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Mass customization and mass personalization meet at the crossroads of Industry 4.0: A case of augmented digital engineering

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Abstract

After mass production and then mass customization, the time is almost ripe for mass personalization. The goal is to offer unique products designed for the needs of each customer. However, production in larger series of products also has its advantages, and the promise of "lot size one" is still far from being the norm in several sectors of the economy. As a result of an action research project in a small household ceramic producer, this paper explores the potential of a hybrid strategy. Augmented digital engineering is adopted to (1) ensure customer participation along the entire product design lifecycle, (2) maintain the benefits of modularization and low cost, (3) minimize the waste of time and materials during product design, and (4) seek a minimum trade-off between customer desires and engineering strategy. For theory, our work describes Industry 4.0 technology's role in achieving individual customer interaction and value co-creation in hybrid strategies of mass customization and mass personalization. For practice, we present an example of technological architecture to implement augmented digital engineering in Industry 4.0, accessible to scenarios of hand-intensive work and creative design processes.

KEYWORDS

augmented digital engineering, augmented reality, ceramics, Industry 4.0, mass customization, mass personalization

1 | INTRODUCTION

Industrial revolutions brought significant changes in production lines and new forms of interaction between the business and its increasingly demanding customers. Since the introduction of steam engines and mechanization in the XVIII century (the first revolution), passing through mass production popularized by Henri Ford (the second), or "going digital" with the massification of computers towards the third industrial revolution, the interplay between humans and technologies never left the agenda. This is also the case of the ongoing digital transformation in the industry (Industry 4.0) involving a combination of technologies such as cloud, mobile, robotics, 3D printing (additive manufacturing), digital twins, augmented reality, and manufacturing execution systems (MES).[1]

It is surprising that the concept of mass production only emerged a century ago. At that time, large quantities of standard products flooded the market. However, the role of digital technologies in the paradigm shift to the customization of products is even more remarkable. Mass customization uses "*modularization to simultaneously increase product variety and maintain mass production efficiency*" and technology "*to tap more effectively all the diverse capabilities of employees to service customers*",[2] extending the mere automation of tasks from the past of mechanization. Mass customization is a strategy to create an offer to a broad market with the possibility to configure the final product according to the need of specific customer segments.[3] Modularization and delayed differentiation are vital pillars of this strategy.[4] For example, online tools can help select the most interesting configuration of the desired car (e.g., the model, color, or accessories) and accelerate production orders with real-time tracking features.

More recently, mass personalization promises to make "*the market of one a reality*".[4] The move *from* customization *to* personalization is still a phenomenon of the masses, explained by three main limitations in mass customization.[5] First, the limited customer participation since the early design phases. Second, the controlled set of possible product combinations defined by the design team. Finally, the evidence that customization is not entirely capable of satisfying all the individual requirements of the customer,[6] requiring a shift to self-organizing networks in manufacturing contexts.[5] Therefore, mass personalization differs from mass customization by identifying specific customers' needs and planning how to address them "since every product can be unique".[5]

The adoption of 3D printing can be regarded as one of the various possibilities to achieve the mass personalization paradigm, where customers and manufacturers co-design a product (eventually a single piece), and Industry 4.0 allows the controlled-time adaptation of the required production systems[7] and the foundations for systems of systems.[8] Moreover, the carbon footprint can be reduced with 3D printing,[9] enabling more efficient product prototypes and small-scale productions, reducing waste. New manufacturing systems are emerging with increased mobility, innovative hierarchical structure, and control mechanisms.[10] According to Hu[7] "[w]*hile the goals of mass production, mass customization and personalization can be summarized as economy of scale, economy of scope and value differentiation respectively, the role of the consumer also changes from 'buy', 'choose', to 'design participation'*". Moreover, a trade-off is crucial in the increasingly digital integration of design and engineering that "*involves making decisions involving multiple stakeholders with diverse and, potentially conflicting, objectives. As more and more data become available with digital engineering, big data, and data science, trade-off analytics will be an increasing important tool for engineers*".[11]

We argue that hybrid strategies of mass customization and mass personalization are essential to consider. On the one hand, predetermined limitations in product engineering may occur for economical (e.g., maximize modularization to ensure variety at an optimal cost, design strategy), technical (e.g., raw material or production process), or even societal reasons, as happens in the pressure to create sustainable products and minimize environmental impacts, "guiding the customer choice". On the other hand, customer participation throughout product design is essential to understand the market's needs and continuously improve the product quality, "guiding the company strategy". However, mass customization requires an agile and effective process reconfiguration,[12] and not all companies are ready for mass personalization strategies.[4] For example, traditional household ceramic companies involve a large amount of manual work and produce similar products using moulds. There are also significant barriers in adopting Industry 4.0 by small and medium-sized companies that "*seem to have adopted Industry 4.0 concepts only for monitoring industrial processes and there is still absence of real applications in the field of production planning*".[13] Moreover, it is not economically feasible to radically transform all the manufacturing plants into high-tech lines of fully automated 3D printers.

This situation raises the question: Would it be possible to implement a hybrid strategy that simultaneously adopts mass customization (which already occurs in ceramic products composed of standard parts, with the possibility of changing colors or patterns) and mass personalization in the Industry 4.0 context? This paper presents a possible approach using augmentation technologies of Industry 4.0. Expanding the digital engineering definition presented by the Defense Acquisition University[14] and adapting the concept of augmented product information,[15] augmented digital engineering is a digital approach that explores new layers of information about the product and the process, aiming to improve sustainability, using "authoritative sources of systems' data and models as a continuum across disciplines",[14] "tailored to each stakeholder and lifecycle phases".[15]

The following section reviews the literature on mass customization, mass personalization, and augmented reality. Subsequently, the action research approach[16,17] adopted in a traditional ceramic company is explained. Section 4 presents the results of the problem-solving interest and the research interest[18] of our case company. The discussion of the findings and the augmented digital engineering proposal are included in Section 5. The paper closes by summarizing the main conclusions, limitations, and opportunities for future work.

2 | BACKGROUND

2.1 | From mass customization to mass personalization

Industry 4.0 has several enabling technologies such as ubiquitous manufacturing solutions, augmented reality, cloud, or 3D printing.[19,20] Nevertheless, this digital transformation is sociotechnical[21] and creates new forms of interaction with the customer. The customization of products, for example, using web interfaces to configure the desired characteristics and color, is now possible in real-time.[22] Customization is particularly relevant in the context of heterogeneous customers' requirements, fashions, creation of product families to allow differentiation, and capturing the consumers' preferences "*without tradeoffs in cost, delivery and quality*".[3] Product designers can implement mass customization when defining the best possible configurations for their markets.[3]

Nevertheless, capturing customer feedback after a defect, allowing "*flexibility and quick responsiveness*[2]" is less effective than anticipating changes and adopting a proactive stance to meet the customers' needs. More recent proposals move beyond customization and address the entire lifecycle of products tailored to the needs of each customer,[23] making the design for changeability principles[24] more relevant than ever. It is the era of mass personalization.[4,6,7,25] A recent study published by Zheng et al.[26] presents an example of this change throughout the product's life cycle. The authors explain the early stages of product configuration and co-design with customer participation and technology capacity during the manufacturing and use phases. Self-organizing networks are a possible solution to the increasing dynamics that mass personalization brings to manufacturing,[5] and collaborative networks can also apply to SMEs aiming to support their personalization goals.[27] New practices became possible; for example, "*the personalisation of products tailored to the individual needs and preferences of the customers can now be achieved through mobile applications, namely apps*".[28] However, the adoption of mass personalization in traditional SMEs is still nascent.

Recent studies reveal how SMEs in traditional manufacturing sectors (despite their inherent difficulties in innovating) can implement more tailored and straightforward approaches to adopt Industry 4.0.[29] However, more research in this context is also crucial.[29] This gap must be closed with new empirical studies because companies need to prepare for their transformation, and many sectors of the economy are not prepared for mass personalization,[4] requiring a gradual approach to the problem. Additionally, boosting product variety with tools like 3D printing has advantages but also increases risks in product uncertainty and requires a careful evaluation of profitability.[30]

2.2 | The mass customization—mass personalization continuum

Industry 4.0 expands the product engineering continuum. For example, the work entitled "Industry 4.0: a way from mass customization to mass personalization production[6]" argues that "the concept of mass customization is not necessary to satisfy individual requirements and is not capable of providing personalized services and goods".[6] Therefore, personalization is a shift to "a higher degree of one-to-one marketing vision".[31]

Hybrid approaches, combining mass customization and mass personalization in digital engineering lifecycles are also possible. An analogy can be made with the reality-virtuality continuum in mixed reality solutions,[32] suggesting that there are intermediate points between 100% natural (physical) solutions and others 100% virtual. Augmented reality is an example of an intermediate strategy in the reality-virtuality continuum[32] using a combination of real elements and virtual layers of information presented to the users. Some authors suggested that the shortcomings of mass customization could be addressed with co-creation activities,[33–35] as happens in mass personalization strategies. Hybrid strategies were also identified in the furniture sector, where hybrid mass customization is defined as "*hybrid form between pure mass customization and mass personalization, where product design is launched by a single customer order but where process follows standardization rules and efficiencies proper of a mass production*". We argue that augmented digital engineering is an interesting approach to implementing hybrid mass customization and mass production strategies.

FIGURE 1 Augmented reality applications. (A) A virtual dressing room mirror. Ikusuki, CC BY 2.0 < https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons. (B) Ikea Place app showing how a sofa would look in the living room. Picture from Mark Hillary on Flickr https://www.flickr.com/photos/markhillary/48317217561.

Virtual environments can support collaborative design, revealing compelling benefits, for example, in error detection.[36] Moreover, the potential of augmented interactions with customers is vast, and there are significant contributions in this area, as presented in the next section.

2.3 | The augmented forms of customer engagement

Companies can engage customers through AR (Augmented Reality) applications at various moments of the customer's journey, from searching for a product to helping in performing maintenance work. AR applications can add value in different ways,[37] such as improving conversion rates, reducing return rates, enlivening static retail inventories, driving store footfall, and providing a means to offer personalized pre-purchase evaluations. For example, being able to "try out" an outfit or makeup while looking at a smart mirror (Figure 1A) can increase customer confidence and improve conversion rates. On the one hand, augmented reality can assist a new sale, as exemplified in the study addressing footwear customization for children.[38] On the other hand, seeing how a piece of furniture will look in one's living room, for example, with the IKEA Place app, can reduce the chances of customers returning the product after buying it (Figure 1B).

Different models have been proposed to explain how AR applications can positively influence brand engagement. For example, Dacko[37] proposes that AR novelty, interactivity, and vividness are contributing attributes that influence the perceived ease of use, usefulness, enjoyment, and subjective norms that, in turn, have a positive influence on brand enjoyment through AR. On the other hand, Heller et al.[39] propose that AR can provide tangibility through the feeling of spatial presence in digitally automated services. For example, Converse's Sampler app allows customers to virtually see how the shoes would look on them, providing some tangibility to an otherwise fully imaginative process while buying shoes online.

An interesting perspective is given by Jessen et al.,[40] which considers the creative dimension driven by AR applications. They propose that "*AR enables customer creativity by visually displaying the relations of products and services in their intended context of use*".[40] For example, the IKEA Place app or the Dulux Visualizer from Azko Nobel, which allows customers to see Dulux paint colors on their walls, helps customers solve a problem, and promotes the emergence of creative solutions not necessarily driven just by a utilitarian need. AR apps can also help foster intimate consumer-brand relationships. A study about Sephora's mobile AR app[41] showed how consumers incorporated it into their life rhythms.

The work presented above is inspiring to adopt AR in different phases of the product lifecycle. Moreover, the heterogeneous technologies of Industry 4.0, like cloud and mobile apps, can be combined to integrate industrial information in the MES[42] and provide augmented product information to end-users.[15]

3 | RESEARCH APPROACH

Among the multiple forms of action research, its canonical form (CAR) is one of the most popular and well-documented,[16,17] evolving in cycles of *diagnosing, action planning, action taking, evaluating, and specifying learning*. Canonical action research was selected for our project, with the dual aim of solving a practical problem and contributing to knowledge.[43] This approach is well suited for complex situations that require a holistic understanding of the problem and context-centric research that produces action in a client system architecture.[44]

The theory is essential during the entire action research cycle to guide the actions from their early stages and as an output of the research. Aiming to ensure rigor and validity in our action research project, we have followed the *Principle of the Researcher–Client Agreement; Principle of the Cyclical Process Model; Principle of Theory; Principle of Change through Action; and Principle of Learning through Reflection.*[16] Our research's practical outcome is a technological infrastructure for Industry 4.0 in a traditional economy sector. The theoretical outcome is the approach to developing hybrid mass customization and personalization strategies supported by augmented digital engineering.

The client participating in our research is a household ceramic company that exports most of its production. Their work is built to client specifications, but they are also interested in exploring their own design. The managers bought a 3D printer (for prototypes), but manual work in their process is still very high. Our CAR evolved in different cycles, and we report the most recent in this paper, including the development of apps for manufacturing and design. The pilot projects started with a limited set of models[45] and continued to the full product with a mobile MES[42] prototype.

The production context and some examples of the case company portfolio are presented in Figure 2.

The most usual technique for household ceramic production is the use of moulds (on the top of Figure 2, a final product may require one or more moulds for each of its parts). Therefore, mass personalization in ceramics could be achieved via 3D printing, where the customer designs the desired shape. However, "[s]*trictly speaking, a 3D printing process represents only a forming procedure involved in the many steps within the preparation route to the final ceramic parts* [and…] *obstacles to the wider use of 3D printing in ceramics fabrication still exist. Industrial mass production can be very challenging*".[46] These authors also present the aerospace and medical industries as the areas of most potential for 3D printing of ceramics. The barriers to "lot size one" are still significant in traditional decorative household ceramic making 3D printing a good option for prototyping—which can later be used to produce series or unique and much more expensive products.

Our case company's product models already share common parts or moulds (e.g., ceramic columns and bases of specific pots). Their customers can choose from different models available, but it is also possible to change colors or decorations or propose entirely new models. Customization is already part of their business, but a lot size one is far from viable using traditional moulds. The company was interested in Industry 4.0, particularly 3D printing and new digital platforms to manage production (mobile MES prototype development). They were also interested in augmented reality to assist design and marketing, showing positive results in their pilot projects. For example, simulating model changes or visualizing the product in real environments. However, the initial Industry 4.0 diagnosis revealed a low maturity in the three axes represented in Figure 3.

The market and customer access (on the right) obtained the lowest evaluation (near 1 on a scale up to 5 – dark red line representing the current maturity stage). The value chain and processes (on the left) and the business model, product, and service portfolio (on the top, in both cases below level 2) also revealed improvement opportunities. Compared to the organization's strategic objectives (the "to-be" stage represented by the light red line), they were in the initial stages of digital transformation.

The team made a joint reflection about the company opportunities. On the one hand, mass customization was the most interesting approach because it is possible to modularize ceramic products. A single mould shape can be incorporated in multiple final products (e.g., a specific vase part with variants in shape and decorations), reducing product design costs and achieving economy of scale. The number of defects in ceramic production is high, requiring to produce more

FIGURE 2 Client-system infrastructure: production line and product collections.

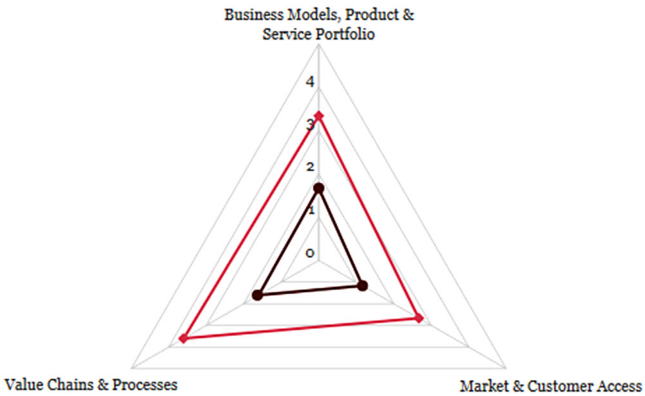

FIGURE 3 Industry 4.0 diagnosis of the case company according to the model proposed by PwC.[47]

products than necessary. Therefore, modularization reduces waste and increases efficiency (it is possible to reuse remaining products resulting from overproduction in other orders). On the other hand, customer participation in the early design stages is also crucial.

At that stage, how customer participation could be increased via augmented digital engineering tools was a priority. For example, augmented digital engineering could be used to generate prototypes faster, reduce waste, or generate the 3D files needed to print moulds that, in turn, could be used to produce small lots or even lot size one products. This challenge is not related to mass customization or modularization. However, it is unquestionable that combining modularization with data-driven design is a competitive advantage. The data collected directly by their users' inputs could provide information about common trends in specific markets. According to the company managers, different world zones have particular tastes in ceramic design. Mass personalization could contribute to identifying those trends by comparing the type of products generated with augmented digital engineering tools.

The following section presents the results of our action plan and field implementation.

4 | AUGMENTED DIGITAL ENGINEERING: CASE DESCRIPTION

We describe next the custom MES solution that was developed for the ceramic company.

4.1 | System architecture

This cycle started with creating an Industry 4.0 architecture enabled by a mobile MES platform, 3D printing, and the augmented reality app. These elements share the product model database (e.g., existing forms, possible colors, raw materials, packaging requirements) and its hierarchical representation. For example, a product "jar J" can be composed of part A (common to other products of the same collection or another collection) and a unique part B. Moreover, each product form can have multiple decorations available and one or more files attached to the database (e.g., photos, .obj, or .stl 3D files).

Figure 4 presents the most relevant elements of the proposed architecture using Archimate.[48] This enterprise architecture language developed by the Open Group includes different layers. Its suitability for Industry 4.0 was already suggested[49] and adopted in digital interoperability representations.[50] Our model uses three layers, namely, the physical and technology layer (green), the application layer with digital solutions (blue), and the business layer (yellow), representing the main processes and business services. The physical layer (bottom-right block) represents the infrastructure located inside the factory. For model simplicity, we only include the most relevant connection between each block.

The architecture includes the product catalogue database (on the bottom left), including data and source files used for 3D printing or integration in the augmented reality app. The model also includes an application server for the MES, converting client requests (e.g., product reference ABC, decoration D1) into production orders (each ABC unit may require producing three units of part A, one of B, and another of C). Therefore, the product structure is required in the database.

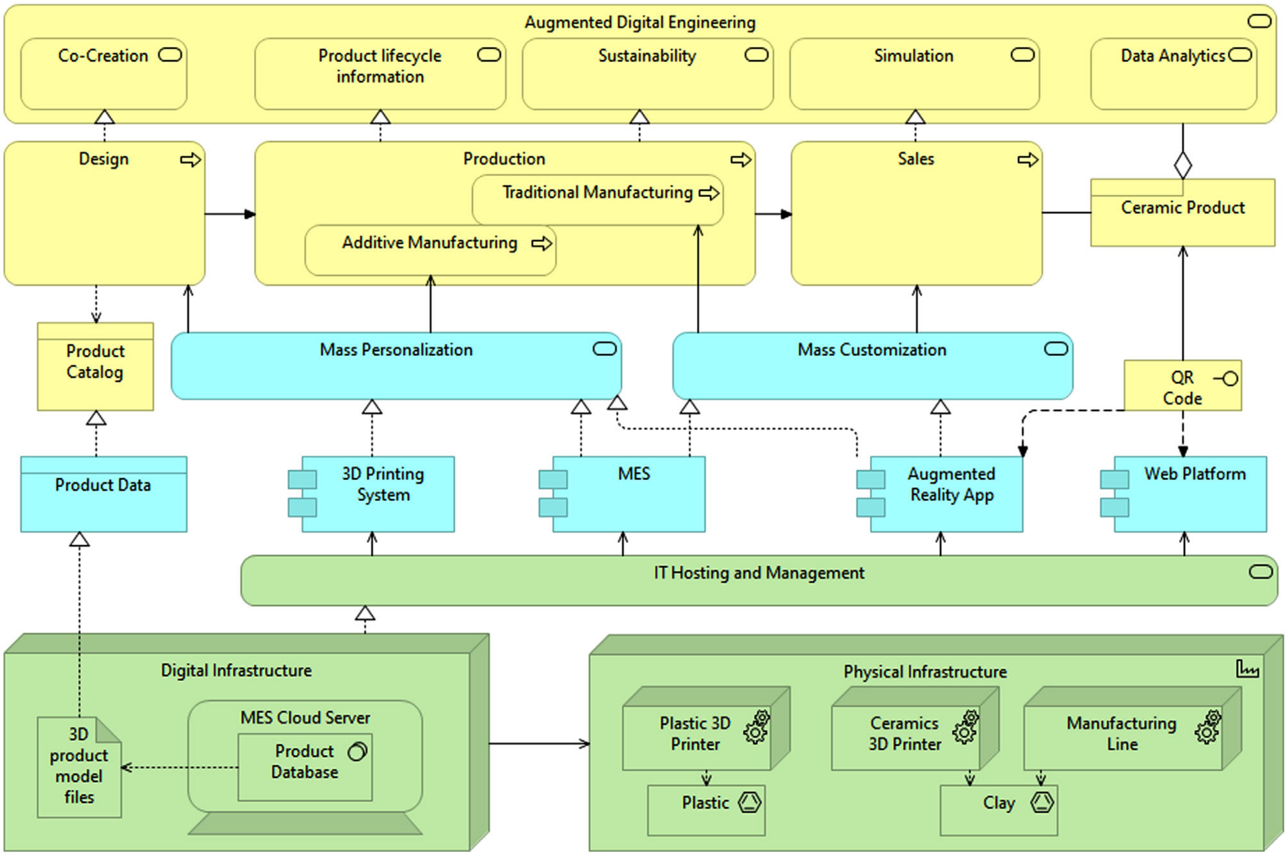

FIGURE 4 Architectural model for augmented digital engineering in the ceramic company.

On the bottom right are represented the essential ceramic production equipment, namely, 3D printers and the manufacturing line.

Four application components are presented in the architecture (blue elements): the 3D printing system, the MES, AR app, and website, supporting personalization and customization services to the central business processes (yellow elements). The physical product (prototype or end product) may also include a quick-response (QR) code that redirects the user to the product presentation and ensures authenticity.[51] On the top, the five critical user services supported by the augmented digital engineering solution are represented, namely, co-creation involving the user in (interactive) product design since the early stages, complete product manufacturing information, ensuring that personalization reduces wastes (e.g., adopting 3D printing to create efficient prototypes, and restricting the customers' choices to sustainable models), simulation, and testing (e.g., visualizing the product with the AR app), and collecting valuable data about user preferences in specific markets regions.

The proposed architecture aims to integrate the needs of mass customization and mass personalization. On the one hand, the product portfolio is identified by all its possible parts and configurations. This structure simplifies the production orders. For example, 1000 units of product P1 and P2, both composed of two units of part PA1, P1 composed of one PA2, and P2 by two PA2 may be achieved automatically by a work order including 4000 PA1, and 3000 PA2; later assembled and decorated according to the respective specification. Moreover, it limits the client's choices to the most profitable and sustainable products of the company. On the other hand, the products become available for simulation using the mobile app or prototype production in the 3D printer (each product design requires a 3D file with a compatible format), allowing customer participation in the design and the proposal of new models not yet included in the company portfolio.

4.2 | Deploying the augmented digital engineering infrastructure

The mobile MES development included three main modules: product management (interacting with the 3D model database), work order management (integrating with the enterprise resource planning (ERP) of the company, generating work orders of necessary customized parts according to the customers' requests), and production management (an interface for the company workers and dashboards). The MES structure is presented in Figure 5.

The MES comprises a software component suitable for the production staff (e.g., order inputs or product information with design details) and an interface for manufacturing management (e.g., stocks, orders, product structure definition) and data analysis. Examples are included in Figures 6 and 7.

The development corresponded to the problem-solving interest of action research cycles presented by McKay and Marshall.[18] The system

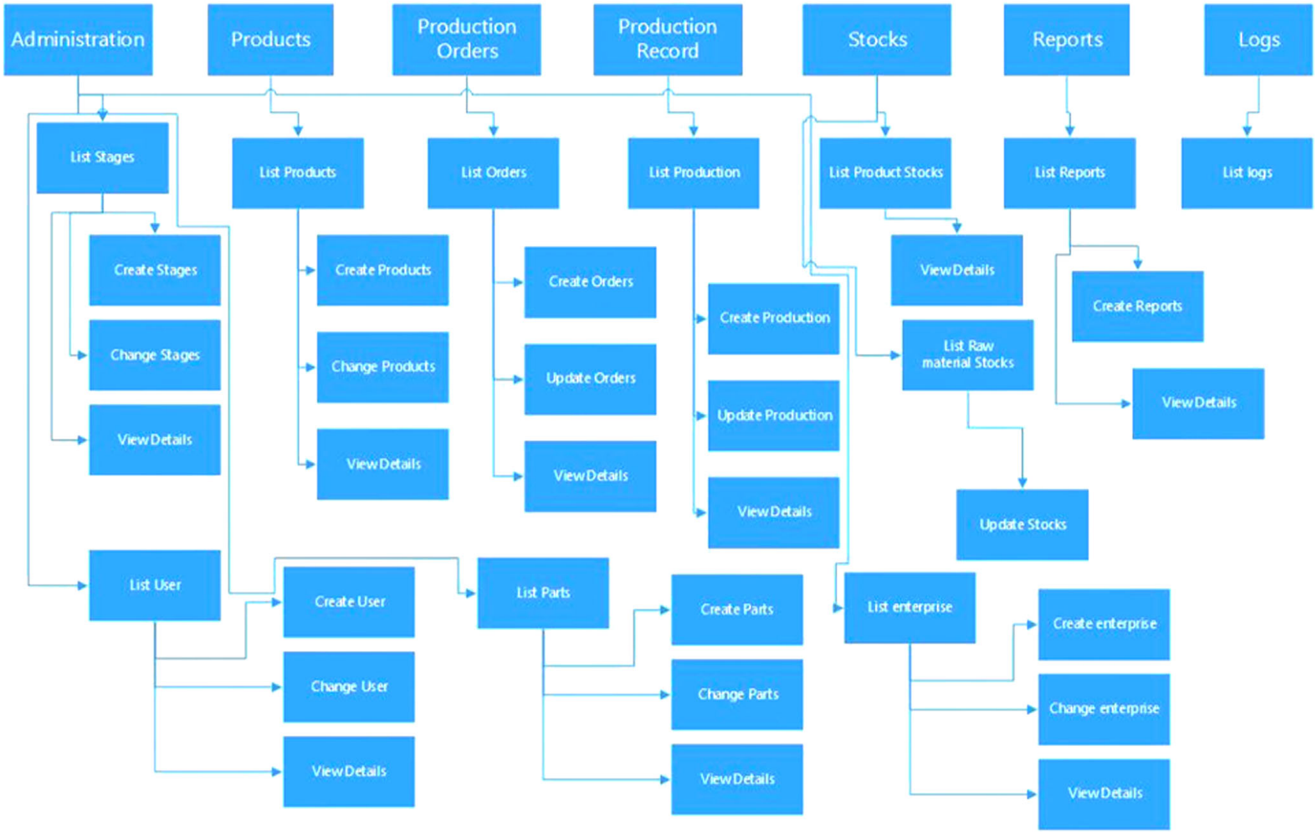

FIGURE 5 Manufacturing execution systems (MES) navigation structure.

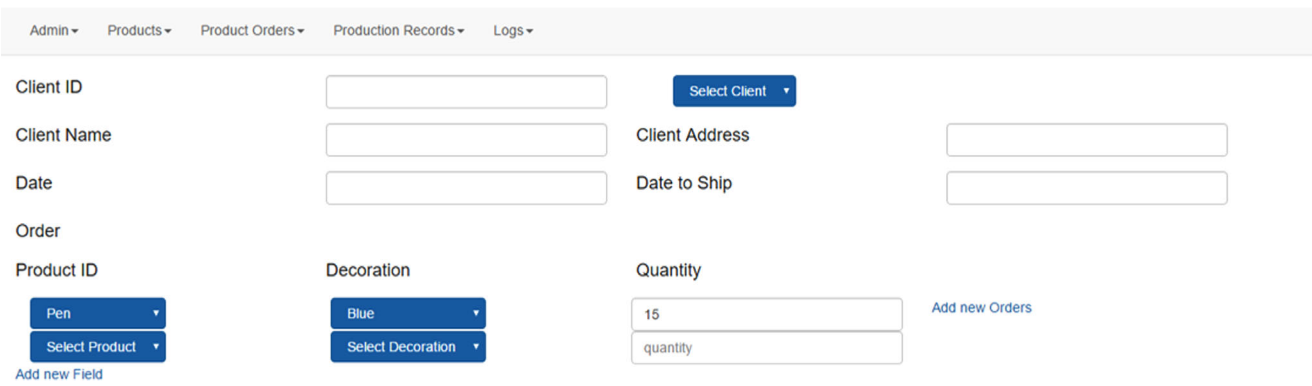

FIGURE 6 Manufacturing execution systems (MES) interface for order management.

was prepared for mobile use on tablets or smartphones, minimizing the company's investment and promoting agile and simplified records in the production line.

The deployment of the AR component included QR code markers, which can be interesting to incorporate into product catalogues or attached to the product. One of these examples is included in Figure 8.

Figure 8 presents an interface created using Vuforia Augmented Reality SDK. The example includes changing color (top-left icon) and size (sliders on the right of the image). The visualization presented in the figure can be used in internal work orders (to assist the worker in identifying the piece characteristics) or in external catalogues, placing the QR code near the collection or model. The company products are included in the MES database in OBJ, a 3D Object File widely used for exchanging 3D information, which is also compatible with being imported to the selected AR tool.

Another version used a selector of shapes and patterns. The markerless version of the app is presented in Figure 9, which can be used for simulation on-site.

The mobile AR app presented in Figure 9 allows customization with the selection of predefined models and personalization of the form

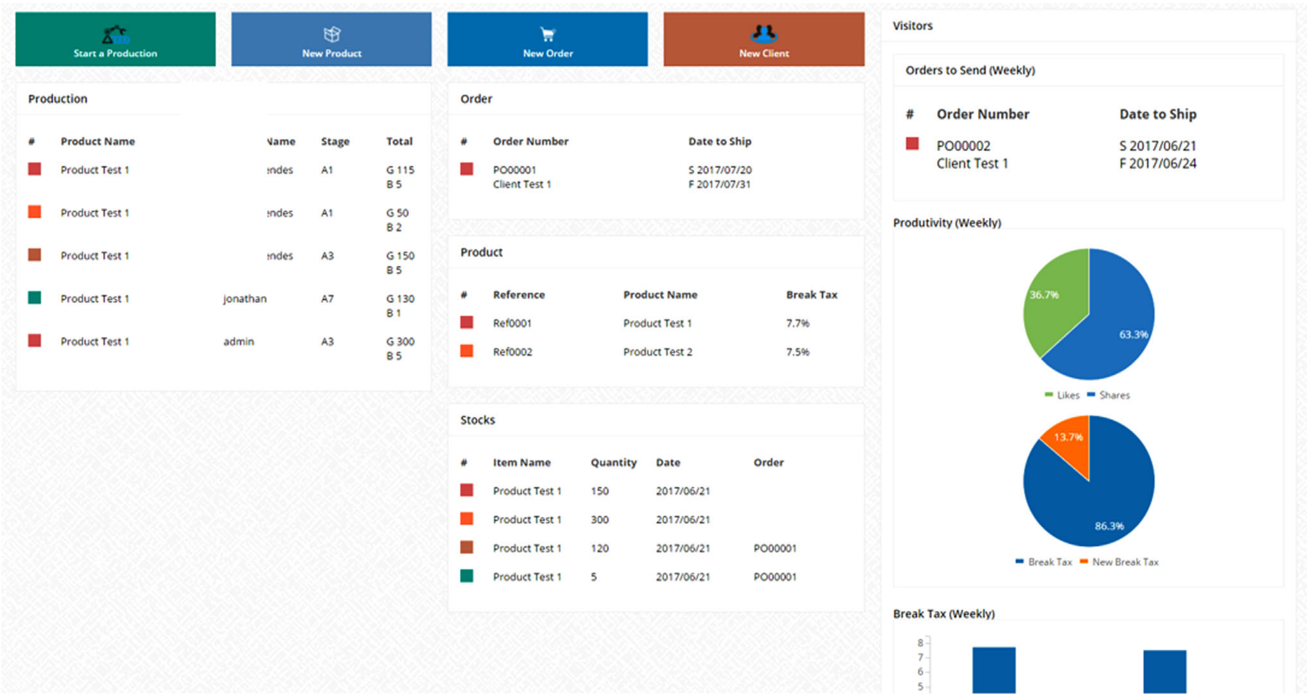

FIGURE 7 Manufacturing execution systems (MES) dashboard example.

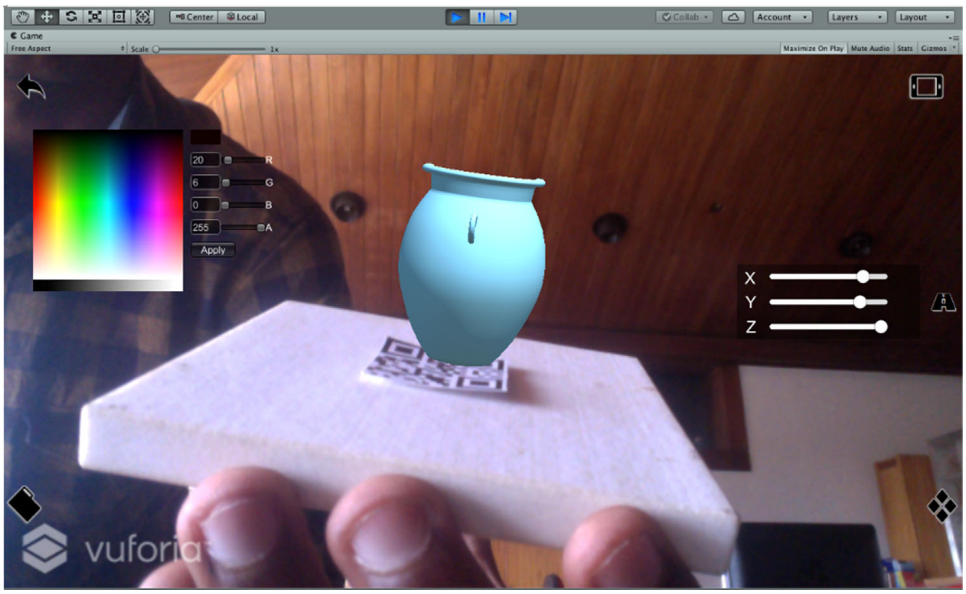

FIGURE 8 Augmented reality (AR) development to personalize form and color.

(requires the production of a new mould or selection of the 3D printing process to create the shape). The target users of this app are the company distributors (e.g., simulate new elements in a collection, changing colors) or end-users to (1) simulate customized products at the interior of the building or (2) propose unique models (e.g., hotel designers) with only a few units or even one piece (produced in a 3D printer).

5 | DISCUSSION: THE CONTINUUM OF AUGMENTED DIGITAL ENGINEERING

The ambitious industrial goal of achieving constant product flows to the customer at a minimum environmental and economic cost is more critical than ever. Nevertheless, combining these goals with product variety and increasing interactions with the customer is challenging.

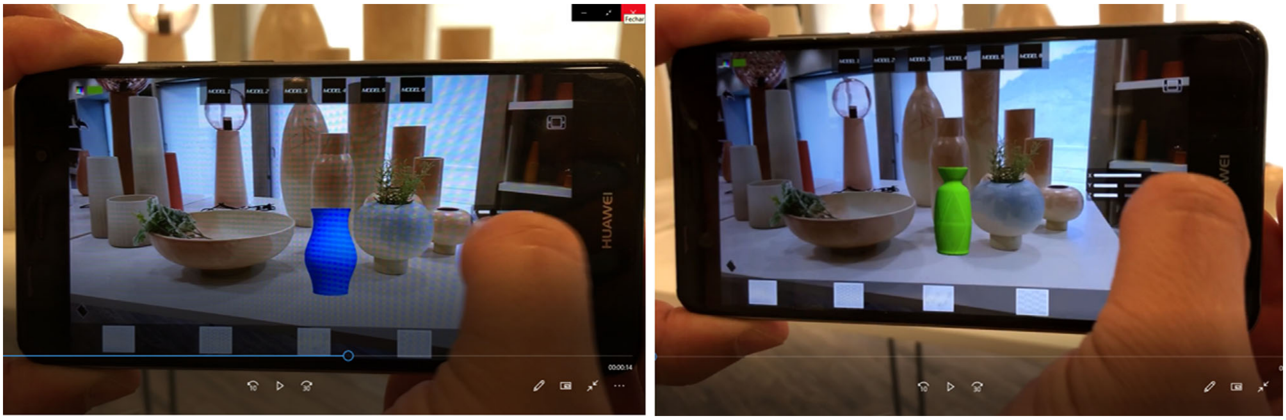

FIGURE 9 Augmented reality (AR) app to personalize the object on the target scenario.

This case reveals that mass personalization is also emerging via 3D printing and visualization in traditional companies. However, the strategy "from customization to personalization" may be transformed in a journey towards augmented digital engineering.

On the one hand, reality is augmented with digital representations of the physical products accessible to the customer. On the other hand, the instantiation of digital forms in authentic products via 3D printing has the dual goal of prototyping and building market-ready products. The proposed solution follows a knowledge-based approach to improve the product portfolio and discover valuable product variants proposed by Luh et al.,[38] using Industry 4.0 technologies to support the process. Moreover, the proposed approach supports collaboration and horizontal and vertical integration for augmented digital engineering and has a lightweight mobile infrastructure optimized for an SME's needs.

The integration of mass customization and personalization varies,[52] but companies "*not adapting their strategic formulations to include personalization at affordable costs will soon be struggling for survival*".[4] This paper reveals the vital role of augmented reality in this process. On one end of the spectrum, AR can make "lot size one" possible in ceramic industries supported by 3D printing. On the other end of the spectrum, AR supports customer interactions in the customization strategy (1) allowing configuration within specific limits (e.g., product size, carbon footprint), (2) promoting reuse of the most profitable company models, (3) obtaining feedback from the changes made in the models by the customers, and (4) supporting the sale directly, by enabling the visualization of the product in its environment. Nevertheless, 3D printing is still limited when compared with manual work or other manufacturing techniques, particularly regarding the size of the objects that can be currently produced through commercially available 3D printers. We can, however, expect that this technology will continue to improve and will allow larger formats in the future, as already happens in the construction industry, using more advanced robotic systems or separating larger products into smaller parts.[53]

Digital technologies promoted the transition from an economy of scale to an economy of scope,[7] while Industry 4.0 accelerated mass personalization.[6] However, in some industries, like the one addressed in this work, variety is not synonymous with "lot size one". For example, a global hotel chain may need hundreds of similar products to promote a coherent image worldwide. Some customers do not have time or even interest in having a unique piece, preferring to share the design of a renowned artist. Product brand value is not always a synonym of "fewer units"; in fact, it is questionable that automotive brands, even the most exclusive, could survive at this moment producing unique cars to all their customers. New strategies for mobile MES are necessary to obtain synergies from customization and personalization.

In the practice of the case company, we could observe how the benefits of both mass personalization and mass customization can be explored, not compromising modularity, sustainability concerns, and customer-centric engineering. The same product line can be used to produce a series of 1000 pieces or a single piece made in a ceramic 3D printer (that will enter later in the process as it still needs to pass through the oven, packaging, and so on). The major change occurs in the parallel design path and the interactions made possible between humans (e.g., customer and design team) and production technology (e.g., AR app model and file for the 3D printer). Figure 10 illustrates the synergies obtained via augmented digital engineering to mass customization and mass personalization.

Augmented digital engineering allows more than the sum of the parts. For example, personal interactions with the customer aiming to create new models can be a source of ideas for a new collection to the market. The same customizable collection can later be adapted to produce unique pieces or more restricted collections, reusing parts of other models. Some concepts of mass production are still relevant nowadays (lower costs, optimize production lines). However, the concept of "standard product" is replaced in augmented digital engineering by "minimum standard design": *the most specific market segment to reach the widest market scope and production value.*

There are five primary motivations for company managers, particularly SMEs, to adopt the proposed solution. First, the system goes beyond customization (defined as a choice among predefined possibilities), allowing to define unique sizes that suit the customer's needs perfectly, but limits the choices to the "minimum standard product"—product models desired (voluntarily or enforced, as happens in product

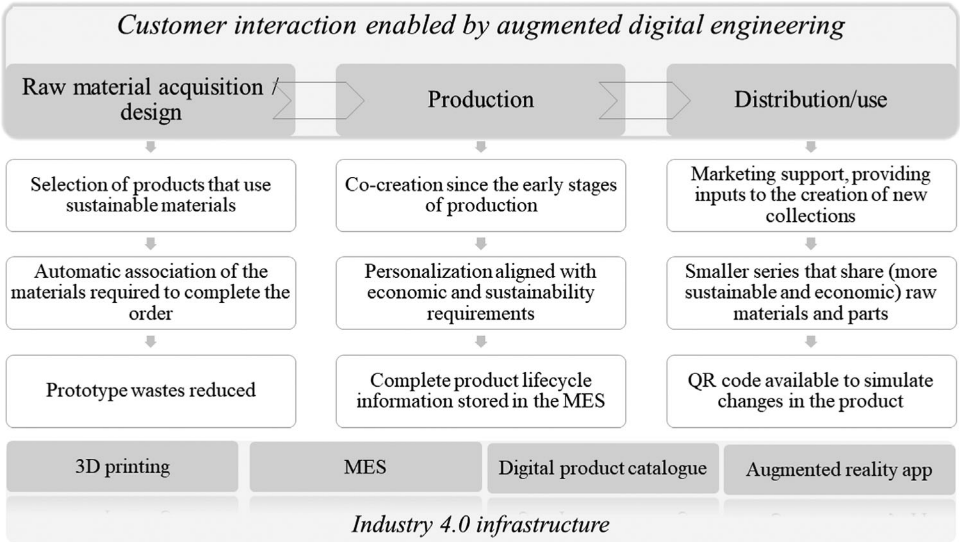

FIGURE 10 Synergies of augmented digital engineering.

regulations) by the manufacturer for sustainability and/or economic reasons. Second, it explores synergies of Industry 4.0 investments, making broader use of digital product files: for 3D printing of prototypes, the mobile app, and the MES order management system. Third, the investment assists commercial staff in trade fair interactions, reducing the need for different physical models and variants in an exhibition (local showroom or trade fair). Fourth, augmented digital engineering can reduce the time necessary for prototyping, keeping the customer engaged in the design and potentially the desire to buy the product. Fifth, augmented digital engineering may be used to explore specific niches that value unique parts and have specific restrictions for product size and visual attributes. Major distribution companies are already exploring design rooms and virtual interaction with their customers. The supply chain of the major distributors may create pressure for the adoption of augmented digital engineering in the early stages of manufacturing. Early SME adopters may gain competitive advantages in large supply chains. Furthermore, they will be in a position to satisfy the increasing consumer interest in short circuits with co-created products.

Action research is relevant to systems practice, allowing to create transferable results. The most immediate opportunity is identified for manufacturers of decorative products, furniture, or appliances that have benefited from customer interaction since the early design stages. It may involve customization of predefined models, size adjustments (e.g., to fit in specific locations like hotels), or defining the requirements of a more expensive lot size one (e.g., a unique certified product).

Evaluating the minimum standard design is necessary for different companies needing to balance the individual needs of each customer and the economies of scale. For example, watches or cars producers presenting options available to customize or personalize (e.g., engrave the name) their offer. Other companies like Ferrari allow creating unique cars by working side-by-side with their designers that "*presenting a range of potential configurations suggestions and showing a real-time virtual preview of the car*".[54] Augmented digital engineering can enable direct customer interaction in high-tech manufacturing industries like automotive or aeronautical. Nevertheless, there are restrictions to the customer's desires, revealing the need to identify a minimum standard design suitable to each business sector. For example, the size of the parts in an airplane is not freely personalizable by the customer, independently of the price they are willing to pay for safety and regulatory demands.

The advances in augmented digital engineering may reduce the gap between customization that maximizes manufacturer profit and the highest (possible) level of personalized product that ensures sustainability. However, there are also significant challenges for SMEs that require additional research, including layout adaptations for additive manufacturing, people training, and data security.

6 | CONCLUSION

This paper adopts augmented digital engineering to deploy a hybrid strategy of mass customization and mass personalization in a traditional sector. Key Industry 4.0 technologies (MES, cloud, mobile, augmented reality, 3D printing) are implemented to transform a traditional household ceramic company, aiming to integrate (1) continuous customer interactions and (2) data-driven design and marketing activities. The project reveals that mass personalization is not the end of the line, and there are significant advantages in exploring the synergies with mass customization using augmentation strategies. Our contribution expands the proposals for augmented internal manufacturing processes, incorporating design capabilities "*especially using the current web and virtual technologies which allow the interaction by many users on the same data items*",[55] in close collaboration with the customer. Augmented reality via digital models and augmented digitality via 3D printing can expand the case company's market scope (ranging from unique products to environmentally friendly and economically feasible configurations of product parts) and simultaneously support their co-creative processes.

Some limitations must be stated. First, the particularities of household ceramics and the case company scenario. Secondly, the exploratory nature of the proposed infrastructure requires a longitudinal analysis to fully understand the company market's benefits. Thirdly, the evaluation was made exclusively in the case company involving researchers and practitioners. Future work is necessary to evaluate the impact on their customers, namely, the tools' usability and benefits. Fourthly, not all companies have their products digitized, requiring a gradual approach to augmented digital engineering. Therefore, the 3D product portfolio is still limited and will require several years to be completed. Some companies like the one presented in our study own thousands of different designs, and decision support systems for customization (few moulds and colors/decorations should produce the maximum variety of end products maximizing profits) are still evolving. The fifth limitation emerges from the same causes, namely, the impossibility of accurately measuring the solution's financial costs and benefits in the company setting.

Future work opportunities for systems engineering integrating augmented reality technologies in MES platforms are vast. For example, the 3D model generated with the AR app can be automatically translated into the required parts (moulds) and generate the mobile MES work orders. The AR App can be used to send new requests for existing products (e.g., more quantities) or suggest new models according to the users' preferences. Moreover, it will be interesting to evaluate the role of augmented digital engineering in the identification of the best product architectures since the early stages of market segmentation. Nevertheless, this future development will require more advanced techniques to implement recommendation services. Another promising opportunity for future research is creating virtual showrooms to interact with the products with more advanced tools (e.g., AR smart glasses) while capturing new product development insights. Future work might also focus on characterizing the differences between sectors with high regulation or substantial constraints versus sectors with little regulation and on how engineering methods to address mass personalization might differ between these sectors.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

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