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Material intelligence as a driver for value creation in IoT-enabled business ecosystems

Abstract

Purpose – The purpose of the study is to identify and discuss the role of intelligent materials in the emergence of new business models based on the Internet of Things (IoT). The study suggests new areas for further research to better understand the influences of material intelligence on the business models in industry-wide service ecosystems.

Design/methodology/approach – The study uses data from an earlier study of intelligent materials in the steel industry networks. The insights are based on 34 qualitative interviews among 15 organizations in the industry. The data are reanalyzed for this article.

Findings – Our observations from the steel industry show how material intelligence can be harnessed for value creation in IoT-based business ecosystems. The results suggest that not all 'things' connected to the IoT need to be intelligent, if information related to the things are collected, stored, and shared for collaborative value creation among the actors involved in the business ecosystem.

Research limitations/implications – The study discusses how IoT deployments allow businesses to benefit from the velocity and variety of information associated with things and guides future research to study the ways in which value is created through IoT-enabled business models.

Practical implications – Rather than focusing on improving the efficiency of the supply network, the study presents new paths for competitive advantages in the new IoT ecosystems.

Originality/value – The study contributes to the mounting research on the IoT by identifying and discussing the critical aspects of how IoT can transform business models and supply networks within end-to-end ecosystems.

Keywords – Internet of Things, Business models, Intelligent materials, Closed-loop ecosystems

Paper type – Viewpoint

1 Introduction

One of the underpinnings for the Internet of Things (IoT)-driven transformation of business ecosystems is the ability to trace objects and items throughout their life cycles. Hence, the IoT can fundamentally transform the ways in which organizations create value across industries, not only in the material and equipment supply networks, but also, for example, in the through-life services and closed-loop ecosystems of the circular economy (Westerlund et al., 2014). Such ecosystems are composed of a combination of sensoring, monitoring, and other data collection technologies, as well as infrastructures that support connectivity and processes that exchange information and knowledge for value creation (Bhimani, 2015).

The traceability that IoT enables is not a new point of interest. For more than three decades, the ability to trace items has been of perennial interest in economics as companies in diverse supply networks have striven to improve their productivity, minimize their stock sizes, and decrease lead times (Porter and Millar, 1985). The prospect of tracing items throughout their life cycle is a shared goal among scholars and business practitioners and across industries and scientific communities. Traceability is expected to improve material efficiency and facilitate novel service concepts (Ness et al., 2015). In turn, digitalization is changing the nature of existing products, giving them new properties and generating new possibilities (Porter and Heppelmann, 2014), while the emergence of different networking capabilities is making the world more densely connected (Akyildiz and Vuran, 2010; Atzori et al., 2012). This newfound connectivity can diminish the information gap in product life cycles (Meyer et al., 2009) and help to manage the product life cycles with low costs, but high benefits. Also, it calls for shifting the focus from a single company toward larger business ecosystems (Iansiti and Levien, 2004).

With wireless sensor networks (WSN), all things can be intelligent and interact (Yick et al., 2008). Moreover, as the technology becomes available to a wider public, sensors will be embedded in all products (Porter and Heppelmann, 2014), resulting in so called intelligent products (Yang et al., 2009). This development is rarely challenged. But do the IoT applications really require intelligence in objects? According to some researchers (Meyer et al., 2009), they may not. Many current limitations and problems, such as power consumption of WSN nodes or radio-frequency identification (RFID) sensors (Anastasi et al., 2009; Ranasinghe et al., 2011), can be circumvented when the intelligence is not local. Intelligence generated through networks provides significant possibilities, including making it possible to bring materials to the IoT. The result is *intelligent materials* – something very analogous to intelligent products.

The increasing connectivity and intelligence lead to data that can reshape industries. As manufacturers respond to the changes in their increasingly ecosystem-centric business models, the transformation blurs the existing roles and responsibilities of the actors in material and service supply networks. According to Granta Design, a company selling design solutions to manufacturing companies, detailed material information for a company equals to better, greener, and safer products (Warde et al., 2012). Therefore, the role of material information at an inter-organizational level and its potential impact should be elaborated. These ecosystem-level benefits can be labeled as *material intelligence*. From this observation derives the main research question of our study: *How does material intelligence influence collaborative value creation in industrial ecosystems?*

So, how can we turn the increasing volume of data into valuable information in industry ecosystems? This is the challenge that our viewpoint addresses. The many alternatives to innovating for value creation with intelligent objects have been actively researched, as they are seen as either a requisite or a consequence of the IoT (Haigh, 2014). Continuing the stream of research that has investigated the business models for the IoT (cf., Dijkman et al., 2015), our study shows that the emerging business opportunities based on the connectedness of intelligent materials have the potential to alter the ways in which value is created in an industry. By reanalyzing the data collected through a field study with 15 organizations in the steel industry, this viewpoint article delineates the key questions for business model innovation in industry-wide business ecosystems. We offer an analysis of the current situation and future challenges, and use our prior empirical insights as concrete examples pinpointing how the situation is developing.

The paper is organized as follows: After the introduction, we provide an overview of the literature on the IoT that addresses ways in which to create the intelligence and its potential influences on business models. Thereafter, we present a summary of the insights from an earlier study on the ecosystem-level transformation of value creation induced by the IoT, explaining how the information can be generated and shared in a novel way in the industry ecosystem. We conclude the paper by delineating directions for future research on end-to-end business ecosystems that use the IoT. In so doing, we especially emphasize the implications of IoT-enabled value creation on material supply networks.

2 Background for research

The IoT discussion is rapidly gaining a foothold in the scenario of modern wireless telecommunications. The emergence of the IoT gives rise to increasingly complex and wide-ranging business ecosystems. The term IoT, which was coined at the MIT Auto-ID Center in the late 1990s (Gubbi et al., 2013), refers to a world connected via devices or sensors to systems in which 'things' are linked, monitored, and optimized through diverse Internet technologies. The influence of IoT on business ecosystems is discussed widely in various fields. The debate is based on the notion that IoT will revolutionize production by enabling new possibilities for information-intensive value creation (Wu et al., 2015). As previous studies have shown, there is a strong consensus that adding sensors to all objects will lead to IoT solutions and intelligent systems (e.g., Porter and Heppelmann, 2014, 2015).

However, research explaining the ways in which the IoT will change value creation in business ecosystems remains scarce. Early signs indicate that the discussion surpasses the building blocks of all products, including materials and other intelligent items. In the established view, material is just a necessity, whereas intelligence is generated through automatic add-on sensors. This view can, and should, be challenged.

2.1 Intelligent things as the bedrock for the Internet of Things

The IoT has been suggested to bring on the possibility of having a variety of things or objects around us interacting with each other through unique schemes of interaction (Atzori et al., 2010). Actualization of this vision in the real world calls for integration of enabling technology, such as RFID tags, embedded sensors, actuators, and other devices like smartphones. The resulting new commercial items are most often referred to as smart or intelligent products (Meyer et al., 2009; Porter and Heppelmann, 2014). They increase the manufacturers' direct access to customer data (Ulaga and Reinartz, 2011) and, therefore, enable different kinds of smart services (Allmendinger and Lombreglia, 2005; Wunderlich et al., 2013).

Intelligent products

In an attempt to connect the contesting definitions of intelligent products, Meyer et al. (2009) propose a concept that elaborates on the differences in how the system is constructed. Following Meyer et al. (2009), intelligent products can be classified using three criteria: level of intelligence, location of intelligence, and aggregation level of intelligence. In their model (2009, p. 140), the *level of intelligence* refers to the degree of sophistication of a product. The simplest products, for example, products that contain passive RFID tags, fall into the first category; they are capable of information handling and can communicate their unique identity. In turn, the decision-making category features state-of-the-art products and systems, such as WSN, and in the most extreme cases, they can completely manage their own life and make relevant decisions by themselves (Kärkkäinen et al., 2003; McFarlane et al., 2013).

Location of intelligence refers to the system employed in the decision-making process; does the decision-making process occur at the object itself or through a supporting network? In the first scenario, objects need computational power, storing capacity, and network connectivity (Meyer et al., 2009), whereas in the latter, products operate as interfaces to the intelligence. In an 'intelligence through network' scenario, each product has a virtual counterpart at a remote server (Främling et al., 2003; Meyer et al., 2009).

Since objects are becoming increasingly intelligent, this might lead to products comprising several components which are intelligent. This leads to the third dimension of the model; 'intelligent items' only manage information, make notifications, or make decisions about themselves, whereas 'intelligent containers' are also aware of the components they are made of and may act as middleware, or a product platform (Thomas et al., 2014), for those components. So, the *aggregation level of intelligence* leads to new demands because the components must be able to converse with each other and even survive product platform changes (Meyer et al., 2009), such as in a shift from one product to another.

Intelligent materials

However, it is improbable that add-on sensors will become so affordable that all items and materials can gain intelligence at the object, even in the future. For instance, a medicine bottle that can ask for a refill and schedule a doctor's appointment (Ericsson, 2012) is likely to remain a pipe dream. Therefore, discussion should reassess the possibilities of creating intelligence through a network. The minimum requirement should be that items need only be unique, not intelligent on their own. The items can be equally well identified by, for example, simple quick response (QR) codes or similar tools (Miorandi et al., 2012). By adding these markings not only to products, but also to raw materials, companies can bring them to the IoT, creating *intelligent materials*.

Therefore, the existing classification needs to be refined to incorporate raw material objects into the IoT. To suit objects that do not meet the lowest basic requirements in the Meyer et al.'s model (2009), new points need to be added to two of the axes. Currently, for the aggregation level of intelligence axis, an 'intelligent item' in the model must be able to manage "*information, notifications and/or decisions about itself*" (Meyer et al., 2009, p. 140). As the basic level of intelligence for 'information handling,' the authors require the product to process and communicate its own information gained through sensors, RFID tags, or other techniques since "*without this capability, it [the product] can hardly be called intelligent*" (Meyer et al., 2009, pp. 139–140). While this view, undoubtedly, has merits in emphasizing the ability to manage information as a criterion for intelligence, we would like to extend this criterion to be more holistic. In particular, when the intelligence is generated through a network, we see that the capability of indicating the object's unique identity will be sufficient. We do not take a stand on how the unique identity of an object is achieved, but simple markings or barcodes are more in line with simplicity and the idea of producing intelligence through a network (Främling et al., 2007). The adaptation to Meyer et al.'s (2009) categorization with our presented classification for intelligent materials is illustrated in Figure 1.

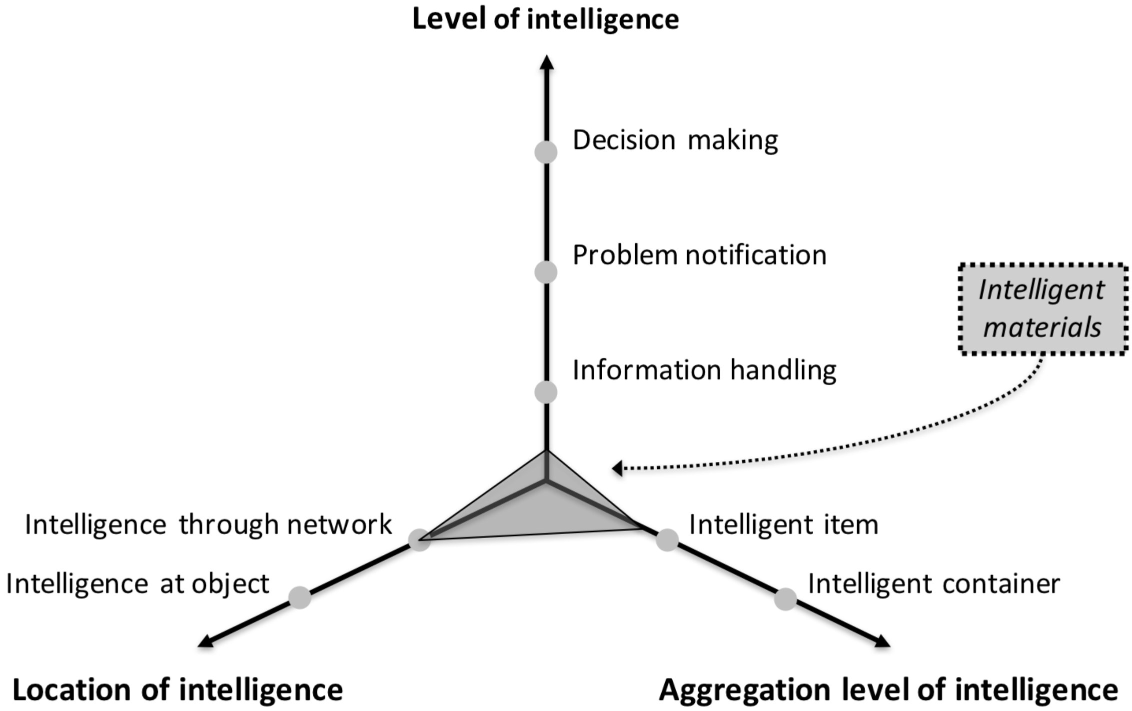

Figure 1 The threefold categorization model for intelligent products, adapted from Meyer et al. (2009)

Leveraging material intelligence by information exchange

While the concept of intelligent materials conforms to existing definitions of intelligent products in many aspects, most importantly the requirement for uniqueness (Kärkkäinen et al., 2003; McFarlane et al., 2003; Ranasinghe et al., 2011), it has some important further implications. For one, the low level of intelligence of the objects dictates that the generated data remain on a very basic level. It is likely that inter-organizational collaboration is needed to turn these data into information and knowledge, which ultimately results in collective *material intelligence.* On a system-level, it will help in creating value with the IoT technologies. To the best of our knowledge, this notion of information exchange between companies that is aimed for collaborative value creation has not been evident in previous IoT discourse. Conversely, the existing solutions designed to create value through better use of information related to goods do not consider material objects as individually unique items, but as a uniform group within a standard (Granta Design, 2016).

There are many reasons to share information in the business ecosystem. Different possibilities for making pieces of material unique should be explored to improve material efficiency (Allwood et al., 2013), facilitate closed-loop material circulation (Kiritsis, 2011), and enable manufacturing companies to provide material as a service (Ness et al., 2015). However, it has been challenging to marry the different perspectives and competing interests. This may explain the inability of steel industry actors in creating systems, which could facilitate the collaboration between actors (Matthyssens et al., 2013), such as intelligent materials. Clearly, companies need a vision of suitable business models that leverage the benefits of collaboration in information management.

2.2 Material intelligence fosters new types of sharing-based business ecosystems

Business models have been a topic of serious interest among scholars over the last decade. In essence, business models seek to explain how companies create and capture value (Zott et al., 2011). They explain how the company delivers value to its customers, entices customers to pay for that value, and converts those payments into profit (Teece, 2010). When evaluating business models, different combinations and approaches can be successful, even within similar constraints.

Industries are moving toward higher information content in products and processes. The information intensity increases when the constant development of information technology enables more extensive connections, easier data collection, and decreased unit costs (Porter and Millar, 1985). Technological development is bound to change the existing business models in different industries like, for example, automation changed the manufacturing industry (Porter and Heppelmann, 2014). However, businesses in which information is the valuable commodity have different rules for success than traditional manufacturing industries (Shapiro and Varian, 1999). As a result, the new technologies have facilitated novel business models that would have been impossible in the past (Casadesus-Masanell and Zhu, 2013).

Information sharing influences actors' roles and responsibilities in the ecosystem

The connections inside business ecosystems have become increasingly important. As the constant technological advancement makes business environments more dynamic, companies need to find strategies to keep up with technological changes (Teece, 2010) and ways to acquire the needed resources and capabilities in the changing environment by adjusting their bundles of capabilities (Barney, 1999). Thus, company-level competition evolves to the ecosystem level (Iansiti and Levien, 2004). Within ecosystem competition, the business model is a tool for firms to align their operational focus, capabilities, and value propositions with those of their strategic partners.

The rise of the ecosystem-oriented business models calls for individual actors' adaptability. To succeed in the long run, companies must be able to evolve their current business models (Casadesus-Masanell and Ricart, 2010; McGahan, 2004) or adopt new ones when their existing model is threatened by obsolescence (Gambardella and McGahan, 2010). This means that the majority of the novel business models emerges from new entrants in the industry, possibly accompanied by completely new technologies (McGrath, 2010), or are targeted to customer segments that the incumbents have not found appealing (Christensen et al., 2015).

IoT-enabled ecosystems are characterized by an environmental dynamism. This drives firms to continuously innovate and develop their strategies and operation to cope with the changing network structures and competitive positions (Brown and Eisenhardt, 1998). Hence, it will further shift the focus from resource ownership toward utilization of external resources that are present in the business ecosystem (Iansiti and Levien, 2004). The ability to use external resources provides greater flexibility for firms to create competitive value propositions.

Connections and collaboration provide the foundations for novel business models

Collaboration is needed to effectively derive value from intelligent materials or products. In the future, smart products and the IoT will lead to rapid accumulation of process-specific manufacturing data (Arica and Powell, 2014). So, as the volume of data expands, gaining more and more data from the same process becomes eventually irrelevant. The point of interest will be in converting the data into information and further into knowledge. In the case of supply chain management systems, it has already been investigated how the ability to share real-time information with other parties leads to improved performance (Pelton and Pappu, 2010). Better information exchange between actors has been proposed as the key advantage of an integrated supply chain (Patterson et al., 2004). Therefore, a successful implementation of such system requires that participating companies derive value from the shared data and information (Fries et al., 2010). New inter-organizational connections are formed as the information-sharing process is established.

Novel business models can be generated by making new connections that enable better use of information. A new business model combines developed technology with its economic value (Chesbrough and Rosenbloom, 2002). Innovative business models are known either to relink existing activities, connect novel activities, or change one or more parties performing the current activities (Amit and Zott, 2012). However, the literature on business models has not emphasized the possibilities of brokering the information flow between actors, in enabling new ideas and innovations for the focal actor, unlike the literature on organizational networks (Burt, 2004; Powell and Grodal, 2006). In the IoT era, the possibilities for new connections expand drastically and, therefore, the ability to broker the information flows provides increasing possibilities. Identifying of important missing connections between actors or sectors becomes important as they can define where new opportunities and competitive advantages lie (García-Muñiz and Vicente, 2014).

To summarize, IoT-enabled information sharing provides novel incentives for creating business ecosystems. The optimal division of labor based on information sharing results in profitability and more sustainable ecosystems. The new models of sharing product data across ecosystem actors resemble those proposed in product life cycle management (Kiritsis, 2011; Kubler et al., 2015). However, attempts to intensify collaboration among actors in the steel industry have stalled due to lack of legitimacy between the potential partners (Matthyssens et al., 2013). The companies' incentives for taking part in the information sharing remain unknown. This is problematic since, according to economics theory, people respond to incentives (Landsburg, 1993). Companies managed by people make no exception. Therefore, when designing systems for inter-organizational information sharing, it is more important to determine *why* to share information than *how* to share it. Our empirical study provided some potential answers for the question of why. For instance, it seems that the IoT data can prove more valuable to some other actor than the focal company. This might help companies stop considering the situation to be a zero-sum game and instead see it as one which can benefit all the involved parties.

3 Empirical insights on the business value of material intelligence

The present study uses data from an earlier study of intelligent materials in steel industry networks. We investigated a globally operating steel industry company, MaterialCo (a pseudonym). The company is exploring the vision of "steel as a message carrier." In addition to creating a comprehensive audit trail, customers could use shared data to automate and optimize their processes. Currently, steel products are considered as homogeneous pieces that conform to a given standard. If enacted successfully, the vision leads to making steel products that are unique. The insights derived from the study are based on 34 qualitative interviews among 15 organizations in the industry. The data are reanalyzed for this article.

3.1 Case setting

Our case study of the steel industry investigated the benefits that could be generated with material intelligence. In particular, we examined how steel industry actors utilize material intelligence in their business operations. The steel industry was selected as the target of this research, since it comprehensively portrays the imminent transition toward utilizing IoT in the industry-wide business ecosystems. The interdisciplinary background of this study rationalizes an abductive research process (Dubois and Gadde, 2002), since the study combines literature from different fields and streams, including IoT, business, and organizational sciences.

At the outset of this study, our informants showed great expectations toward IoT. Steel product manufacturers are forced to compete in an environment defined by fierce competition and low profit margins, with products that are hard to differentiate. Product development and differentiation can be difficult due to rigid standardization processes and customers' tendency to prefer products that they are familiar with. It is understandable how the industry is intrigued by the prospected transformation of steel products. The IoT is expected to affect all parts of the steel industry value chain and to have potential for changing the structure of the entire industry.

This study explores the influences of the IoT in the steel industry and, specifically, how MaterialCo has approached the topic. Together with their partners, MaterialCo has constructed a collaborative inter-organizational network that utilizes detailed information of the materials throughout the life cycle of the material and subsequent products. The detailed material data helps the downstream actors to fine-tune their processes, whereas MaterialCo obtains valuable feedback from their products from their actual usage. In addition to the focal case company, we held interviews with companies in MaterialCo's business ecosystem.

3.2 Data collection and analysis

The research followed an iterative process, which involved continuous reflection of the collected data with the previous knowledge of the phenomenon (Dubois and Gadde, 2002). In systematic combining of empirical and theoretical knowledge, we gained insights from the empirical world, the case environment, theory, and the outlining framework to direct further research (Dubois and Gadde, 2002). We considered all material as usable data (Glaser and

Strauss, 1967), i.e., combining interviews, observational data, workshop meetings, surveys, and public material. The main data source of this research was interviews, but other data sources were used to confirm the validity of the findings made through triangulation (Yin, 2009).

The interviewees were chosen based on their position and experience in the business ecosystem of MaterialCo, acknowledging their relation to the topic of the study. The case study followed a purposive sampling (Eisenhardt, 1989) and semi-structured interview approaches (Yin, 2009), and the interviews were adapted based on previous responses. The interviewees from MaterialCo represented a diverse group across the firm, including high-level managers, sproduct specialists, and industry experts. The interview data were collected in the period between February 2014 and April 2015. We held interviews with the representatives of MaterialCo (n=20) and with companies in its business ecosystem (n=14). The companies act in one or more phases of the steel products' life cycle; primary production (2 companies), assembly and integration (6 companies), use (9 companies), maintenance and repair (4 companies), and sorting and recycling (4 companies). The interviews were recorded and subsequently transcribed. Most of the interviews were conducted face-to-face. All interviewees were offered anonymity.

In order to broaden the perspective of the study, other data sources (field notes, workshops, and company materials) were used to complement the interview material. This was conducted to verify the observations done during this research process. The data were analyzed in an abductive process. An abductive analysis of the material involves simultaneous data collection and theory development, focusing on the active interconnection between the two (Dubois and Gadde, 2002). The data were categorized and dimensioned to identify both similarities within each group and intergroup differences (Eisenhardt, 1989). We used cross-case synthesis for primary analysis technique (Yin, 2009), where the findings from each case could be aggregated by comparing the results to other cases (Eisenhardt, 1989). This method results in revealing similar themes across the cases and the differences among cases, while analyzing the reasons for those differences, resulting in the identification of the common themes that are relevant to the case (Yin, 2009).

3.3 Findings

We propose that intelligent materials can fundamentally change the business models of many industry actors. As information becomes an integral part of the materials and objects processed, companies might find themselves selling information rather than materials. To respond to this change, the dominant business models in the steel industry could transform from those typical in manufacturing to those occurring in information-intensive environments. The level of interaction between the actors is destined to increase as efficiency is sought at the ecosystem level. Also, the interaction will be increasingly focused on making use of the information associated with the thing being produced, assembled, integrated, used, maintained, and recycled.

Lessons learned from the steel industry ecosystem

The abundance of IoT-related information can change the ways in which value is generated and shared in industry ecosystems. In an attempt to demonstrate this effect, we analyzed current business models and networks in the steel industry and tried to identify potential changes in the roles and responsibilities of actors in the end-to-end business ecosystems. Figure 2 shows an example of five different roles for steel industry actors and suggests what kind of information these roles should produce and share within the ecosystem. Starting from the upper left corner, a material producer uses vast amounts of recycled raw material[1] when producing new products,[2] and so it benefits from receiving detailed composition of the recycled scrap.[a] When the produced steel is assembled into products,[3] the next company receives detailed information[b] from the material producer[2] that can be used to optimize the manufacturing process. A detailed bill of materials[c] (BOM) is composed regarding the finished product so the data from usage[4] can be allocated to the specific components. If needed, the product can be easily targeted for callbacks and scheduled maintenance[5] or additional services.[d] The repairs and adjustments made are documented by updating the bill of materials,[c] so the sorting and recycling process[1] can be executed accurately. This brief example loop demonstrates how intelligent materials enhance value creation from the primary processing of the material, products, and solutions to value-adding services throughout the material life cycle.

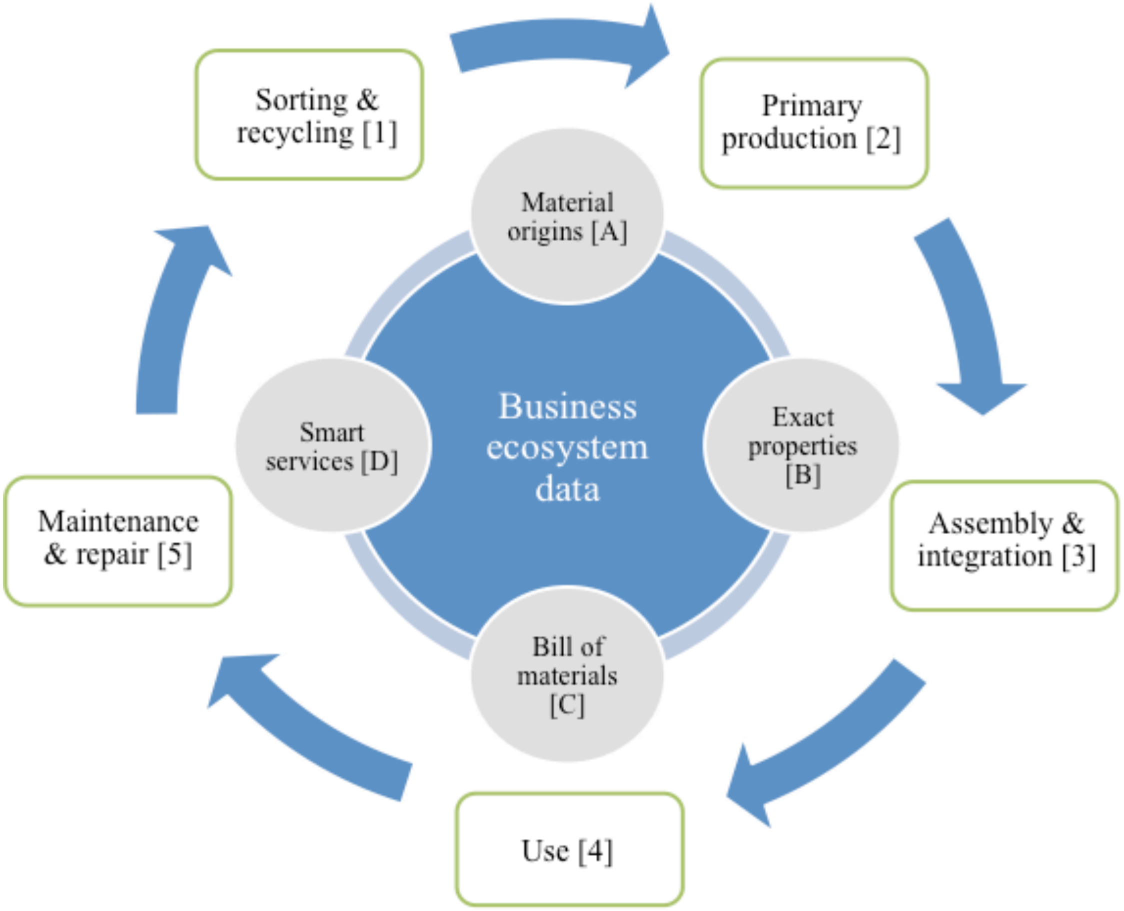

Figure 2 End-to-end business ecosystem for material life cycle services

Intelligent materials will yield new product offerings for industry actors. It seems that along with IoT, the steel industry companies face a transition from the manufacturing domain to the information-intensive business domain. Information becomes a sellable asset rather than raw materials or products. However, it is still unclear how companies can monetize these possibilities. On one hand, they can offer a new service in which the customer's process is optimized. By gaining more refined material information, the customer can exclude variants in the process flow. On the other hand, as the material manufacturer's raw process data can be more valuable to the customers than it is to the producer, one can justify providing this information on the material free of charge. This approach makes the current offering more appealing because the customer can gain more value from the same product.

Material intelligence is a collective affair

Intelligent materials are tools for material intelligence. We propose that to leverage the potential of intelligent materials for business value creation, companies need to focus on adjusting their business models to support new ways of value creation based on information sharing and recombining. Explaining the effects depicted in Figure 2, IoT-related developments will create abundant amounts of data in every process step. However, these data must be converted into information and insights. In fact, our findings indicated that the exact properties[b] from the material producer[2] can prove to be much more valuable to the next actor in the ecosystem because they are used to optimize the manufacturing process. While the primary producer[2] can only accumulate historical data that help to fine-tune the production process, the unique variances in each item[b] can be essential in the next step, when the steel is assembled into products.[3] For example, the elastic response that derives from the stiffness of each steel sheet is a crucial parameter in bending. Without the exact stiffness data, the next actor cannot optimize its bending process. In turn, when the manufacturer[2] receives feedback on suitability[3] and product performance,[4] this will surpass the value of data obtained from the company's own operations. So, for both actors, the data from the other party can prove more valuable than their own. In sum, when intelligent materials are put to effective use across the industry ecosystem, the result can be something of significant value – it becomes material intelligence.

In general terms, all the actors would benefit from the increased information and the increased traceability that intelligent materials produce. These benefits may stem from surprising sources. For instance, in typical material testing, the processes are expedited or the results simulated because the producer is trying to anticipate the materials' behavior in a testing lab over many years to come. The comprehensive audit trail would enable the material producers to gain real-life data on their products from actual usage. While it might sound very ordinary, this prospect has been considered practically impossible in the field of material science in the past.

4 Discussion and conclusions

The present study aimed to investigate how material intelligence influences collaborative value creation in an industry-wide ecosystem. Based on our case study of a steel industry ecosystem, we suggest that sharing data on materials may foster end-to-end business ecosystem for material life cycle services. That is, we find that material intelligence may have a significant role in changing the ways value is created in the steel industry. Materials are constantly developed to achieve better attributes, but this leads to having smaller tolerances. Moreover, the criterion that defines how well the material will suit the next actors' process can be very specific, for instance, when bending thin high-strength steel plates, it is hardness and microstructure on a very particular area on the plates' cross-section (Kaijalainen et al., 2016).

Similar concepts to material intelligence have been introduced recently, aimed for achieving improved usability and a closed-loop life cycle for manufactured goods. These so called 'communicating materials' are capable of communicating and storing data associated with goods, writing new data based on their contingent information during their life cycle, and conveying this information between actors in the value chain (Kubler et al., 2010, 2015). However, the communicating materials proposed by Kubler et al. (2015) are more technologically advanced than what we propose as intelligent materials, as they have both processing and communicating capabilities onboard. The same applies to other previous research, discussing intelligent products (Kiritsis, 2011; Ranasinghe et al., 2011; Yang et al., 2009), or product intelligence (McFarlane et al., 2013). With intelligent materials, the material intelligence can be derived collaboratively by combining the unique identity of each material piece and the data that is generated within each process step. When the two are collected to an external database that all necessary actors in the ecosystem can utilize, such an intelligence of materials can increase the value potential of each product in the value chain. It is also relevant to note that communicating materials are designed to convey predefined, specific messages throughout the product life cycle, for instance, the number of suitable washing cycles on a garment (Kubler et al., 2015). With intelligent materials and material intelligence, the unique items can be coupled with a database that accumulates throughout the product life cycle. This offers the possibility to also retrieve information that was not considered so relevant during the early parts of the product’s life.

4.1 Theoretical implications

The present study has investigated how increasing the intelligence of things stimulates collaboration and information sharing in industrial ecosystems. Combining the empirical insights of our earlier study of intelligent materials in the steel industry networks with the existing body of knowledge in related areas reveals new avenues for research on harnessing material intelligence in business ecosystems. Some critical questions remain unanswered. Based on the insights gained through our empirical investigation of the influences of the IoT on steel industry networks, changes in the competitive dynamics, division of labor, sustainability of value chains, and risks related to sharing information need to be investigated. In particular, there is a need for further theorizing about the role of material intelligence in collaborative value creation.

Information sharing is required to enable material intelligence, but the incentives to take part in data sharing remain unclear. This is a critical perspective on the IoT, but it has not yet received sufficient attention in the research literature. In the literature, scholars have identified numerous important challenges regarding IoT: security, privacy, and data ownership (Whitmore et al., 2015), device and data management (Borgia, 2014), system architecture and design (Mashal et al., 2015), technological constraints like sensors' energy consumption (Anastasi et al., 2009), and the ways to utilize existing social networks in the systems (Atzori et al., 2012, 2014). These topics exemplify that the existing IoT research has focused on how over why. Put differently, the existing research has focused on the technological requirements for companies to construct information-sharing systems, rather than the reasons why companies should participate in the sharing of information on materials.

Insight 1: *Empirically grounded scenarios concerning the ways information can be created, stored, and shared through the IoT, including descriptions who derives value from data sharing, are influential in fostering collaborative value creation based on shared material intelligence.*

Furthermore, our empirical insights shed light on the ways in which the IoT enables value creation for the entire supply chain. Based on our observations, the IoT provides potential for collaborative value creation in industry ecosystems. However, the drivers for the system development remain unclear. The lack of clarity of the potential drivers has led to a situation in which different companies have a mutual desire for data sharing systems, but still fail to create them (Matthyssens et al., 2013). The economic viability of intelligent product systems are unknown, both in the company and the ecosystem level (McFarlane et al., 2013). Therefore, we call for more empirical and conceptual studies on how the collaborative use of IoT, such as material intelligence, can help firms improve material efficiency, utilization of external resources, sustainability of operation, and transformation of the roles and responsibilities of actors in end-to-end business ecosystems.

Insight 2: *Understanding of the incentives for companies to share data within an ecosystem is needed to justify their investments in developing practices for data sharing in IoT-enabled ecosystems.*

We suggest that material intelligence has system-wide influences on business ecosystems. Since material intelligence is intended to create ecosystem-level benefits, companies must understand their role and position in the ecosystem and take a stance on their inter-organizational relationships. They need to choose whether they aim to foster close collaboration and strategic partnerships or stay distant and simply compete in a shared market. Based on our empirical data, there is ambiguity among the actors over such decisions. Firms' boundary decisions have far-reaching effects on the inter-organizational linkages within ecosystems. Naturally, impetuous boundary decisions among the stakeholders may aggravate the lack of legitimacy and trust, both of which are crucial for collaboration (Ahuja, 2000), and therefore inhibit the establishment of information-sharing systems (Matthyssens et al., 2013), such as material intelligence.

To address these issues, more work is needed to determine the appropriate value-sharing mechanisms among supply partners and customers. Thus, we call for more research on the influences of the IoT on supply actors' roles and positions in the ecosystem, as well as on partners' value propositions, value creation strategies, and value capture potential. Changes in these issues are likely to affect network structures and organizational boundaries. Hence, profound insights on business models for IoT ecosystems are needed. In particular, the actors need conceptual tools and models for how to capture a fair share of the value for each of the contributors.

Insight 3: *Evidence of the ways in which the IoT provides competitive advantages in business ecosystems is essential for establishing the practices for sharing value among the actors involved.*

The IoT can change the competitive environment across industries and it may call for decisions between cooperation and competition. In the steel industry, and probably in many other industries, new IoT business models involve systemic innovations (Chesbrough and Teece, 1996). It is possible that the companies will end up in with coopetitive strategies (Brandenburger and Nalebuff, 1998), which simultaneously involve cooperative actions to increase the total size of the market and competitive actions to protect the firm's own position in the growing market. Put differently, innovation in an actor's value creation and capture inherently changes the roles, responsibilities, and opportunities of other actors to create value in the same industry. Hence, we suggest that further research concerning IoT-enhanced business model innovation should increasingly take the dynamics of the business ecosystems into consideration.

The practical solution to mastering material intelligence can be seen as a form of supply chain or industry platform (Gawer and Cusumano, 2014). Thus, it can act as a foundation that becomes the center of an ecosystem that augments the existing products, brings together different actors, and enables them to innovate complementary products, technologies, and services (Eloranta et al., 2016; Suarez and Cusumano, 2009), fostering strong network effects (Eisenmann et al., 2006). However, platforms have an inherent need to balance between openness and control. Openness encourages new participants and makes the platform easier to grow, while control maintains the platform sponsor's proprietary right to affect the platform's technology (Eisenmann et al., 2009) and command over value capture. Therefore, deciding whether the company wants to actively participate in the design and inception of new industry platforms may become an essential managerial decision in the future. To provide an understanding for these decisions, how these entry choices (Zachary et al., 2015) affect the situation should be further investigated.

Insight 4: *The current barriers to employing material intelligence, such as the lack of mutual trust and the interest to participate in novel industry ecosystems have significant effects on the entry choices of actors in industry platforms.*

The complex and continuously changing environment of the IoT forces the ecosystem actors to identify potential information management risks and develop appropriate responses to them. Previous research on the security of information networks has studied how inter-organizational networks can be made more secure (Jarvenpaa and Ives, 1994), as well as the technological risks of IoT, with a special interest on securing the privacy of users (Atzori et al., 2010; Yan et al., 2014). Companies are encouraged to assess what kind of information should be embedded in products, in order to minimize the risks of data breaches (Porter and Heppelmann, 2014, 2015). Increasing awareness of the risks has made companies more cautious toward data sharing. Yet, the outcomes of realized risks are not well known. Further research should place particular emphasis on the business risks related to IoT ecosystems, and the outcomes of fraudulent behaviors within them. In particular, future research could identify what data is valuable for the network, but not too sensitive to be shared. In addition to valuation of IoT investments (Lee and Lee, 2015), better tools are needed to evaluate the business value of IoT data. These might alleviate companies' concerns regarding the potential loss of valuable knowledge. Future research should address the potential risks of participating in information sharing and identify sets of actions to mitigate these risks.

Insight 5: *Explanations of business risks associated with sharing data in the IoT and the methods to assess the economic outcomes of IoT investments are needed to foster material intelligence.*

4.2 Managerial implications

For managers, our findings from the steel industry emphasize the need for continuous innovation in the era of changes induced by the IoT across industries. The key implication of this study for further research and managerial practice is that increased intelligence of materials may fundamentally alter the ecosystem-level competition and the business models of the actors in the industry. The insights derived from our field study and the avenues suggested for further research are relevant for both scholars, who are intrigued by constructing more comprehensive explanations of the changes the IoT will bring on, and business practitioners, who are more interested in developing their competitive position in the IoT-enhanced business ecosystems.

Detailed material information are expected to enable better, greener, and safer products for the companies (Warde et al., 2012). Incorporating materials into the IoT will be important for manufacturing companies as they seek to mitigate process variance in the quest for quality control. Diverse actors throughout the material processing life cycle collect excessive amounts of process data that help them monitor their performance and optimize every part of their process. But manufacturing companies handle materials based on standards and consider different pieces to exhibit the same properties. In reality, no two pieces are exactly the same. As standards merely define the acceptable level of variation for different parameters, the differences within this tolerance may have drastic effects on manufacturing process performance (for a detailed example, see Kaijalainen et al., 2016). Thus, the manufacturers will benefit from knowing the exact parameters of different material pieces, rather than relying on the deviation limits of the standard.

With IoT, the manufacturing value chains will amass large quantities of context-specific data, which can be approached in many ways. These data can be seen either as sellable assets or as complementary supplements to existing products. In our previous studies, companies have expressed intentions to protect the data as sellable, valuable assets. However, successes along this front remains limited. Therefore, it would seem logical that the data can be put into more effective use when utilized collectively inside an ecosystem, benefiting all the participants by making the ecosystem more vigorous. The result is coopetition, which may be a suitable mindset: "*Business is cooperation when it comes to creating a pie, and competition when it comes to dividing it up. This duality can easily make business relationships feel paradoxical. But learning to be comfortable with this duality is the key to success"* (Brandenburger and Nalebuff, 1998, p. 264). This notion seems to have growing importance in the IoT era.

One potential route for manufacturing companies to turn intelligent materials into material intelligence is engaging in coopetition. To take full advantage of the arising possibilities of intelligent materials, they must explore the collective benefits of implementing the enabled uniqueness and traceability in their business environments, and simultaneously compete with each other in producing the best possible offerings in the changing business environment. Intelligent materials can, for instance, enable new types of smart services (Allmendinger and Lombreglia, 2005; Ness et al., 2015) and pave the way toward a circular economy (Allwood, 2014). When the accumulated data from intelligent materials are collaboratively harnessed to produce collective benefits in the business ecosystem, the result is material intelligence.

4.3 Limitations and concluding remarks

Our analysis emphasizes that the existing literature has taken an overly complex perspective of the possibilities to increase the intelligence of objects and materials. The envisioned systems (e.g., Kalay, 2006) may have been suitable for the expected needs, but they have proven impossible to execute using the available technologies. Therefore, it is important to note that the potential value related to intelligent materials, outlined in this work, can be equally well realized using simple methods. This can be achieved by orchestrated action in the business network, based on a smart division of labor and trust among the actors, which enables sharing the information related to intelligent materials and products (Meyer et al., 2009).

In this paper, we posit that intelligent materials are things that have a unique identity, which can be referred to a database to gain detailed material properties. When the intelligence concerning fleets of information-intensive material instances are put to ecosystem-wide use, we refer to the situation as material intelligence. However, the conceptualization of 'intelligent materials' and 'material intelligence' is far from complete. Further research should continue explaining the contingencies in which data associated with intelligent materials turn into material intelligence and what factors make material intelligence valuable in business ecosystems.

Moreover, originating from a study in the steel industry, the present paper delineated the potential roles and responsibilities of actors in one kind of business ecosystem making use of material intelligence. While the insights may be valuable to actors in similar contexts, we call for more research across all manufacturing-intensive industries to gain a better understanding of the contingencies of different industry architectures and the premises by which actors may benefit from material intelligence in diverse IoT-enabled business ecosystems.

Finally, the observations presented in this paper demonstrate that ecosystem-oriented business models shift the focus from competing by resource ownership to learning to utilize the opportunities created by the increasing information intensity of the operations, especially in accumulating material-related knowledge. Eventually, challenges pertaining to management of the mounting information resources, including the velocity, variety, and volume of data (cf., Laney, 2001) within diverse business networks, must be resolved to harness the material intelligence for new value creation.

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