A Systematic Approach to Design Product Traceability in Industry 4.0: Insights from the Ceramic Industry

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Abstract

Departing from a case in the table and ornamental ceramics industry, we propose a comprehensive approach to design product traceability for Industry 4.0. Our design-science research approach includes a review of traceability technologies and participative enterprise modeling. We find benefits in combining Business Process Modeling Notation and Goal-oriented Requirement Language representations to (1) improve communication in complex Information System Development scenarios, (2) promote reflection by experts with different backgrounds, and (3) reach consensus in a solution that addresses the goals of multiple stakeholders. The resulting model combines technologies in different stages of product lifecycle. Depending on each stage and strategic intention, the identification code can be embedded in the product, transport, or package. Our contribution can assist managers in the creation of digital ecosystems to support traceability integration at (1) technological, (2) vertical, and (3) horizontal levels that are required in the fourth industrial revolution.

Keywords: Traceability, Ceramic Industry, BPM, GRL, Digital Ecosystem, Industry 4.0.

1. Introduction

Product traceability – defined by ISO 8402 as "*the ability to retrace the history, the use or location of an article or an activity, or similar articles or activities, by means of recorded identification*" [15] – is crucial in what the World Economic Forum calls the unfolding 4th industrial revolution or Industry 4.0 [29], with its higher complexity supply chains and real-time requirements. Current concerns of industrial managers include preventing errors in the supply chain (e.g. incorrect product selection, or misidentification of customers' requirements); managing risks of product use (e.g. identification of components, origins of materials, and counterfeit products); obtaining efficiency in inspections; and improved control of quality, inventory, manufacturing, and logistics [36]. The importance of traceability is also present in the popular quality management standard ISO 9001:2015 [16], which highlights this requirement in Sections 8.5.2 (identification and traceability) and 8.6 (people responsibilities). Additionally, [36] mentions the need to consider the goals of stakeholders that are internal and external to the firm and distinct phases of product lifecycle. Namely, product development, production, use, and disposal. Still, according to [42], it is necessary to consider different traceability technologies in industry "*because of changes in material properties and various operations in process stages. Therefore, suitable traceability methods need to be identified for different process sections*". Also, [43] suggests that it is necessary to integrate various mechanisms for traceability, because each one has its strengths and weaknesses. Despite all this, in some sectors of the economy, product traceability is still in initial stages of development, for example, the millenarian production of ceramic that is addressed in our study.

Ceramic industry can be divided into ten sub-groups: bricks & tiles, floor & wall tiles, sanitaryware, table and ornamental, refractories, abrasives, clay pipes, expanded clay, porcelain enamel, and technical ceramics. The European Union accounts for 23% of global ceramics production. According to the Eurostat [12], this sector represented a production value of 28 billion Euros in Europe and over 200,000 direct jobs. In this paper, we focus on the table and ornamental sub-group characterized by concurrent production of many different products. For example, a tableware product line can include different models (e.g. cup, jar, and dish) with multiple decorations. Product diversity, aggressive environmental conditions (e.g. kiln firing temperatures above 1000ºC; dusty production environments that difficult reading and sensing), and the multiple operations in the production line make product traceability a major challenge in ceramics.

We propose that designing traceability systems can be addressed by enterprise modeling, "*an activity where an integrated and commonly shared model describing different aspects of an enterprise is created*" [34]. It can be carried out with the participation of the system stakeholders to improve the quality of the proposed solution, obtain consensus and commitment from the users [24, 34]. The need to include traceability in the agenda of ceramic production and the need to identify potential technologies and implementation methods motivated us to formulate the following research questions:

1. *How to model ceramic product traceability systems involving multiple stakeholders?*
2. *Which traceability technologies can be used in table and ornamental ceramic production?*

The remainder of this paper is presented as follows. Section 2 introduces our design-science research approach that involved a national technological center for ceramic and glass industries. Next, we explore studies addressing traceability technologies and application cases in distinct sectors of the economy. Section 4 details our proposal for product traceability using participative enterprise modeling. Afterward, Section 5 discusses results and we conclude in Section 6, stating study limitations and opportunities for future work.

2. Method

Design-science has its foundations in the work of [30] and seeks to produce innovations, and create and evaluate artifacts aiming to solve specific organizational problems [14]. For the purpose of our research we adopt the broad definition of Information System (IS) artifact suggested by [18] that integrates "*information artifact*", "*technology artifact*" and "*social artifact*". According to the authors, "*technology artifacts (such as hardware and software), information artifacts (such as a message) and social artifacts (such as a charitable act) are different kinds of artifacts that together interact in order to form the IS artifact*".

We followed the phases proposed by [25] starting with (1) problem identification and motivation, (2) definition of the objectives for a solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication.

The motivation to study traceability in table and ornamental ceramics emerged in a technological center with the mission to support ceramic industry development in Portugal. This country is one of the top exporters of these products: the first in the European Union and the second worldwide [5]. Consequently, public and private organizations are joining efforts to evolve the ceramic IS support and achieve competitive advantages towards Industry 4.0. First, we conducted a review of relevant literature presented in Section 3. Based on the identified cases and technologies and in contacts with ceramic experts, we construct a holistic model for traceability in table and ornamental ceramic production that implements a manufacturing execution system and, to external stakeholders, provides real time information to the customer about its order and product quality attributes (e.g. results from quality tests during production of ceramic products). Design and development (step 3 according to [25]) was inspired by participative approaches to modeling in Information System Development (ISD) [24, 34]. Our proposals were demonstrated to a Portuguese ceramic company that provided positive feedback. We concluded our design research with a joint assessment of the results by researchers and practitioners, documenting and publishing the findings.

3. Literature Review

We searched for traceability design studies on Google and in academic papers in EBSCO, ScienceDirect, IEEE, Google Scholar, and Mendeley. Given the comprehensive nature of the topic, we searched for journals and conferences, without a time restriction. The combination of search terms included "traceability design" [yielding 254 results in Google Scholar, excluding patents and citations, 24/04/2017], "product traceability" + "ceramic" [yielding 94 results]. We followed the guidelines presented by [40], focusing in specific concepts and using backward and forward searches in the literature. For example, [17] was found in the references of [1]. Finally, we annotated each paper in Mendeley reference management tool.

In Section 3.1 we describe the concept of traceability design and the opportunities to advance in this area. Section 3.2 summarizes the most relevant technologies for product identification and traceability in industry. In Section 3.3., we discuss the implementation of these technologies in different sectors of the economy.

3.1. Traceability Design

Product traceability can have a strategic purpose, going beyond the mere identification of where products are [1]. There are also design principles to build traceability systems that suggest considering multiple actors and elements of the supply chain [23]. Other researchers have proposed different solution for traceability design. For example, [11] proposes a mathematical model for product recall. Other authors, for example [17] addressed graphical solutions to model traceability in manufacturing using graphs. According to these authors, a "*gozinto graph represents a graphical listing of raw materials, parts, intermediates and subassemblies, which a process transforms into an end product, through a sequence of operations*" [17]. The study presented by [10] adapts the axiomatic design method combining both modeling techniques: graphical and mathematical. The authors start by the identification of traceability functional requirements and graphically map them to the physical processes. Their proposal extends traceability design to different areas of the supply chain.

These studies give important contributions for traceability design in industrial contexts. However, mathematical models have limited use in the initial stages of traceability design, involving multiple experts in the process. The graphical approach suggested by [17] provides detailed information of the operations and the elements involved. Yet, existing models do not address strategic aspects of traceability, namely, (1) the contrasting perspective of multiple stakeholders, (2) the list of possible technologies and the priorities of their implementation, and (3) the participative approach to modeling. There are opportunities to test different modeling techniques to design product traceability in industries.

3.2. Technologies for Traceability

There are multiple technologies available to implement traceability in industrial processes. Examples of popular identification technologies include barcode, Quick Response (QR) code, and Radio Frequency Identification (RFID). Their main purpose is to identify a specific product or group of products (e.g. production lot), but many other technologies can be used individually or even combined for traceability.

Linear barcodes, namely the Universal Product Code (UPC) and European Article Number (EAN) variants, are amongst the most used identification technologies, for example, in the food sector [19]. Barcodes encode product data such as part number, serial numbers, supplier numbers, and more. Barcode scanners allow accurate reading and enable companies to track product information in multiple phases of the supply chain, reducing human errors that are common in manual data entry. Barcodes are a popular way of identification affixed in most products available in supermarkets, but they also suffer from limitations of applicability in industry due to the nature of the materials typically used. For example, in the wood industry the "*barcode traceability system is simple and low cost, however, it is difficult to be massively applied in wood trade and traceability, because of the nature of wood*" [37].

QR codes are two-dimensional codes that provide high speed reading [33]. Its graphical image stores information vertically and horizontally, thus providing a higher data density when compared to linear barcodes. One of the possible uses of QR codes is to protect consumers and retailers from counterfeit products and they can contain Uniform Resource Locators (URLs), texts, and geo co-ordinates, among other possibilities. Examples of QR code use include advertising campaigns, linking to company websites and contest sign-up pages. More recently, QR codes are being tested in the metalworking industry to identify metal parts [39]. According to the authors, QR codes can be engraved in the products overcoming the problems of detaching that are common in labels.

RFID is another popular identification solution, having its foundations in the work of the physicist Léon Theremin during the last century. It was developed and used by the military to identify and differentiate friendly and foe aircrafts. Since then, it has been used also in commercial airplanes, as well as in many other industry sectors. Nowadays, RFID's are used in laptops, mobiles, building access systems, passports, car keys, and ID cards. An RFID tag can store more information when compared to linear barcodes, for example, adding the production date or the expire date to the product identification code [26]. Another advantage is that it does not require line-of-sight scanning because it uses radio waves to communicate with the reader. The RFID tags are classified as active (using battery to emit radio waves, readable from larger distances) and passive (generating the required power from the scanner's interrogating radio waves) as per the need in the business.

The list of traceability technologies is vast and includes many other options, some of them associated with the emerging topic of Industry 4.0, a priority for Europe and for the entire globe [32]. Wireless solutions, communication technologies such as 4G/5G, mobile devices including smartphones/PDAs/Tablets, Near Field Communications (NFC), Indoor/Outdoor GPS and Cloud platforms are now available to tackle the challenges of traceability in modern supply chains [7]. In fact, Industry 4.0 design principles of interconnection, decentralized decisions, and information transparency [13] require real-time identification of products and their production stages. The priority to reduce lot sizes, individualize production [8], and ensure individualized trace data, call for a combination of technologies and new competencies for the industry [27].

Popular as they are, there are common limitations to traceability tags such as RFID, barcodes, and QR codes, for example, in highly adverse environments such as the case of high temperature processes. Exposures to temperatures of around 1000ºC require solutions that do not require direct contact with the product. Possibilities include computer vision to count/identify specific products. However, in spite of the potential of this technology in quality inspection of defects [9], these types of systems have not yet been tested in the table and ornamental ceramics sector, where there are significant challenges posed by the hundreds or even thousands of possible product formats.

3.3. Application Cases: Solutions and Opportunities

This Section reviews examples of traceability solutions found in different sectors of the economy. For example, construction, wood, food industry, and healthcare.

Multinational companies are investing in traceability solutions. For example, Hitachi provides solutions targeting the beef and the steel industries [22]. Examples of internal and external traceability solutions in construction, food, and manufacturing are described by [36], accounting for backward and forward traceability. The former providing information about product history and production details (e.g. responsibilities), with the latter describing what will happen to the product in the supply chain [36].

Traceability in the wood industry can use a combination of techniques such as punching, painting, barcodes, QR Codes, micro-wave sensors, DNA-fingerprinting, and RFID [37]. On one hand, the sector is evolving from traditional punching and barcodes to digital systems that involve QR Codes and genetic technologies. On the other hand, some authors identify that "*few countries in the forest sector and generally the wood industry are using IT methods of wood traceability*" [37], and it would be interesting to develop a standard traceability method to assist this traditional sector of the economy.

The food industry is one of the most critical for human safety and, consequently, for traceability requirements: procedures and systems for the identification of outsourced production; product identification; producer data; and destination of all supplied products. The importance of tracking technologies using carriers tags (e.g. RFID and barcode) in food manufacturing is explained in [38]. However, the authors also state that "*data carriers alone do not establish traceability. The use of RFID facilitates chain information management because it eases the automated data capture process, but it does not establish traceability itself. Traceability requires association of identifiers with locations and processes, and following such identifiers through the chain from their emergence until their obliteration*".

The healthcare sector is making important investments in mobile technologies and the use of QR codes, for example, for medicine prescriptions [21]. Moreover, barcodes are commonly used in pharmaceutical products. The initiatives for mobile health using remote monitoring are creating opportunities for the use of healthcare applications with mobile devices.

Benefits of product traceability in the cases described are extensive, including the possibility of obtaining complete information for the customer, trace suppliers' production and logistics, identify quality issues, enhance product visibility, inventory control, certification, counterfeit goods protection, or ethical and legal responsibilities [36, 39, 41]. But in spite of the many existing applications, applications in ceramic industry are scarce. In fact, a Google Scholar search with the keyword combination "product traceability" AND "ceramic manufacturing" returns a single result about current trends in ceramic. Extending the scope of our search criteria (e.g. "traceability" AND "ceramic" AND "RFID") we found a master thesis directly related to sanitaryware traceability [31]. Sivers and Sjögren [31] compared different technologies and suggested the use of (product engraved) Datamatrix 2D codes, consisting of black and white modules, usually arranged in a square pattern, which are similar to QR codes but more usual in industrial settings. However, the author focused on internal traceability techniques, not addressing the design method and external stakeholders' involvement in the system design, such as end customers' goals.

The lack of solutions for our target ceramic sub-group and the possible benefits of combining technologies reinforced our decision to continue the research with participative enterprise modeling, as described in Section 4.

4. Modeling Product Traceability in Table and Ornamental Ceramic Industry

Our participative approach involved experts in ceramics, IT, and electronics. After reviewing potential traceability technologies we visited an ornamental ceramic industry and interviewed an expert in the ceramic process from a private research and development institute. The simplified process of table and ornamental ceramic production is presented in Figure 1, using Business Process Modeling and Notation (BPMN).

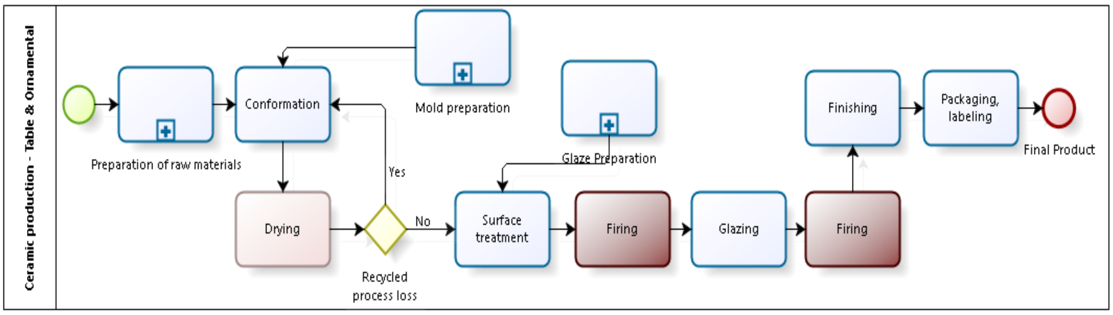

Fig. 1. Ceramic production model (adapted from [28]).

Ceramic production requires the preparation of raw materials, conformation (in ornamental ceramic, slip casting is poured into a mold), drying, and surface treatment. After processing materials and shaping the ceramic product it is necessary to remove superficial imperfections. According to [28], the temperatures at this stage range between 50 and 350 ºC (during a period of about 12 hours in our ceramic sub-group). Then, the product enters the firing and decoration phase (e.g. glazing). In ornamental ceramics there are usually two firing steps, before (biscuit firing cycle to provide strength and absorbency required for glazing) and after decoration, occurring a number of chemical and physical changes to provide the required characteristics to the product (e.g. dimensions and mechanical strength). The firing process occurs at high temperatures, hindering the use of traceability technologies such as RFID tags at this stage. The ceramic pieces are placed on kiln-cars on fireproof firing auxiliaries submitted to firing temperature intervals for ornamental and tableware that are, respectively, 1000-1100ºC and 1180-1280ºC. Before labeling and packaging, the final treatment can include polishing, cutting, or other product finishing techniques [28].

Having learned about the production process, we detailed it further, including actors external to the company, as represented in Figure 2.

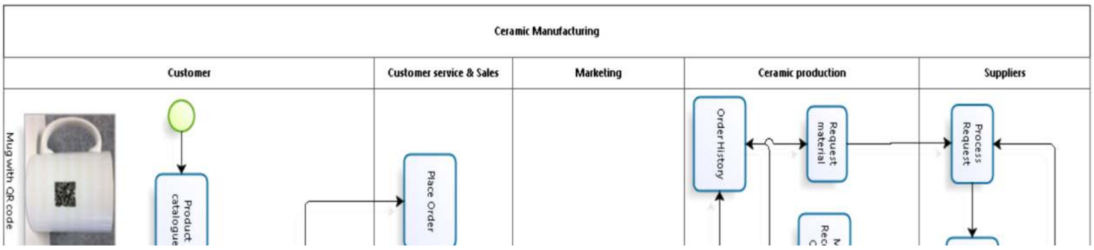

Fig. 2. Business process model for traceability identification (extract of process lanes).

Our process model includes five main participants: Customer, Customer service & Sales, Marketing, Ceramic production, and Suppliers. For each participant the design team identified the main activities in ceramic supply chain and potential technologies to support product traceability identified by our team. Figure 3 presents an extract of technology identification for ceramic production steps (fourth lane in Figure 2).

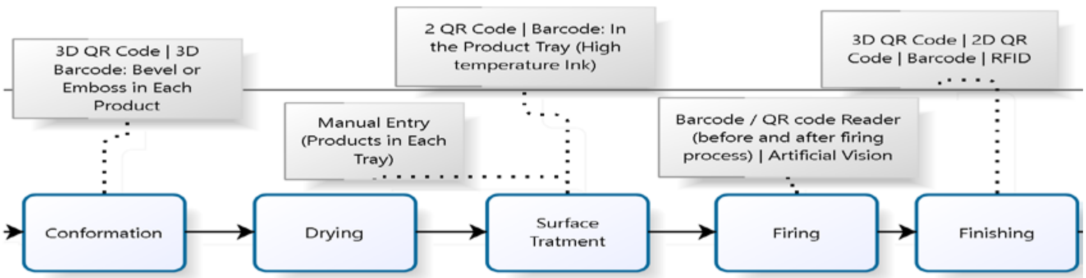

Fig. 3. Business process model for traceability identification (extract for production activities).

We highlight (1) QR codes, barcodes, or 2D Datamatrix embedded in the ceramic product at conformation stage, (2) high temperature ink to make the codes readable during/after firing above 1000ºC (there are multiple intrusive/non intrusive marking techniques available that are out of the scope of our paper, such as laser marking, dot pen or ink jet), and the possible use of computer vision for automatic product count in areas of difficult access. The automatic reading of trays before and after the firing process will allow real time identification of the product under fire and ready for finishing activity.

The team found the process model of Figures 2 and 3 useful, but insufficient for our purpose. The model did not explain *why* the technology was needed or used in each activity. Therefore, we could not establish priorities and clarify the comparative interest of the specific technology. For example, if an activity could use barcode and QR code, which one was the best for that activity and for the overall traceability purpose? In a second stage we decided to create goal models with the jUCMNav Eclipse plug-in [3]. The elements of goal models are presented in Figure 4.

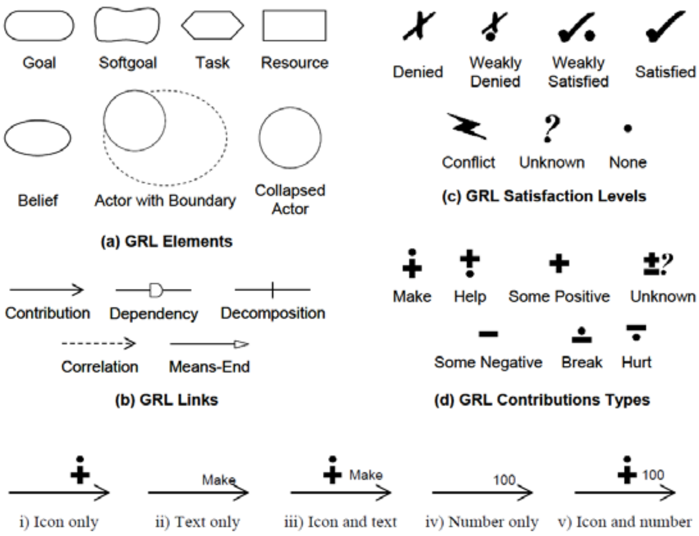

Fig. 4. Basic Elements and Relationships of GRL [2].

Figure 5 presents an extract of the GRL model we developed for the customers.

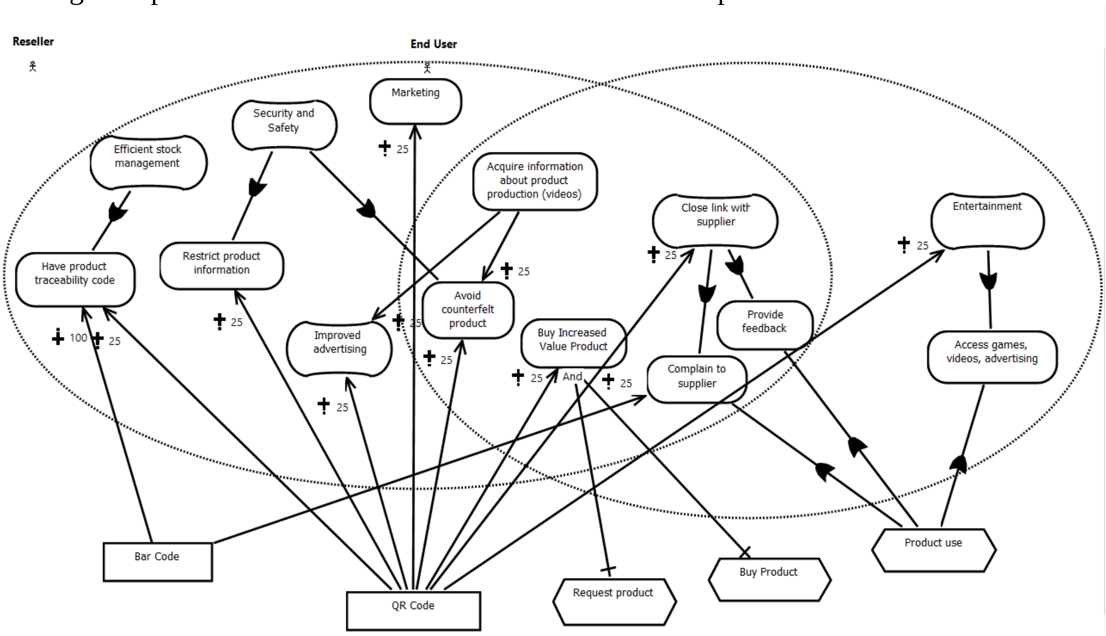

Fig. 5. Goal model for traceability identification (extract for customers: reseller and end user).

Goal models can be useful for communication in the initial modeling process, identifying requirements and the main goals of the system actors. There are recent studies adopting GRL in participative enterprise modeling [6]. Figure 5 includes two main traceability technologies that the design team found more valuable for the customer of table and ornamental ceramic: barcode and QR code (represented as GRL resources in the bottom-left of Figure 5). The team connected the resources with the goals of the actors and considered barcodes useful for only two goals (two contribution arrows – to "Have a product traceability code" and to support "Complains to supplier"). QR codes could address eight goals and/or soft goals of the customers, which suggest that it was preferable to the actors in this scenario. After completing our models we established the most important traceability technologies for each actor and process activity (represented as tasks on the bottom-right of Figure 5). In our goal model, resources (traceability technologies) are connected with goals, not tasks, but we can identify the link of resources and tasks via contribution arrows. Moreover, in this model we can identify *why* the technologies are used (e.g. in support of the identified goals of the actors), thus adding information that was not available in the BPMN model.

In the course of our design-research project we identified the possibility to embed the QR, 2D Datamatrix, or barcode in the product. This solution is problematic due to the low consistency of the ceramic product at molding stage. Another possibility that can be tested is to create a parallel process of additive manufacturing with a 3D printer to create the codes. In this case, the 2D/1D code would be added to the product after conformation stage. This innovative way of embedding the codes in ceramic products emerged while building and reflecting about the models and the support of technologies to the actors' goals.

Figure 6 shows the traceability landscape for table and ornamental ceramic.

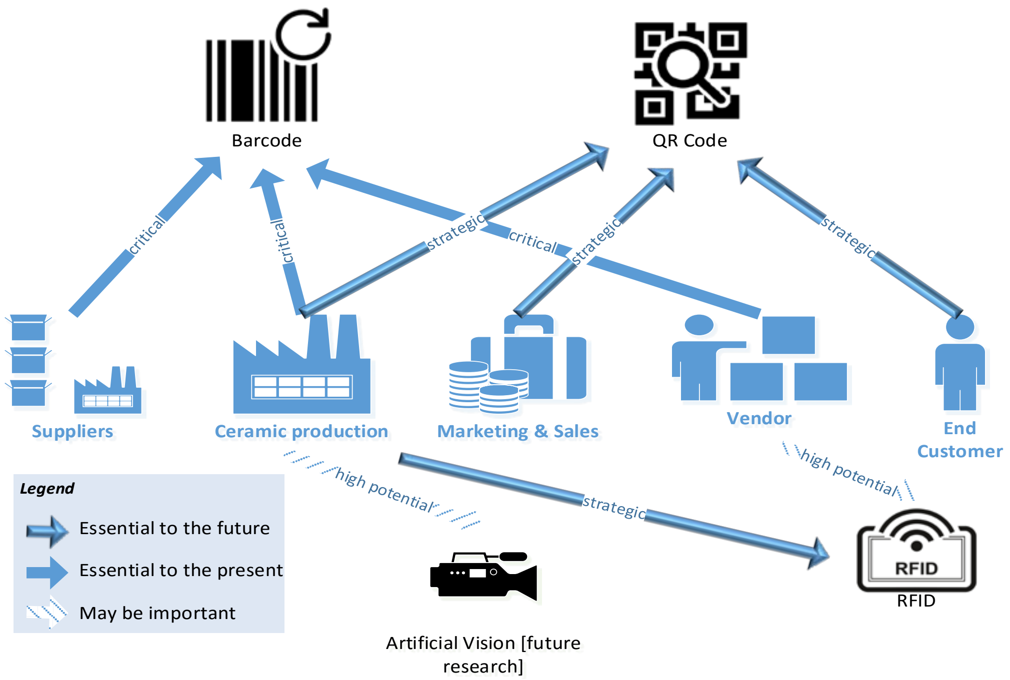

Fig. 6. Product traceability landscape: model for table and ornamental ceramic.

This model suggests that QR codes are strategic for internal processes and to customer use. For example, the end customer (reseller or end user) can access a web page to see a video about the product or the production. However, external partners such as suppliers and vendors/retailers need barcode for lot checking and sales process (e.g. supermarket). Due to its higher cost, RFID is an option for high-value products, for example, with intensive manual finishing or historical value, but it can be used in the future to track transport cars. For this classification of traceability technologies, we got our inspiration in the McFarlan strategic grid [20], detailed in Figure 7 for the ceramic production stage.

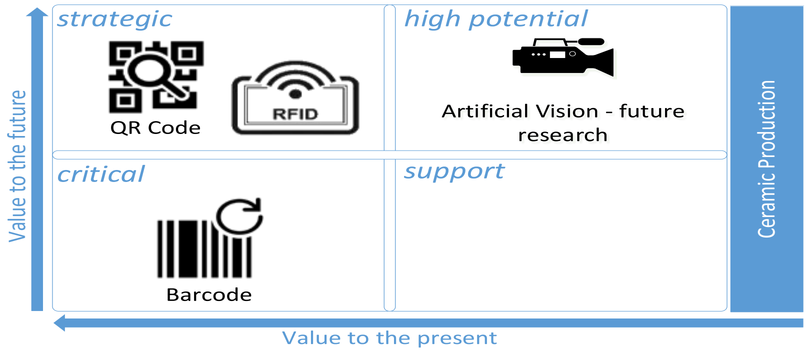

Fig. 7. Product traceability: Technological portfolio - production (adapted from [20]).

The grid presented in Figure 7 is created for each actor of the system – the example is for ceramic production but it can be extended to the end user, vendors, and other actors. According to [20], strategic solutions (on the top left of Figure 7) are important to the company future, critical (bottom left) to the present, and high potential (top right) may be important to the future. We did not identify support systems for production stage – marginal contribution to the company strategy. The design team considered QR codes strategic to provide increased value to the customer and contextualized information during production stages, RFID strategic to identify transport cars location in the factory, and computer vision high potential solution for product traceability that requires additional field testing. We also found an opportunity to identify product moulds with barcodes to improve traceability of the tools used in the process (e.g. how many products were made by each ceramic mould).

We discussed the product traceability landscape with a ceramic company that agreed to participate in a European Union co-funded project to develop and validate the integrated traceability system. According to the company manager, this model can provide the foundations to build a digital ecosystem for table and ornamental ceramic, supported by traceability technologies, and integrating multiple actors of the ceramic production supply chain. The manager stated that "*nowadays, it is no longer useful to think about traceability for mere* [internal] *production control. Product traceability is needed for different parts of the supply chain and it is necessary to integrate systems for Industry 4.0 (…). The product history is as important as the price tag […and] information must be available at all stages of cradle-to-cradle or cradle-to-grave design*". The manager stressed the importance of traceability for the current industry trend of circular economy and sustainable product development.

5. Discussion

In spite of the different options available for product traceability in ceramic production we did not find a single technology that could be used throughout the entire product lifecycle and address the needs of internal and external stakeholders. QR codes are interesting for consumer information, while linear barcodes are low-cost and efficient for tray identification during a production process. RFID can also be used for transport cars identification and for increased value products but has several handicaps in aggressive environments such as those we can find in the ceramic industry, limiting their application during production.

To deal with the problem of selecting a suitable mix of traceability technologies for the particular industry in our study, we found benefits in using multiple representations of the production system with participative enterprise modeling. First, the contrast of different models – BPMN and GRL – improved the reflection about traceability challenges amongst experts of different domains. BPMN clarifies the sequence, interactions, and elements of the supply chain, while GRL explores the "*why*" of the system actors, their requirements, beliefs, goals, and resources. Second, it helped in the construction of a consensual perspective for the next steps that includes sourcing the traceability system aligned with the company strategy. On one hand, RFID has several advantages for storing data and reading at a distance, but it was not compatible with high temperature, the large cost when compared to the low average price of ceramic products, and limited features to the consumer. On the other hand, QR codes provided advantages for multiple goals of stakeholders (e.g. consumer) and to develop online web services (thanks to the ability to encode full URLs), but we can't simply eliminate linear barcodes because retailers need them (e.g. in supermarkets). The strategic grids [20] provided a clear picture of the priorities for the investments.

The use of multiple modeling techniques helped us move the focus from technology to the actors' needs. When the team started this project, the goal was to identify candidate technologies for product traceability with (1) numerous different products and (2) complex environments that include high temperature and materials with low consistency (e.g. ceramic products in early stages of production). Then we shifted our attention to the goals of the different stakeholders included in BPMN and GRL models. We agree with [4] in that the operational backbone of the organizational IS must be complemented with digital services targeting different stakeholders. Traceability in the context of Industry 4.0 requires supply chain integration increasing the importance of IS modeling and the need to use multiple models, accessible to different experts and ensuring a strategic focus [20].

Cloud, wireless, and mobile can provide "the glue" for the traceability information system across the supply chain. The information traced in the product line can be available to customers or to specific suppliers to plan deliverables of raw material according to the plan. The use of smartphones in the production line also opens possibilities for future research, taking advantage of QR/ barcodes in products, and trays. For example, for quality control, embedded QR codes can simplify product recall (e.g. the same product model can have problems in a single production lot while the others conform to specifications).

6. Conclusions

We presented an approach to model product traceability that integrates multiple technologies and stakeholders' viewpoints. The ceramic industry provided the setting that includes adverse environmental conditions for traceability technologies. An overall model for product traceability landscape is proposed, inspired by the classification of [20]. Our results suggest that a multi-model approach has the potential to contribute to team learning and creativity in complex scenarios. We also confirmed previous studies pointing to the benefits of enterprise modeling for achieving consensus in ISD [34]. Moreover, we found new opportunities to use traceability technologies and promoted debate amongst team participants using the models.

As for limitations, first, the technologies and application cases identified in our literature review are restricted to those found in the consulted literature databases. Second, we restricted the modeling artifacts to BPMN and GRL models because the design team was already familiar with BPMN tools and recent research suggested benefits of GRL for participative enterprise modeling [6]; other modeling methods and languages can be used. Third, in spite of our participative approach to enterprise modeling, traceability in ceramics production is highly complex and the environmental conditions (e.g. temperature and dust) present challenges to system implementation that require additional research. Nevertheless, our project identified opportunities to use mobile devices and automatic tracking in traditional product lines, including product, transport, and package identification codes. Fourth, although we already found a company that validated our initial model and is willing to invest in subsequent implementation steps, we do not have experimental evidence of the benefits for efficiency and effectiveness of the overall model. These are opportunities to address in upcoming phases of our research that may be extended to other sectors of the economy.

Currently, we are developing a prototype of the traceability system. We selected action research [35] to continue our work, improving the problematic situation of traceability in ceramics while studying the social changes that can occur in the supply chain and product lifecycle. The main contribution of the present project is a graphical approach to design product traceability integrating multiple stakeholders' viewpoints. Moreover, our design-science research evaluates existing artifacts (BPMN and GRL) concluding for their positive synergy in the development of product traceability. For managers, we identify traceability technologies and suggest digital innovations in the context of table and ornamental ceramic.

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