Business Process Management Journal

The Internet of Things in manufacturing innovation processes: Development and application of a conceptual framework

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Revised 30 May 2015
Received 30 August 2015
Accepted 20 October 2015

Abstract

Purpose – The purpose of this paper is to contribute and enrich the scientific debate about the phenomenon called the Internet of Things (IoT) from a managerial perspective. Through the lenses of management and innovation literature, the authors investigate the main facts that characterize the IoT and developed a conceptual framework to interpret its evolution. The framework has then been applied to the case of a three-dimensional (3D) printing technology used for additive manufacturing.
Design/methodology/approach – A theoretical analysis of the phenomenon of the IoT and its main elements has been performed to construct a conceptual framework in a managerial fashion able to describe the evolutionary impacts of the phenomenon on the manufacturing industry.
Findings – Through consequential steps, namely radical, modular, architectural and incremental innovation, and by adopting and integrating the Henderson and Clark model, the authors explain the cornerstones of the evolutionary impact of the IoT on the manufacturing industry. Finally, the authors apply the framework to the case of additive manufacturing and 3D printing.
Practical implications – The framework's practical value is related to its employability in interpreting and possibly forecasting the evolution of manufacturing industries thanks to the advent of the IoT, allowing managers to capture value arising from technological changes.
Originality/value – This study offers a clear and simple model to interpret the impacts of the IoT. Such a goal has been obtained by systematizing the disconnected research on the topic and arranging such contributions into solid paradigms of the managerial literature.

Keywords Innovation, Additive manufacturing, 3D printing, Manufacturing industry, Evolutionary model, Internet of Things (IoT)
Paper type Conceptual paper

1. Introduction

In recent decades, challenges in the competitive arena have grown exponentially. Companies are nowadays experiencing extreme competition, mainly due to increasing pressures from technological changes and global challenges. These "emerging" pressures result in the globalization of manufacturing, characterized by faster transfers of materials, complex payment systems and the compression of products' life cycles, which drive the need for the superior integration of technologies with increasingly

Business Process Management Journal
Vol. 22 No. 2, 2016
pp. 383-402

1463-7154
DOI 10.1108/BPMJ-05-2015-0072

sophisticated customers' needs (e.g. Shepherd and Ahmed, 2000). Successful companies do not only respond to their current customers' or organizational needs, rather they anticipate future trends by developing ideas, products or services to rapidly and effectively meet future demands. Such an ability is an essential requirement to develop and sustain a competitive advantage (Porter, 1985; Peteraf, 1993). Thus, through innovation in products and processes, companies increase their capacity to enter or create new markets and this ultimately represents an key for success (Li *et al.*, 2013; Teece, 2010).

Among all the sets of pressure of a technological nature, the advent of the internet has deeply affected companies' approach to production and has strongly reshaped organizational and operational structures. However, the role of the internet in manufacturing is still understudied as it is for the "Internet of Things" (IoT) phenomenon, i.e. the advent of sophisticated networks of objects and items connected through the web, often equipped with ubiquitous intelligence (Xia *et al.*, 2012). The pertinent literature on the topic is fragmented and mostly focussed on in-depth analyses of specific cases, predominantly with a focus on engineering aspects (e.g. Ashton, 2009; Gubbi *et al.*, 2013; Guinard *et al.*, 2010). Despite acknowledging the fine-grained knowledge retrievable from such cases, such "disconnected" works do not allow for clear possible categorizations and evolutionary roadmaps of the phenomenon of the IoT, especially in terms of managerial implications.

Thus, the aim of this paper is to investigate the main facts that characterize the IoT and through this, theorize a conceptual framework coming from the innovation literature in order to analyze and interpret the past, present and future dimensions of the influence of the IoT on manufacturing. Since the IoT is still a developing concept, our model also contributes by clearly positioning and framing the phenomenon into traditional models of the managerial literature.

The paper is structured as follows. In the first part, we present a wider view of innovation in manufacturing. By using the definition and evolution of Intelligent Products (IPs), we retrace the evolution of the IoT phenomenon in the manufacturing industry, presenting four main facts that have characterized it over recent years. Consequently, we reframe these facts into four evolutionary stages in the light of the most accepted innovation theories in order to build a conceptual framework, while also highlighting the implications for product and process innovations from manufacturing firms. Finally, we apply our conceptual framework to the emerging phenomenon of three-dimensional (3D) printing in the larger sector of additive manufacturing to demonstrate the validity of our model.

2. Manufacturing and the challenges of internet-based technology

Innovation in manufacturing is an historical field of study (e.g. Schroeder *et al.*, 1989). Many empirical studies have linked the survival of firms to the possibility of sustaining a continuous innovation process (Adner and Levinthal, 2001). In a recent systematic literature review on manufacturing, collecting contributions from the period 1993 to 2003, Becheikh *et al.* (2006) clearly show how innovation is considered to be one of the main factors affecting companies' survival. However, it is also true that the actual competitive situation has speeded up the pace of innovation in terms of its discovery, implementation, introduction and diffusion into the market. This has provoked a reinforcing self-fueled loop that has pushed companies to continuously innovate products and services to guarantee a better performance (Lööf and Heshmati, 2006; Prajogo, 2006).

This fact is even truer with the advent of the internet and the third industrial revolution, called the digital revolution (Devaraj *et al.*, 2007). Advanced manufacturing technologies strongly rely on various ICT technologies to achieve higher productivity, higher quality and lower production costs. Such an effect is especially focussed on processes of manufacturing automation, and of information systems (Anaya *et al.*, 2015; Tian *et al.*, 2002).

Indeed, the advent of internet-based technologies has led to the emergence of new manufacturing philosophies and new forms of organization, such as virtual organizations, remote manufacturing, computer-integrated manufacturing systems and internet-based manufacturing, i.e. wireless milling machines, coordinated measuring machines, networked sensor arrays and surveillance systems (Bi *et al.*, 2008; Dewan *et al.*, 2000; Pratt *et al.*, 1997). For example, "design anywhere, manufacture anywhere" is a new approach to production which shares design and manufacturing data across multiple platforms and infrastructures (Kellmereit and Obodovski, 2013; Manenti, 2011). Recent studies have confirmed such trends, indicating that the future of manufacturing firms will be mostly information oriented and knowledge driven, leading to a much more flexible and an abudance of automated operations systems (Davenport and Short, 2003; Li *et al.*, 2010). Any manufacturing technology thus will need to be integrated in a network system and to work in "distributed environments," i.e. environments populated by interconnected physical items and virtual systems able to perform integrated tasks, regardless of the physical location of specific machineries, devices or processes, dealing with different databases or information acquired externally (DaCosta, 2013; Kehoe and Boughton, 2001). The benefits of internet-based solutions within manufacturing environments are recognized, especially in terms of scalability with the demand and of flexibility in deploying and customizing solutions (Dewan *et al.*, 2000).

Cloud-based design and manufacturing provides a good example of these benefits. It refers to a service oriented, networked, product development model in which service consumers are able to configure products or services and reconfigure manufacturing systems (Devaraj and Kohli, 2003).

In detail, "Cloud-Based Manufacturing (CBM) refers to a networked manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource allocation in response to variable-demand customer generated tasking" (Wu *et al.*, 2015, p. 2). Thus, this technology may permit the improvement of operational efficiency by boosting the interaction in business-to-business (B2B) relationships, such as manufacturer-to-wholesaler or wholesaler-to-retailer. Such solutions may reveal promptly a lack of stock regarding a particular item hastening the process of re-ordering. Consequently, this environment provides a structured way to orderly and efficiently store, integrate, manage and control both data and process from manufacturing to distribution (Yusuf *et al.*, 2004). Therefore, internet-based technology by supporting B2B integration, in turn affects the operating performance in terms of cost-cutting, quality, flexibility and delivery performance (Devaraj and Kohli, 2003).

2.1 IoT

As previously noted, production and distribution processes have to face a completely different environment from that of the past. Items or "things" are embedded into the environment, meaning they are continually connected and interacting with each other, exchanging information flows.

This phenomenon has emerged quite recently in the academic and practitioner literature and been given the name of IoT, although some pioneer works on similar topics can be traced back to the beginning of the new millennium (e.g. Kruth *et al.*, 1998; Tian *et al.*, 2002; McFarlane *et al.*, 2003; Yam *et al.*, 2005).

Being in its infancy, the concept has not yet found a shared and univocal definition (Xia *et al.*, 2012). For this reason, a systematization of the whole set of implications and knowledge around the concept is extremely necessary and aimed at through this paper. The following sections will serve such a purpose, elaborating on the scattered and disconnected existing literature to draw a more complete and systemic model.

We begin our discussion by referring to one of the most complete definitions of the IoT, which refers to a networked interconnection of everyday objects and items, which are often equipped with ubiquitous intelligence (Xia *et al.*, 2012). Therefore, the IoT occurs when the object-system is integrated into the internet space, allowing such an object to be constantly connected. Yet another advantage of this phenomenon is that despite a better virtual reachability, such objects remain uniquely identified in a network, even in the vast world of the internet. The IoT environment connects and shares data from inanimate objects, but this can also include sensors connected to living "entities," such as people, animals and plants (Ashton, 2009). For example, this is the case with monitoring biomedical devices, which while monitoring life parameters can autonomously and in real-time deliver such information to the healthcare institutions that can then perform a faster diagnosis and intervene in the case of abnormal values (Rengier *et al.*, 2010).

The IoT is the basic approach employed by many technologies such as Radio Frequency Identification (RFID), Near Field Communications (NFC), Internet Protocol version 6 (IPv6) and/or even the simple wireless connection that allows both mobile and fixed devices to remain constantly connected to the web (Chao *et al.*, 2007; Gubbi *et al.*, 2013; Ilic *et al.*, 2010).

This integration between objects (the IoT) has inevitably also changed the concept of products (Kiritsis, 2011), leading to the emergence of what are called IPs (Meyer *et al.*, 2009), and we will focus our analysis on this specific topic within the large world of the IoT. An IP is defined as an item that: first, possesses a unique identity; second, is capable of communicating effectively with its environment; third, can retain or store data about itself; fourth, deploys a language to display its features and production requirements; and fifth, is capable of participating in or making decisions relevant to its own destiny (McFarlane *et al.*, 2012). Departing from such an inclusive description, we are unpacking all its implications in detail.

Kärkkäinen (2003) analyzed the role of IPs in the supply chain, with a focus on the traceability of products. IPs are constantly monitored and connected along their life cycles and this may provide a consistent flow of information for a supplier to improve production efficiency. The necessity for such innovation comes from the increasing number of product variants, leading to an increased complexity and reduced performance in supply chain management. Such a condition is generated by the large amount of data to be handled, variance of items and increased transaction volumes. Thus, capacity planning and forecasting the demand becomes limited without a clear system of identification for each product, component or variant, both during production and distribution (Holmström, 1997). Processing real-time information "anytime and anywhere" suggests a process that belongs to the IoT paradigm, and this calls for an open, scalable, secure and standardized infrastructure capable of recognizing items with unique identification codes. Thus, IPs' embedding identification codes (Haller, 2010) provide strong data support to the Enterprise Resource Planning (ERP). This process influences all functions, such as purchasing, inventory, sales, marketing, finance and human resources. The ERP is crucial to match suppliers' and customers' needs efficiently in the workflow from production to distribution. This evolution has dramatically changed the production system and generated a new environment that enables items' functions, which were not possible in the past. Therefore, we argue the following:

Fact 1. The IoT is populated by unique identified items.

As we said, IPs are unique identified items; however, such identification also allows the items to be monitored in different environments. IPs continually monitor their status, react to specific conditions and actively communicate with the user (Yan and Huang, 2008). As Ventä (2007) pointed out, this condition leads to wider implications for IPs. For a better understanding of what an IP does in this regard, smart packaging can be taken as a good example. This particular packaging is "a system that is capable of carrying out intelligent functions (such as detecting, sensing, recording, tracing, communicating, and applying scientific logic) to facilitate decision making to extend shelf life, enhance safety, improve quality, provide information, and warn about possible problems" (Yam *et al.*, 2005, p. 2). These functions are responsible for sensing the environment and processing information, they allow the packaging to respond to stimuli from the environment and to become autonomously active in case of trigger events.

Smart packaging can play an important role in facilitating the flow both of materials and information in the supply chain cycle. In the food industry, a smart package can be equipped with a label that offers visual indications of temperature history during distribution and storage. This is critical information, for example in the distribution chain of frozen food products (Caleb *et al.*, 2013). Yet, smart packaging can also incorporate biosensors that detect, record and transmit information pertaining to biochemical reactions in order to ensure the safety conditions of food (López-Gómez *et al.*, 2009). Thus, such intelligent system tracking products, and monitoring their conditions, facilitates real-time data access permitting a rapid response and timely decision-making process (Yam *et al.*, 2005). Due to the availability of such real-time data and interconnections of the items, IPs may be enriched by new functions simply by adding new modules, avoiding a change of paradigm in their structures. Therefore, we argue:

Fact 2. The IoT is populated by active items.

As mentioned above, IPs can also be useful in decision-making processes; however, such a situation occurs only if the items considered are able to produce flows of data. From this perspective, IPs are considered to be a connection between physical products and information-based technology (such as a database) to provide data to a decision maker (McFarlane *et al.*, 2003).

Internet developments, in general, have been largely driven by user-generated contents, i.e. data provided by users, through processes to manage such data. Web 2.0 is the term associated with this kind of development and emerging "star" businesses are indeed web-services firms based on such evolution, including Facebook, YouTube, Twitter and Wikipedia (Fleisch, 2010). Thus, the IoT has increased the complexity of data by adding the self-produce dimension. This innovation in in regard to "things," or part of the connected system that can generate information by itself and automatically provide a new architecture that, for the first time, enables us to measure the world in a cheaper and simpler way (smart objects).

According to what has been premised, IPs have a unique identification, a permanent connection to the decision-maker environment and now we are adding the ability to be "smart." This opens up new frontiers for management whose decisions can now draw upon a large set of high-quality and low-cost information (LaValle *et al.*, 2013; McAfee and Brynjolfsson, 2012). Rental car, car-sharing and logistics companies may be the perfect context in which to see the benefits of the previously described conditions. Vehicles equipped with smart technologies can synchronously be fed with information, i.e. location and status, the decision-making dashboard allowing managers to make prompt decisions based on the actual needs (e.g. Caputo, 2012).

Many business applications in production and the supply chain management can use smart items such as a tagged truck, forklift, pallet, carton and work-in-progress bin. Thus, interconnected objects produce value by producing data flows eligible to be used in business processes. Compared to the past, this information was not accessible in such a direct manner due to the technological limitations of infrastructures and systems (Vitzthum and Konsynski, 2008). Accordingly, we sustain:

Fact 3. The IoT is an environment populated by items that produce flows of data.

Finally, a large number of studies (e.g. Ashton, 2009; Devaraj *et al.*, 2007; Fleisch, 2010; Kiritsis, 2011; Ventä, 2007) have shed some light on the necessity to integrate or embed products and production methods with advanced sensor array technologies to produce and collect data from birth to the end of products and production processes. This group of sensors follows the item from the beginning to the end of its lifecycle and constantly analyzes the environment in order to communicate requested data to the user. Examples of sensor data include temperature, acceleration, localization, orientation, vibration, brightness, humidity, noise, smell, vision, chemical composition and life signals. Those sensors allow a smart thing to constantly sense its condition and environment for relevant movements, and initiate actions based on preprogrammed rules (Fleisch, 2010).

The growth of the IoT in industrial environments also makes manufacturing "smart," not only the objects populating this environment, but with the possibility of a new range of automation and control equipment. In particular, the IoT generates benefits in manufacturing companies by collecting data from sensors and communicating them to plant workers, plant managers, software systems and the supply chain. "Linked together, items can provide humans with a measurement tool that opens the door to many new findings and applications" (Fleisch, 2010, p. 5). This possibility represents an opportunity to be implemented whereby computers can measure an "environment," making available large amounts of detailed information at a reasonable cost.

Consequently, this phenomenon contains a low degree of innovation, but radically changes the way in which firms use the data. This is possible, due to the incremental evolution of the data environment that permits the exchange and use of data between product and process. The main benefit refers to simply reframing the existing module; the product then allows the production of a flow of data that can be used by decision makers (management) to control and be aware of the product and process. Therefore we argue the following:

Fact 4. The IoT is an environment populated by items that constantly exchange data with each other.

These four main facts emanating from the interpretation of the reality and evolution of the IoT, show how this innovation strongly impacts on all manufacturing procedures, and, in turn, has rapidly changed the manufacturing industry in the last decade. The pertinent literature on the IoT phenomenon mostly addresses such facts and implications but in a technical fashion aimed at solving technical and practical problems. However, a more comprehensive and systematic approach able to talk to a "non-technical" audience is still lacking.

Thus, as previously stated, the development of a conceptual framework to systematize the evolution of the IoT concept may be valuable. To do so, first we integrate the above-mentioned four facts with the innovation literature, in particular Henderson and Clark's (1990) model. Then, we interpret the model in a dynamic fashion that explains the different facts in relation to evolutionary stages. Finally, we focus our attention on how this innovation impacts on the product and process innovation outcome, especially in the manufacturing industry.

3. The IoT in manufacturing: a conceptual framework

3.1 Classification of innovations

This section aims to build a "bridge" between the general literature on innovation management and the technical knowledge about the IoT phenomenon. Thus, briefly we will present the conceptual blocks to create and build a coherent, interpretative model.

As we said in the introduction, the innovation process is crucial for firms' survival (Damanpour, 1991; Smith and Tushman, 2005). The internet, and in particular the IoT, creates a dramatic change in manufacturing procedures. This innovation is not easy to understand with the classical paradigms coming from the past. In fact, one of the most cited definitions states that innovation is the "adoption of an internally generated or purchased device, system, policy, program, process, product, or service that is new to the adopting organization" (Damanpour, 1991, p. 556). Another famous definition of innovation applied to the manufacturing industry is the dichotomy product versus process innovation (Adner and Levinthal, 2001; Crossan and Apaydin, 2010; Utterback and Abernathy, 1975).

However, this classical dichotomist classification does not completely allow us to grasp the complexity of the IoT era.

Product innovation refers to new products and services introduced in the market, usually to meet the customer's latent needs (Damanpour, 1991). In manufacturing, however, this concern focusses on the outputs of production. In this regard, the IoT enables firms to make available on the market items such as wearable devices that, by virtue of a proper environment, are able to connect, gain and transmit data from sensors through the internet (Swan, 2012).

On the other hand, process innovation refers to new elements introduced into a firm's operations and production processes, such as new materials, machinery or information workflows. Thus, it consists of changes of production processes of the product/service, and may not necessarily have explicit impact on the final output, while increasing the productivity and/or reducing producing costs (Damanpour, 1991; Utterback and Abernathy, 1975). The IoT embeds microelectromechanical systems including accelerometers, gyroscopes and magnetometers, which are a good example of process innovations. The IoT makes it possible to create a new range of products totally independently, especially in manufacturing, where production will become more networked until everything is interlinked with everything else.

According to this definition, product and process innovations are useful to comprehend the outcome of the IoT but seem not to be sufficient to understand within a wider approach to the phenomenon. Thus, this dichotomy can be enlarged by using the model of Henderson and Clark (1990) based on four dimensions; two more traditional for the innovation literature known as radical and incremental (e.g. Dewar and Dutton, 1986), the others, i.e. architectural and modular that consider the innovation as a system and as such, addresses problems of the whole and its parts. Yet, this wider approach understands the discontinuity of an innovation by reason of its environment too, and this seems perfectly fitting to explain the IoT phenomenon.

Radical Innovations create dramatic changes that transform an actual paradigm of competition, existing markets or industries. A radical or disruptive innovation could, for example, change the structure of the market, create new markets or render existing products obsolete, therefore increasing uncertainty. However, it might not be immediately clear that an innovation is disruptive until a long period after its introduction as it generally focusses on processes, products or services with unprecedented performance features (Sood and Tellis, 2005). Incremental innovation is not about huge sweeping changes. Firms that innovate incrementally tend to do so just a little bit at a time, exploiting existing technology and focussing on cost or feature improvements in existing products, services, processes, organizations, and/or methods whose performances have been enhanced or upgraded (Norman and Verganti, 2014). This innovation can take place in two forms: first, a simple product can be improved by employing higher performance components or materials; or second, a complex product comprising a number of integrated technical subsystems may be improved by partial changes to one of the subsystems.

Modular innovation may result in the complete redesign of core components, while leaving linkages between the components unchanged. Modular innovations will require new knowledge for one or more components, but the architecture remains unchanged. However, modular innovation does involve new, or at least significantly different, components. The use of new or different components is the key feature of modular innovation, especially if the new components embrace a new technology. New technology can transform the way in which one or more components within the overall system operate, but the system and its configuration/architecture remain unchanged. On the other hand, architectural innovation changes the nature of interactions between core components, while reinforcing the core design concepts. Components need to be interconnected tighter with a proper architecture that generally evolves after a major component upgrade. This type of innovation will have a great impact upon the linkage of components, but the single components will remain the same (Henderson and Clark, 1990; Magnusson *et al.*, 2003).

3.2 Presentation of a dual axis model: component vs architecture

Having presented the Henderson and Clark (1990) model, we use such a "theoretical compass" to systematize the four facts characterizing the IoT phenomenon. To do so we are going to develop, first a dual axis model that we will later interpret in a dynamic fashion, showing the evolutionary path of the IoT in manufacturing. In our model, the axes represent the innovation either on the architecture of a system (or the whole) or on a single component (or part). Specifically, the architecture (associated with the axis *x*) is a system of inter-linking elements or subsystems and its outcomes comprise the overall task or purpose for which the system is designed. The system can be interchangeably a product, a process or an organization, as we premise. The component, on the other hand (associated with axis *y*), represents a specific part, element or subsystem of a broader environment that is devoted to a specific function. Surely then, the impact of the innovation on both elements, i.e. architecture and component, can be high or moderate. Thus, crossing such dimensions, and focussing on the innovation and intensity of such an impact, we can obtain the model that we are going to use to explain and interpret the IoT phenomenon.

A high innovation impact on both architecture and components (quadrant 1) is completely redesigned and the whole system ends up with a possible completely new system; in managerial terms this results in new markets and opportunities (radical innovation). However, the impact of innovation can be very high on only a component, part or subsystem, but the overall system structure may remain substantially unchanged (quadrant 2). In this case, the system is integrated and upgraded by new functions (modular innovation). Conversely, an innovation may leave unchanged the single parts of a system but deeply reshape the interconnections between them (quadrant 3). In this case, the effect is a possible innovative purpose and employability of the re-assembled system (architectural innovation). Finally, an innovation may have a low impact both in terms of architecture and components, and in this case the overall effect is limited (quadrant 4). This is the case of an improved performance of existing functions (incremental innovation).

Having stated the general model, we position the aforementioned facts about the IoT to build a specific model for this context (Figure 1). *Fact 1* is characterized by both a high impact on components and a high impact on architecture; *Fact 2* is characterized by a high impact on components and a low impact on architecture; *Fact 3* is characterized by a low impact on components and a high impact on architecture; finally, *Fact 4* is characterized by both a low impact on components and a low impact on architecture.

The presented model has not only a descriptive purpose; in a dynamic fashion, the four facts characterizing the IoT can also represent evolutionary stages, describing the shifts between different categories of innovation that took place. *Stage 1*, which stems from *Fact 1*, is the starting point of this innovation, as for most of the innovation discontinuities. This shift dramatically changed both the architecture and component, and started the revolution of the IPs. According to Kärkkäinen (2003), items are able to be unique and fully traceable among all of the supply chain and the user experience. This is a purely radical innovation because it breaks through all past manufacturer and user experience. *Stage 2* is not a paradigm shift. The architecture that connects the objects does not change, but added components permit the object to autonomously interact, so as

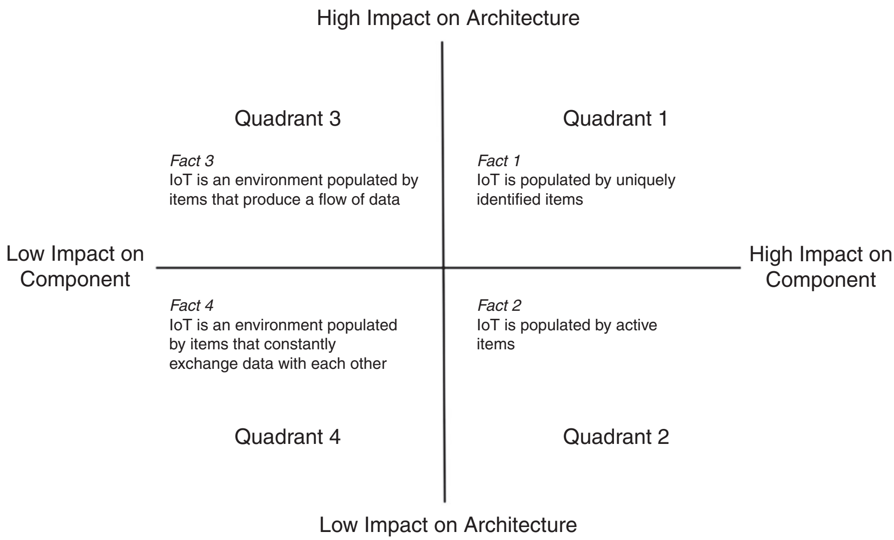

Figure 1.
A dual axis model

to be "active" (*Fact 2*), with the environment in which they are embedded, thanks to sensing and active modules. Consequently *Stage 3* is an architectural shift; the new interconnections between objects and sensors permit the transfer of information across a network of the web, producing big flows of data (Big Data) (*Fact 3*). Thanks to the IoT environment, the information produced directly by the items is not isolated, but evolves in a populated environment made by other active and interconnected items. This is what we actually define as the IoT; thus *Stage 4* is the final shift of the evolution, and simply regards the way in which a firm can be able to use the data. *Stage 4* is the natural evolution among the previous phases. The first involves the IoT as an environment populated by unique identified items; the second shows the IoT as a "world" composed by active items, and the third shows the IoT as a complex environment where items, as a result of the aforementioned facts, produces a constant flow of data. Thus, *Stage 4* regards not the data themselves, but the use of data. It involves the knowledge produced by items as a base for decision making; it involves the awareness of an interconnected environment. The level of technology advancement in this final step is very low but has more impact on firms because it permits the use of items to respond and make decisions in a completely new way. The facts shown before also have an impact in terms of the evolutionary process of this innovation.

Despite the definition of innovation for the IoT used by Gubbi *et al.*, they stated an articulated definition that covers our model. They stated that the IoT is "a radical evolution of the current Internet into a network of interconnected objects that not only harvests information from the environment (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analytics, applications, and communications" (Gubbi *et al.*, 2013, p. 1646).

This definition considers that the IoT phenomenon has occurred in a single moment and this would justify the use of the only concept of radical innovation; however, our model by taking into account all of these features proposes a better fit of the impact of the IoT in the manufacturing industry, also considering an evolutionary perspective (Figure 2).

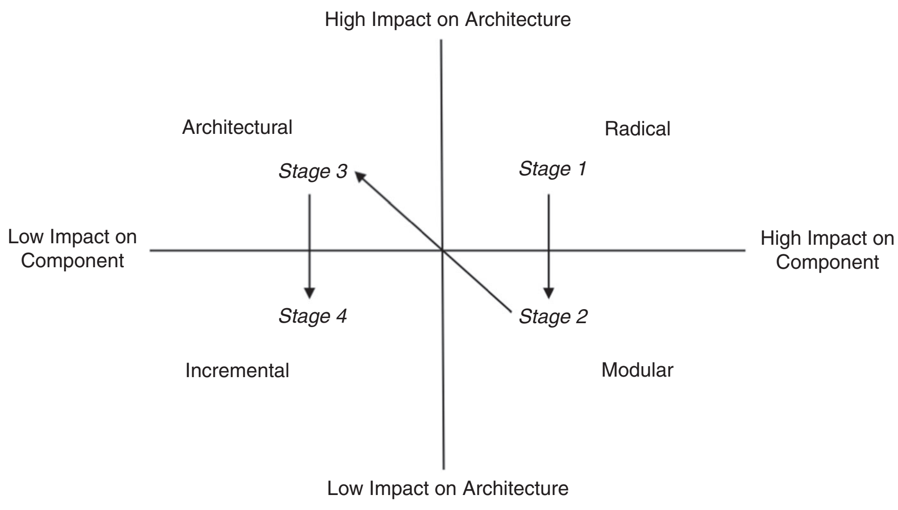

Figure 2.
The evolution of the dual axis model

We want to add a final clarification of this dynamic perspective. The IoT has provides a continuous inflow of "innovation" for the business context. Despite that, the evolution that it is presented today seems to be near to saturation, and thus we may soon expect a new, radical renewal for such a phenomenon. Indeed, the IoT through its stages presents a constantly decreasing level of innovativeness described in a visual fashion in Figure 3 and analytically in Table I. In other words, the IoT was a completely new innovation, i.e. radical, in the first stage of its evolution. However, in the long run, it evolved with modular, architectural and incremental innovations that are defined with a lower level of innovativeness, although with increasing functions and complexities of the final product (Adner and Levinthal, 2001; Crossan and Apaydin, 2010; Dewar and Dutton, 1986; Ettlie *et al.*, 1984; Henderson and Clark, 1990; Utterback and Abernathy, 1975). The modular innovation introduces new components but under the same architectural structure (*Stage 2*); the architectural innovation brings a new structure by reconfiguring previous components (*Stage 3*); finally, the incremental innovation simply boosts the performance of existing components and architectures (*Stage 4*).

3.3 Product and process implications of the IoT

At this point in our discussion it is useful to close the circle of our argument and relate our model to the product and process implications of the IoT in manufacturing. We have so far classified the different types of innovations in manufacturing to develop a dual axis model by integrating the Henderson and Clark model with the four facts characterizing the IoT. Now, our logical process brings us back, within this section, to relate our model to the original classification of product and process innovation (Figure 4).

The first thee facts generally influence product innovation. Indeed, *Stage 1* makes it possible to produce revolutionary and breakthrough items, a new product is developed and introduced. *Stage 2* involves, generally, the product function due to new equipment

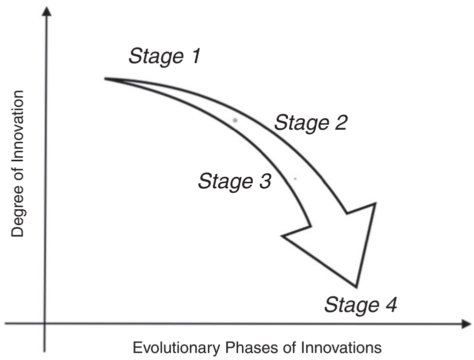

Figure 3. Degree of innovation and evolutionary phases of innovations

Table I. Summary of the model

Innovation	Components	Linkage between components	Facts	Stages
Radical	New	Reconfigured	*Fact 1*	*Stage 1*
Modular	New	Minor change	*Fact 2*	*Stage 2*
Architectural	Improved	Reconfigured	*Fact 3*	*Stage 3*
Incremental	Improved	Minor change	*Fact 4*	*Stage 4*

enabling items to sense the environment, new modules being introduced to the existing product and thus making it "smarter." *Stage 3* is in regard to the process of data production, when the architecture is developed to gather and utilize data.

This evolutionary process involving the first three stages leads us to the importance of Big Data. Indeed, the rise of Big Data in manufacturing procedures allows a huge amount of data to be available for integration in the production and distribution processes. The impact of the IoT is therefore not negligible. Recent literature has also investigated the importance of process innovation as a source of competitive advantage and its importance to sustain firms' development over the years (Damanpour, 2010). The importance of environmental and organizational determinants, as key factors that influence the dynamic of product and process innovations, are underlined (Damanpour and Schneider, 2006; Reichstein and Salter, 2006).

Finally, *Stage 4* implies how these data are used in strategic decision making to promote process optimization. This final step involves only processes inside firms by redesigning the decision-making processes, thanks to the availability of data.

4. Applied conceptual framework: the case of additive manufacturing

To represent our conceptual framework in a wider perspective, we apply the developed dual axis model to a revolution that is happening in various industries: additive manufacturing. Additive manufacturing represents a technological innovation that in recent years has attracted growing interest and is proving to be a viable trajectory for technological innovation in different sectors. It is certainly a current topic; however, at the academic level, the problems related to this innovation have been addressed almost exclusively from a technical point of view within optical engineering or architecture and design. The novelty of our paper is therefore to address this innovation from a management perspective through the application of the conceptual framework developed in this paper.

4.1 Additive manufacturing

Additive manufacturing, i.e. the production of items through the sedimentation of layers, fits in the wider context of digital manufacturing (Lee *et al.*, 2011), which for decades has been seen as an integration of digital and manufacturing technologies through the automatic control of machinery and computers. The Big Data environment, through information sharing made possible by the spread of the internet, additionally increased its use (Lucke *et al.*, 2008; Zuehlke, 2010).

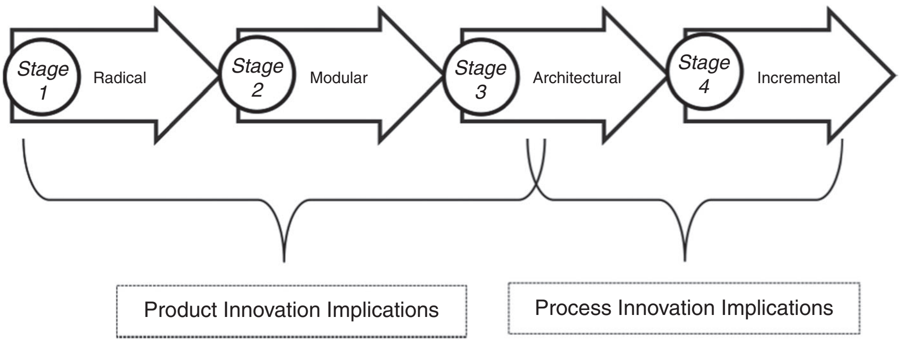

Figure 4.
The conceptual model and innovation phases

Additive manufacturing can be regarded as process innovation (Kruth *et al.*, 1998). In particular, the additive manufacturing production method uses different technologies that allow the creation of items by generating and adding successive layers of material. This contrasts with what happens in many of the traditional production techniques, such as turning and milling, in which we proceed by subtraction from solid material (subtractive manufacturing). This innovation comes from new machinery, such as 3D printers, which can be used in prototyping or directly in the production of either semi-finished or finished products. There are three basic 3D printing methods that can be differentiated based on the input material: powder, liquid or solid (Lipson and Kurman, 2013).

First, the Selective Laser Sintering method uses a laser to sinter (fuse) thermoplastic powders, metal or silicates The machine creates layer after layer, fusing powders on a table that lowers gradually. The main advantage of this technology lies in the fact that various types of raw material may be employed with a high return in mechanical and thermal yields (Kruth *et al.*, 2003).

Second, Stereolithography (SLA) is based on the polymerization of liquid resin, with a laser focussed on the work surface through optical systems that build items layer upon layer. Once the item is completed, it will be extracted and put in an ultraviolet oven to harden the material and make it usable for further steps. SLA allows for the production of parts with complex geometries and surfaces in a better way than other additive processes, but it is still only used only for small lots (e.g. custom jewelry) due to the amount of time required to produce each piece (Dimitrov *et al.*, 2006).

Finally, Fused Deposition Modeling is comparable to an inkjet printer that works with thermoplastic polymer, instead of ink, which is solidified on the various layers. In this case, the machine works by depositing plastic material layers to *x-y-z* axes to build up a 3D item that is immediately ready to be used or colored. Solid materials can be plastic and rubber, such as ABS, PLA, PPSF, polycarbonate and politermide. This technology is best appreciated by the "makers" movement who has elected it to be a mainstay of digital fabrication due to its cheapness (Zein *et al.*, 2002).

The first applications of additive manufacturing came from prototype making. In recent years, this technology has evolved and it has now also been used in the production phase. Currently the production of finished products through 3D printers is widely considered the true "frontier" for the future development of this technology (Boccardi *et al.*, 2014).

4.2 Additive manufacturing and the IoT

It is easy to understand the connection between data flow and the IoT, as being any item connected to a network producing data that can be collected and analyzed. Yet, the connection between 3D printing and the IoT is not immediately clear and requires further consideration. For this reason, we suggest that the application of the developed conceptual framework can be a useful tool to contribute to the understanding of this relationship and stimulate future research on the topic.

First, regarding *Stage 1* of our conceptual framework, products from 3D printing and additive manufacturing need a unique identifier code embedded within the object, such as RFID tags that are useful in the IoT product identification (Bak, 2003; Ilic *et al.*, 2010). Using 3D printing, it is possible to build unique 3D codes inside the material of the object itself (Lakafosis *et al.*, 2010). The ability to embed readable codes directly into the items would mean that any object created in this way could immediately be a part of the IoT. In addition, the constant cost reductions for RFID technologies has pushed firms worldwide toward integrating this type of technology into product and process innovation, making its adoption extremely widespread.

After that, regarding *Stage 2*, items are equipped with active sensors directly connected by a pre-embedded code, which allow the product to be uniquely identified and equipped with active sensors. The ability to embed readable codes directly within objects would mean that any object created in such a fashion could immediately be a part of the IoT (Pandey *et al.*, 2013). Moreover, supporting *Stage 2*, the 3D printers can always be connected to the internet, and therefore share data with the environment.

Consequently, *Stage 3* is a natural evolution from *Stages 1* and *2*. Items and 3D printers can be "unique" on the internet; they are equipped with sensing instruments and constantly connected. This means that they produce a constant flow of data in two ways. The first, as explained above, refers to product, and the second refers directly to the 3D printers, which thanks to being connected to the internet, can be remotely controlled and monitored (e.g. Ilic *et al.*, 2010). This is an important shift through the concept of smart manufacturing (Davis *et al.*, 2012), where the control of a networked manufacturing system across information management plays a crucial role in developing the "smart factory" (Lucke *et al.*, 2008).

Therefore, additive manufacturing is eligible to be called "smart manufacturing" in relation to this new technological shift that converges in *Stage 4*. Production can be modified in the light of data provided by items. *Fact 4* underlines the importance of connection between items and data to forecast and adjust production to demand (Xu, 2012). This evolutionary process then results in "smart manufacturing" which is the natural order begun by the IoT and additive manufacturing.

Our interpretation of this new emerging phenomenon is summarized in Figure 5 using the aforementioned framework to demonstrate the wide application of this model.

5. Conclusions

This work aimed at enlarging the understanding of a quite recent emergent topic in the life of businesses: the IoT. Among the many possible applications of the IoT in business, which are all under-investigated due to the novelty of the concept, we decided to focus our attention on the manufacturing industry. Through our theoretical discussion we integrated concepts from both innovation and management literature to develop a dynamic conceptual framework that explains the impact of the IoT in this industry. Nevertheless, as with similar breakthrough innovations, applications

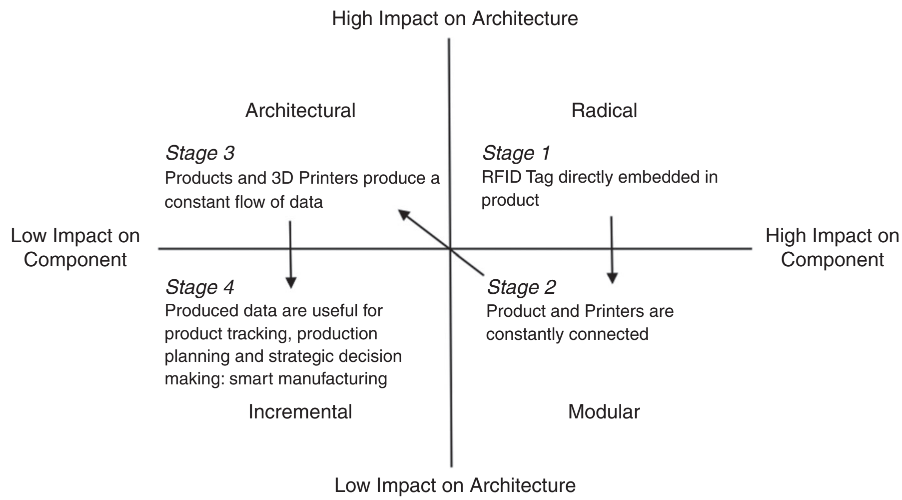

Figure 5.
Application of the dual axis model to the additive manufacturing

of the IoT in manufacturing can be infinite and an investigation of such a topic in a journal article would result in a simplification of the concept making it unsuitable for scientific research. Therefore, we agreed to investigate a case study within the spectrum of manufacturing: that of additive manufacturing or 3D printing.

We started our theoretical argument by systematizing the main elements, that we called facts, that characterize the phenomenon of the IoT, and we reached the following conclusions: first, the IoT is an environment populated by uniquely identified items (Ashton, 2009); second, these items are "active," in other words, they may autonomously respond to internal and external stimuli (Yan and Huang, 2008); third, they produce a massive flow of data (McAfee and Brynjolfsson, 2012); and fourth, can constantly exchange data with each other (Lee *et al.*, 2013). Such facts however, also represent the evolutionary steps of the impacts that the IoT has had on manufacturing. Reconstructing these facts, it is easy to follow that the introduction of the IoT in production environments has been a radical innovation for the whole market. The ability of the items populating the environment to react and self-activate in response to events has been possible only with the development of new components integrated into those items. On the one hand, such evolution did not change the whole structure of the products, rather just a few additional components representing a modular innovation. On the other hand, their ability to produce real-time information through the same components required a substantial restructuration of the whole system of interconnections among them. Since this innovation targets a different combination and relation among already developed components, it is an architectural innovation. Finally, once the item-system has been able to produce the data, only with an innovation of a minor entity, i.e. incremental, could items communicate and exchange information with each other.

As explained, this consideration can be included in a coherent conceptual model built around these four steps that describe the evolutionary impact of the IoT on manufacturing processes. To strengthen our conceptualization, the resulting model has been applied to a real manufacturing context, such as that of additive manufacturing and 3D printing. Indeed, the model is able to clearly describe past, present and future patterns that the IoT has on additive manufacturing. In providing our explanations, we are aware of the existence of general and specific variables that might affect the shift from one stage to another in different industries to additive manufacturing. We speculate that general variables can account for those forces coming from the economic environment that influence the adoption and spread of new innovations; while, specific variables might differ from industry to industry, and we predict that those will mainly relate to the technical capabilities necessary for the evolution to happen. Our model offers a base from which future research can investigate which those variables are and how they interplay. We explicitly call for future research on this topic, similarly to what has been done in agile manufacturing (e.g. Jin-Hai *et al.*, 2003), as the current knowledge on the topic does not yet allow for a systematic investigation of those variables.

The model has several practical implications, since it can predict and describe the evolutionary path of any sector within the manufacturing industry due to the advent of the IoT. Managers can benefit from the application of the model to their industry allowing them to predict how the industry will evolve and which technologies will represent the bottlenecks (e.g. Bakar and Ahmad, 2010; Kogut and Zander, 1992; Rigby and Zook, 2002; Teece, 2010), allowing their firms to capture value and effectively navigate technological shifts and competition.

We acknowledge the study also has some limitations, which are mainly related to the use of a deductive method to systematize the existing literature on the topic. We try to cope with such limitations by presenting a real case study on the 3D printing technology to assess the validity of our model.

In conclusion, we can consider additive manufacturing and 3D printing as two of the major innovations that will change the approach to production in the years to come. At this time, there is not a wider set of data and information to interpret the evolution of this technology, but it is possible to interpret the possible outcomes using the literature and reframing the past events (*Facts 1-4*) by using the model in order to have an idea of the challenges in the future.

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