle phase of sociomaterial design, namely, to understand how the agencies of human and technologies enact in specific sectors of the economy. The expectations to the future impact of our work are threefold: first, speed up the fourth industrial revolution in traditional sectors of the economy allowing their integration in global supply chains; second, put design and action on the top of the agenda of sociomaterial studies; and third, attest that sociomateriality is a solid theoretical lens to reinvigorate action research in IS.

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