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A STRATEGIC VIEW ON INTERTWINING DIGITAL AND PHYSICAL MATERIALITIES ACROSS LIFECYCLES OF PRODUCTS AND SERVICES

Research paper

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Abstract

Opportunities to use virtual, augmented, and mixed reality (VAM-R) are emerging in various sectors of the economy. To seize them, managers need to develop comprehensive strategies that intertwine digital and physical forms of materiality. This paper proposes a way to assess and steer the transformations of the reality-virtuality continuum across lifecycles of products and services. Our approach identifies use cases for VAM-R according to the (1) strategic imperative, (2) physical materiality, (3) reality-virtuality assessment, (4) digital materiality, (5) information value, and (6) project portfolio. The findings result from three action research cycles in manufacturing and healthcare. For theory, we propose a framework to evaluate the reality-virtuality continuum and guide VAM-R transformations. For practice, we propose and test an artefact accessible to domain experts with different backgrounds, and a sequence of steps to assist managers in their digitalization strategies with VAM-R. Lifecycle approaches offer an alternative perspective to situational transformation, potentially improving the pervasiveness of organizational changes using information technologies.

Keywords: digital strategy, digital transformation, reality-virtuality continuum, VAM-R.

1 Introduction

Digital transformation is altering the boundaries of physical and digital forms of materiality (Yoo, Boland, Lyytinen and Majchrzak, 2012). It is increasingly difficult to differentiate between what is “real” and what is “virtual” in the most disruptive innovations, opening up room for different configurations in the reality-virtuality continuum (Milgram, Takemura, Utsumi and Kishino, 1994). This term was coined over two decades ago to illustrate the range of possibilities in mixed reality (MR): on one hand, pure physical objects; on the other hand, the fascinating virtual reality (VR) environment of fully modelled worlds. Since then, much has changed in information systems (IS), including the possibilities to combine physical and virtual objects in the same social experience, as it happens with augmented reality (AR). This *fusion* of different forms of materiality is particularly relevant to IS research that holistically addresses the social and the technical realms (Hirschheim and Klein, 2012).

Several studies focus on the use and communication of augmented objects, but approaches for their development are lacking (López, López, Guerrero and Bravo, 2014). In fact, “*these systems are currently in their infancy, but in the future, companies will make much broader use of augmented reality to provide workers with real-time information to improve decision making and work procedures*” (Rüßmann et al., 2015). One of the few integrated approaches, presented by López et al., (2014), suggests six phases: (1) defining the problem, (2) the context of use, and (3) the requirements, (4) selecting the candidate object, (5) developing the augmented object, and (6) testing. Yet, this leads to new questions such as “how to identify opportunities to change the reality-virtuality continuum?”, “how to

select candidate objects for digital transformation in dynamic organizational settings?”, “how to establish priorities for the developments”, and “how to identify the value and the information requirements for virtual, augmented, and mixed reality?”. We agree with Walsh and Pawlowski (2002) about the multiple research opportunities in the reality-virtuality continuum, for example, in design theories and field studies. Moreover, the opportunities in each industry vary (Walsh and Pawlowski, 2002; Porter and Heppelmann, 2017; Tabrizi and Sanguinetti, 2018), requiring sector-specific investigation to guide managers in their strategies for virtual, augmented, and mixed reality (VAM-R). In this paper, we will adopt the term VAM-R when referring to the full range of possibilities in the reality-virtuality continuum and to the specific implementation (e.g. AR mixing physical and digital objects, VR being 100% digital) when the case is restricted to a form of instantiation.

Our two-year research project extends the work of Porter and Heppelmann (2017), which suggests that all organizations need an augmented reality strategy. According to these authors, “AR enables a new information-delivery paradigm (...) will become more and more integral to every firm’s strategy [... and], when needed, VR adds a fourth capability – simulate – to AR’s core capabilities of visualize, instruct, and interact” (Porter and Heppelmann, 2017). Our field work highlights the interest of several companies in creating that strategy. It sheds light on the questions stated above and it proposes an approach to (1) evaluate and (2) change the reality-virtuality continuum according to the lifecycle stage of products and services. The approach was outlined in close collaboration with a research and technology institute (RTD), manufacturing companies in the materials sectors, and a district hospital.

In the remainder of this paper we start by explaining the study motivation. Subsequently, we present the opportunities and challenges of VAM-R. Next, the research approach is introduced. Section 5 details our field work and, in section 6, we summarize the lessons learned. The discussion is in section 7 and the paper closes with the conclusions, the limitations, and the opportunities for future research.

2 Problem Identification and Motivation

Our work started in a private non-profit RTD institute, created thirty years ago to support the Portuguese industries of ceramics and glass. Its shareholders include public organizations with the aim to promote industry advances at a national scale, and leading companies in the materials supply chain. Despite the fast advances in high-tech companies (e.g. automotive, electronics), traditional sectors of the economy are still in their early stages of digital transformation with VAM-R. The majority of ceramics and glass companies are small and medium sized (SMEs), facing difficulties in the development of key IS competencies (Cragg, Caldeira and Ward, 2011). Therefore, the RTD institute is determinant for the competitiveness of the entire sector. The institute wanted to create VAM-R roadmaps to assist the manufacturing companies in their efforts to bridge the digital and physical worlds, amplifying “their power to create value and reshape competition” (Porter and Heppelmann, 2017).

According to the RTD institute, examples of VAM-R in ceramics and glass are scarce. We confirmed that few studies discussed its use in traditional sectors of the economy. To address this gap, we have started our research with ceramic and glass companies selected by the institute. Their main goals were to (1) identify cases of VAM-R use, and (2) conduct experiments with VAM-R for the target sectors. After reviewing the literature on VAM-R development approaches, the research team concluded that these goals were aligned with a scientific contribution to advance VAM-R in manufacturing organizations. However, the service sector was not considered in our initial scope. Then, in 2018, we enlisted a medium-sized district hospital that was interested in developing a VAM-R strategy. Its administration was aware of advances in virtual healthcare, but the examples were dispersed. This was our opportunity to refine and test a VAM-R transformation framework in a service organization.

3 Background

In the next subsections, we review contributions discussing VAM-R in the target sectors of our case organizations: materials manufacturing for construction and healthcare. Our goal is to provide a frame of reference for the subsequent phases of the research and identify potential use cases of VAM-R.

3.1 Where we are

Several studies have concluded that VAM-R is important for the construction sector (Sacks, Perlman and Barak, 2013; Harborth, 2017; Chu, Matthews and Love, 2018). Reasons include that “(1) it reinforces the connections between people and objects, and promotes engineers' appreciation about their working context; (2) it allows engineers to perform field tasks with the awareness of both the physical and synthetic environment; and (3) it offsets the significant cost of 3D Model Engineering by including the real world background” (Behzadan, Dong and Kamat, 2015). The healthcare service sector is also taking advantage of VAM-R, for example in surgery, training, nursery, and in improving treatments (Malloy and Milling, 2010; Zhu, Hadadgar, Masiello and Zary, 2014; Khor et al., 2016). However, most studies focus on specific applications of VAM-R, lacking contributions that address the evolution of predetermined or emerging changes in organizations following a tailored reality-virtuality strategy.

The cost-benefit analysis of VAM-R is a current line of research. On the one hand, there are three main cost categories to consider: technology-related, personnel, and organizational (Oesterreich and Teuteberg, 2017). The first category involves initial and ongoing costs of the hardware, software, technology maintenance and deployment. Personnel costs consider training in application use, management of the activities, application development, and changes. Finally, the organizational costs are a consequence of change and include business process reengineering, disruption, and the overheads. On the other hand, there are direct and indirect benefits of AR (Herterich et al., 2015; Oesterreich and Teuteberg, 2017; Chalhoub and Ayer, 2018). The direct benefits can be grouped in operational, tactical, and strategic, (1) reducing costs, (2) reducing time, and (3) increasing sales. Improvements in growth and success, market share, customer relationship and satisfaction, and corporate image are examples of indirect benefits (Oesterreich and Teuteberg, 2017). A specific example for healthcare is the reduction of pain and discomfort using virtual reality (Malloy and Milling, 2010). Examples in manufacturing include AR to assist operators in assembling processes (Chalhoub and Ayer, 2018), concluding for performance benefits and reduced number of errors. There are important cost-benefit studies that can guide managers in the selection of candidate objects and potential applications. However, we could not find a guide to conduct cost-benefit analyses for strategy development purposes, requiring a global perspective of the organization and its goals in the medium/long term.

Other authors have studied methodological aspects, for example, Zaher, Greenwood and Marzouk (2018), to monitor the progress of construction projects using a smartphone application using AR. The proposed solution explores the use of building information model (BIM), a three-dimensional representation of the building that also includes its characteristics. Another recent study presented by Chu et al. (2018) concludes that BIM and AR can improve information retrieval, task efficiency, and productivity in construction, which is aligned with the conclusions of Tabrizi and Sanguinetti (2018). These authors used a marker-based system in 2D plants to test the participants' behaviour and impact in their activities. Examples of methods to use BIM models in AR are included in Kahn et al. (2012) and Williams, Gheisari, Chen and Irizarry (2015). A systematic review of 101 papers (Shi, Ding, Zuo and Zillante, 2016) identifies the importance of materials lifecycle identification and tracking, for example, using RFID and GPS. Although twenty-five of the selected studies address AR in construction sites, we could not find examples for the construction materials supply chain, integrating supplier information via AR or VR solutions. We observe different rates of adoption of AR in supply chains: one, moving faster than ever, addressing the needs of building design with 3D models, construction operations, and inspections on site; another, still in the early stages of development, involving materials suppliers (the companies targeted by the RTD institute) that are mostly reacting to market needs.

Despite these important contributions, we could not find studies that address the managerial task of creating a VAM-R strategy for the organization: one that is not restricted to a specific process, department, experience, product or service. One that reflects the lifecycle of the key products/services, intertwining digital and physical materialities. Such an approach should consider the entire reality-virtuality continuum, which means that there are multiple opportunities in the same context of virtuality, ranging from 0% (purely physical) to 100% (purely virtual). Transformations in the reality-virtuality continuum have a bidirectional influence on the social dimensions of the organization, for

example, people skills and process improvements. In fact, as proposed by sociomaterial theory, humans and objects are indivisible, although it is possible to consider their differentiation for analytical purposes (Gaskin and Lyytinen, 2011). Therefore, managers must consider both the social and the material elements (physical and digital) in their strategies.

3.2 Where we want to be

The opportunities for VAM-R are increasing. A recent study presented by Li et al. (2018) identifies opportunities in safety training, inspection and instructions, and in assisting the use of high-risk equipment. Examples of such applications can be found in Kim, Kim and Kim (2017), to avoid hazards in construction sites using AR in wearable devices, and in Zhou, Luo and Yang (2017), for segment displacement inspection during tunnel construction. According to Alsafouri and Ayer (2018), data interaction, visualization, and real-time simulation can also be achieved with AR that “allows users to bring model contents (including text-based information and 3D elements) into the site”. This group of studies suggests that the potential of VAM-R is not restricted to adding product/service value to end customers, but also includes the quality of work and employee safety and comfort.

AR in marketing is also promising for manufacturing. For construction materials, there are examples of simulation using AR, namely in bathrooms (Villeroy & Boch, 2018) and in ceramic tiles (Revigrés, 2016). Companies in the habitat domain are also taking advantage of AR in their marketing strategies, for example, offering coffee mugs with an augmented reality app for entertainment (Hashmugs, 2018). Early studies already suggest potential applications of AR for prototype design and for consumer marketing (Omar, Cheshire and Wu, 2005) but also for services, namely in the tourism sector (Kounavis, Kasimati and Zamani, 2012). VAM-R for porcelain, pottery, and glass in museums and art galleries is more accessible nowadays. The importance of non-intrusive methods to identify the products and, in some cases, its uniqueness (e.g. for works of art) puts AR at the top of the candidate technologies for product classification. The Museum of Modern Art in New York City (MOMA) is promoting pioneer work using AR for innovative exhibitions in art galleries (MOMA, 2018). These examples can inspire organizations where distinctive product and service design is a competitive weapon.

3.3 How to get there

There are emerging opportunities for VAM-R, for example, for traceability (Shi et al., 2016), real-time simulation (Alsafouri and Ayer, 2018), quality (Chalhoub and Ayer, 2018), safety (Chalhoub and Ayer, 2018; Li et al., 2018), marketing (Omar et al., 2005), and training (Zhu et al., 2014; Herterich et al., 2015). Yet, a major gap to address in our research is how to integrate them in a comprehensive VAM-R strategy, not limited to a technology, department, or business process.

Future research should integrate VAM-R in the entire lifecycle of products and services. Focusing on single processes or products can provide situational improvements but poses the risk of missing opportunities in the transformations that occur over the entire lifecycle. For example, creating a training VR app that instantiates only part of a treatment in healthcare. Another risk is the creation of a solution for a product/service that does not include all the information required by its user throughout the entire lifecycle. For example, developing an augmented reality app for product simulation (useful in the selling phase) but missing information for the end-user of the product (e.g. maintenance instructions), or even recycling, which is important for circular economy.

Although it is possible to identify the potential of VAM-R adoption in our target sectors, there are many issues to address. For example, glass transparency and reflection can be challenging for VAM-R adoption. It is necessary to identify which digital layers of information should be included in the portfolio of each industry cluster. Managers should consider VAM-R potential in the entire product lifecycle and different candidate objects to augment, for example, the products, equipment, and context (e.g. site, habitat environment). Finally, devising guidelines to assist managers in different fields requires sector-specific experiments and the consideration of company-specific priorities. An approach to develop VAM-R strategies must be participative, tailored to each product/service lifecycle, and accessible to domain experts with different backgrounds, such as management, engineering, or marketing.

4 Research Approach

It is impossible, from a socio-organizational viewpoint, to create a new systems development methodology without intervening in the real world to test it (Baskerville and Wood-Harper, 1996; Baskerville, 1999). To address the challenge of developing a new VAM-R approach in cooperation with organizations, we have selected action research in its canonical form (Susman and Evered, 1978) as our method of inquiry. Its main steps are:

- *Diagnosing*, identifying, or defining the situation;
- *Action planning*, specifying courses of action to improve the problematic situation;
- *Action taking*, causing change to occur and trying to create improvements;
- *Evaluating* the consequences of the actions, involving a critical analysis of the results;
- *Specifying learning*, defining the outcomes that will add to the body of knowledge.

There are multiple forms of action research, involving cycles of joint action and learning (Brydon-Miller, 1997; Checkland and Holwell, 1998) as a relevant mechanism to improve and transform organizations, aiming to produce research with “*a very practical concern for useful outcomes*” (Brydon-Miller and Coghlan, 2014). Our option for canonical action research (CAR) was based on solid guidelines for its adoption (Davison, Martinsons and Kock, 2004; Avison, Davison and Malaurent, 2018) and discussions of the role of theory (Davison, Martinsons and Ou, 2012). Our study adopts sociomateriality (Orlikowski, 1992; Orlikowski and Scott, 2008) as the focal theory, and new sociomaterial lifecycles of digitalized products and services (Yoo, 2010; Barata and Cunha, 2018) as an instrumental model to guide the outcomes of the intervention (Davison et al., 2012). According to Davison et al., (2012), a “*focal theory provides the intellectual basis for action-oriented change in a CAR project [... and] an instrumental theory is used to explain phenomena (...) including those processes and tools that are used to establish and verify focal theories*”. Action research has a central role in modern IS research (Avison et al., 2018). According to Barad (2007), the “*we don’t obtain knowledge by standing outside of the world; we know because we are of the world*”.

Figure 1 illustrates the research cycles.

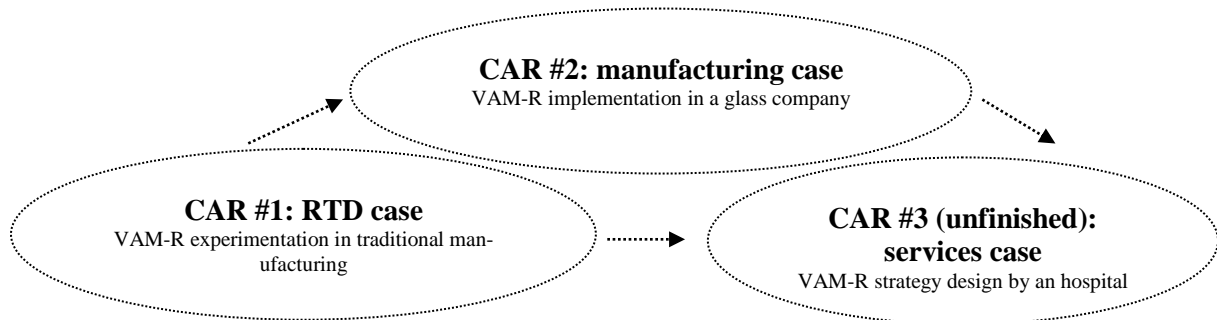


Figure 1. The sequence of the three CAR cycles in its interactions.

The first cycle (CAR#1) explores augmented reality possibilities for ceramic and glass products in the RTD institute that we introduced in the motivation section. The second cycle was conducted in a glass manufacturing company. Examples of their recent projects include Shopping Center Val d’Europe (Paris), Benfica Stadium (Lisbon), and Erasmus Gardens (Brussels) – recognized as the best sustainable real estate project of Belgium in 2017. The company was selected due to their internationalization strategy and potential to act as an example to the sector. Its managers needed guidance on how to develop a VAM-R strategy and put it in practice with a pilot project. Finally, the third cycle aimed at the development of a VAM-R strategy for a mid-sized 154-bed district hospital that employs 621 professionals. This phase of the project involved the hospital quality and safety department, which was interested in exploring VAM-R opportunities and identifying a comprehensive VAM-R strategy to present to their administration. We report preliminary results for this cycle that is still ongoing in 2019.

Data collection included interviews with experts in the target sectors, observation, and compilation of documents in the case companies during the past two years. The first year-long CAR cycle started in 2017 and included the participation of the IS unit of the RTD institute and interviews with experts in ceramics and glass selected by the institute. The top managers and three operational managers (quality, production, IT) of the glass company were the key participants (CAR#2). They were selected by the top manager of the glass company according to their expertise and direct intervention in the field study. The final cycle started in mid-2018 and is still evolving – the field intervention depends on decisions regarding hospital investments, but there are already preliminary results that we report in this paper. Besides the hospital administration, the chief nurse and the quality and safety manager are the participants in our CAR#3. Although each cycle had a specific purpose (see Figure 1), there were interactions between them; CAR#2 used some techniques that we explored in CAR#1, namely using QR codes, while CAR#3 extends the results of CAR#1 and CAR#2, by defining a VAM-R strategy in a new context and adapting artefacts developed in the previous cycles. The action phase of CAR is presented in the next section according to the dual interest of problem solving and research contribution (McKay and Marshall, 2001).

5 Problem Solving Interest: Towards VAM-R Transformations

5.1 CAR#1: experimenting with VAM-R in ceramics and glass

During the first cycle in the RTD institute we have conducted field experiments with marker-based and markerless AR to understand its potential for the target sectors. Figure 2 illustrates the experiments with glass products.

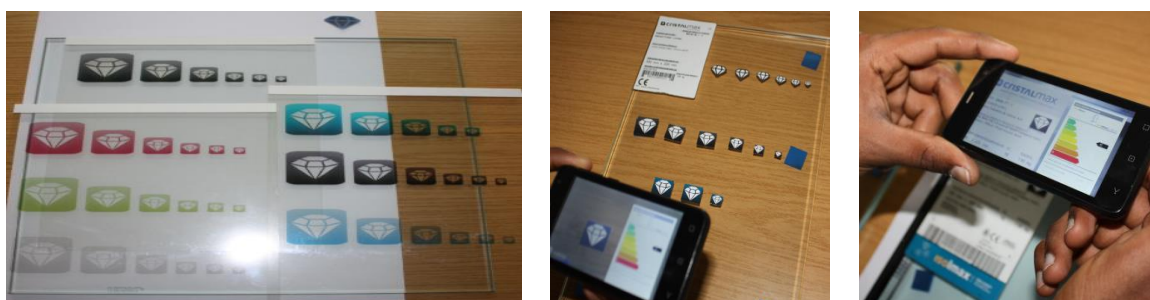


Figure 2. AR experiments with glass products: marks with different shapes, sizes, and colours.

The examples presented in Figure 2 used Unity 3D and Vuforia SDK (Vuforia, 2018) to recognize markers of different complexity, size, and colours/transparency effects. We tested digital tags with information about the product properties (e.g. energy efficiency) and maintenance (e.g. cleaning procedures). We used different samples and conducted tests with image, text, and object recognition.

Figure 3 illustrates our experiments with ceramic objects and virtual showrooms.

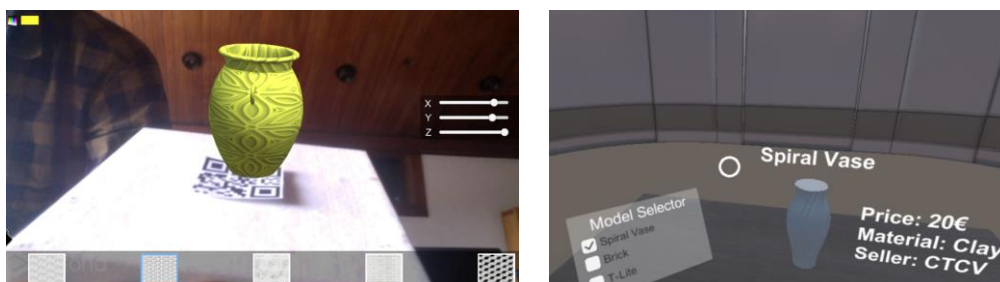


Figure 3. Opportunities for AR (left) and for VR (right) with ceramic products.

The distinctive shapes of ceramic pieces (in contrast to flat, transparent glass windows) enable object recognition, increasing the opportunities to use AR for traceability (e.g. lot characteristics) and for commercial/marketing purposes and model simulation by adding specific layers of information. In Figure 3, the leftmost image exemplifies changing colours, dimensions, and decoration patterns. However, accurate object recognition in curved forms and asymmetrical shapes requires a 3D model of the physical object, increasing the cost of the technology when compared to a simple use of QR codes or image recognition. Nevertheless, this problem may be temporary, as 3D printing is being increasingly adopted for ceramic prototype development, making 3D models available at early stages of the product lifecycle. Our contacts with experts in ceramic marketing allowed us to identify the context of ceramic fairs as a strong possibility for the use of AR. VAM-R can be used for simulation with physical products (e.g. different colours and surface patterns) and to show digital representations in a digital catalogue (e.g. display 3D models using QR markers in the catalogue). While the option for 100% virtual (rightmost image of Figure 3) is interesting for online showrooms, the AR option (on the left of Figure 3) is even more interesting for interacting with the customers. Tuning to the best spot in the reality-virtuality continuum requires the analysis of social processes involved.

5.2 CAR#2: implementing a VAM-R strategy for a glass company

In this CAR cycle we identified the potential physical objects to transform and to what purpose. Since it was important to understand the different phases of product development, we gathered inspiration in the environmental lifecycle assessment approach (Heijungs, Huppel, Zamagni and Masoni, 2011). The artefact presented in Figure 4 was created to represent the VAM-R strategy.

	Manufacture	Distribution	Application	Use	Disposal
Strategic imperative Regulations and Brand Innovation	Productivity Safety	Compliance to standards	Safety information	Increase brand value Minimize visual impact in the glass	Sustainability Environment protection
Context of use Product	Product identification Process instructions	Product identification and simulation	Product Process (BIM)	Product authenticity Energy inspections	Product replacement/removal
Object to augment Product	Product Production equipment	Product Site	Product BIM model	Product	Product
Scope of use Product Information and Traceability	Product quality inspection Lot identification Assembly procedures On-the-job training - New employees / sector changes	Technical files supplied to distributors Simulation of glass colours (serigraphy line)	Product inspection Assembly procedures	Confirm the product origin certificate Product quality certificate	Glass replacements
Information Characteristics	Product characteristics Machine performance (DT-digital twins) Machine instructions (DT)	Price Characteristic 3D model (BIM)	How to implement the glass windows Glass used in the site (BIM)	Glass characteristics	Deconstruction procedures Supplier contacts

Figure 4. Assessing and transforming VAM-R in the glass company (CAR#2 version).

The columns in Figure 4 map the selected lifecycle stages of construction glass (manufacture, distribution, application, use, disposal). The first line includes the identification of the company strategy for differentiation, cost, or innovation (Wiseman and Macmillan, 1984). The description of the objects to augment and the context of use are represented in the next two lines (López et al., 2014), followed by the more specific use cases and information to include. The team considered important to identify the stage of VAM-R adoption (e.g. planned, under development, already implemented), therefore, we have decided to use the well-known Plan-Do-Check-Act (PDCA) (ISO, 2005) to represent the implementation stage, ranging from P (planned) to A (act) to improve a particular VAM-R implementation. The PDCA classification of each lifecycle stage in Figure 4 (in the topmost line) was defined according to the average PDCA classification in the cells of that column (e.g. P–Planned, yellow in the case of ‘Manufacturing’). Nevertheless, planned stages such as manufacturing also include green elements (D–Do) because they are needed for the AR implementation in other product lifecycle moments (e.g. the lot identification during manufacturing is also necessary for inspection during distribution and use). According to the defined strategy, the company should direct their most immediate efforts to the final product augmentation, supporting traceability with AR (scope) and access to product characteristics (information). The more fine-grained analysis and the identification of applicable regulations (e.g. standards, procedures) was performed in meetings with experts of each product lifecycle stage. This case revealed that the interaction with product end-users was critical, but it could be different in other sectors, for example, in automotive – requiring complex assembly procedures – the manufacture lifecycle phase could be a priority for VAM-R developments.

Figure 5 presents a pilot implementation where the brand logo and the energy efficiency rating are read from a tag inside the glass window. Due to architectural requirements, glass producers are under pressure to minimize the visual impact of any markers on the product (e.g. physical tags). This is an innovative solution that differentiates the company while maintaining compliance with energy management standards.



Figure 5. VAM-R strategy implementation (deploy the blue elements “A-Act” in Figure 4).

According to the glass experts that participated in this cycle, the solution displayed in Figure 5 is one of the most promising for the sector of construction glass, because it (1) identifies the product characteristics, (2) has zero impact on glass transparency, and (3) is tamper-proof, since it is located inside the product (while traditional stickers can be removed at the construction site). QR codes are viable options in stickers and can be embedded in some window models but require a minimum size to be readable. Glass reflection poses challenges to marker recognition (especially with transparent backgrounds) and it is necessary to test the optimum solutions for each model. Nevertheless, the implementation of augmented information in glass requires changes in organizational practices, namely, the integration of product lots with the online system and investments in new software for production.

5.3 CAR#3 preliminary results: designing a VAM-R strategy for healthcare

The final cycle of our research started while CAR#2 was still evolving, allowing for some interaction. CAR#3 aimed at the adoption and refinement of the VAM-R approach for a service context. The main purpose of the hospital participants was to identify opportunities for VAM-R developments and pro-

pose an investment plan to the hospital administration. They were aware of pilot experiments, for example, in neurosurgery (Khor et al., 2016), but their strategy could not be based on anecdotal evidence nor left to the agendas of healthcare consultants. The hospital is not the most advanced in the region (a larger one employing thousands of staff exists within a 50km range), so they focused on being the best in the type of healthcare provided to their local population (more complex cases were transferred to the larger hospital). Therefore, a VAM-R opportunity for them was not the same as for other hospitals. The first and most obvious misfit between the artefact introduced in Figure 4 and this case is the lifecycle definition. Services have different elements to consider, for example, in this case, patient admission and “patient life” inside the hospital. The second shortcoming that we addressed in this cycle was the ineffective use of the PDCA to represent simultaneous changes in the social and the material. PDCA does not identify if the element subject to intervention has changed practices, creating value in the organization. Figure 6 presents the VAM-R transformation framework for the hospital setting, replacing PDCA with the sociomaterial transformation lifecycle (Barata and Cunha, 2018).


















































	Admission 	Referral 	Treatment 	Hospital life 	Discharge 
Strategic imperative Regulations and Brand Innovation	Quality  Safety 	Patient/Staff Safety 	Quality of intervention  Patient Safety 	Patient life quality  Staff safety 	Patient safety 
Context of use Product	Process instructions 	Identify spaces 	Intervention process  Pain and dis- tress reduction 	Patient assistant app  Equipment procedures (quality proce- dures) 	Intervention process (self) 
Object to aug- ment Product	Product  Production equipment 	Signals (locations)  Treatment explanation (paediatric care) 	Medical device  Virtual assis- tants 	Signals (loca- tions)  Procedure instructions  Distraction (paediatric unit) 	Medical device 
Scope of use Product Information and Traceability	Relax while waiting  On-the-job training - Interns 	Internment spare time  VR Simulation (cafeteria and bathroom location) 	Intern training  Medical and nursery inter- ventions 	Child infor- mation and distraction  Staff assistant 	E-labels in phar- maceuti- cal com- pounds  Medical device assis- tant (supplier partnership) 
Information Characteristics	Hospital policy 	Safety proce- dures in specific locations  Characteristic 3D model (BIM) 	Procedure instructions  Device simula- tion 	Procedure instructions  Equipment use simulation for training and staff guidance 	Medicine composition and guidance (sound incorpo- rated in medicine label to assist elderly)  Device use / self- application 

Figure 6. Assessing and transforming VAM-R in healthcare (CAR#3 version).

Several improvements were made to the artefact. First, we included illustrations near the most relevant elements of VAM-R strategy to exemplify the technology adoption (not shown here due to space constraints). Secondly, we gathered inspiration in the customer journey and most relevant service touch-points (Zomerdijk and Voss, 2010) to identify the service lifecycle (topmost cells). The service touch-points are comparable to the lifecycle stages of product transformation in manufacturing. Thirdly, we

changed the PDCA notation to the sociomaterial transformation lifecycle phase (Barata and Cunha, 2018): In stage **1 (R-Resources)**, it is necessary to identify the synergies of all the organizational resources for the transformation process. It involves understanding the staff skills and motivations, preparing company layouts, and the acquisition of raw materials and IT infrastructure. Second, the design phase **2 (D-Design)** considers all the planned and unplanned actions that create a new sociomaterial configuration with the VAM-R tool (as-is, should-be, to-be). The next stage **3 (T-Transformation)** corresponds to the enactment of the physical and digital materialities in the organizational practices. Finally, the interactions that emerge from practice (implementation of the new reality-virtuality continuum) stage **4 (I-Interaction)** will allow sociomaterial elements to co-evolve **5 (C-Coevolution)** and produce new generations of routines (Barata and Cunha, 2018). According to the study participants, this notation is more informative about the organizational impact of VAM-R transformation and offers greater potential to assess if the investments had a real effect in practice or if they failed to produce social and material changes that contribute to the hospital strategy. The new version of the artefact was used by the safety and quality department in their meetings with other hospital departments to guide the discussion and share identified VAM-R opportunities, concluding the problem-solving cycle (McKay and Marshall, 2001) of our canonical action research.

6 Research Interest: Proposing a Lifecycle Strategy for the Reality-Virtuality Continuum

Having tested the feasibility of application of VAM-R techniques to glass and ceramics (CAR #1), in our effort to create guidelines to help managers in their VAM-R strategies (CAR#2 and CAR#3) we sought inspiration in the concept of life cycle assessment (LCA). The definition presented by Finnveden et al. (2009) states that LCA “*is a tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management*”. However, lifecycles of products and services have differences. We tested the concept of customer journey and service touchpoints in CAR#3 with positive results (Zomerdijk and Voss, 2010). Although the results presented in Figure 4 and Figure 6 may provide sector-specific suggestions, each organization must design their own VAM-R transformation path.

Managers must be aware that companies with clear IS strategies can have benefits in organizational performance (Leidner, Lo and Preston, 2011). So, it is important to decide the context of using the augmented information/object. In some cases, it is advisable to augment the product, for example, using QR codes or object recognition. In other cases, the focus should be in the process (e.g. manufacturing procedures, machine indicators), and other cases still may focus on improving the customer experience. Our experiments highlighted multiple scopes of using VAM-R, for example, to identify product characteristics (e.g. electronic labels, price), provide information to external stakeholders (e.g. confirm product authenticity, energy performance information), explain guidelines/procedures for product application/use/disposal, simulation in trade fairs (e.g. colour and decoration options), and increase product value with VAM-R layers of information for technical purposes or user entertainment.

The joint evaluation by practitioners and researchers concluded that VAM-R effectively assists managers in the identification of opportunities, inside and outside the organization. This is particularly important when considering the cost of introducing VAM-R and the need to select priorities. Focusing exclusively on the internal information may not be attractive to managers at this stage of VAM-R development, because the cost (e.g. time to develop the app, cost of technology and training) may not justify the replacement of other identification tools such as 2D linear barcodes and QR codes. For construction sectors, our framework can assist in the identification of opportunities to use BIM in VAM-R solutions, extending its use for interaction with physical objects (e.g. onsite simulation).

According to the safety manager in CAR#3, the framework offers “*a clearer roadmap to adopt VAM-R in different phases of the lifecycle to serve our mission: definitive cure or life quality improvement of our patients*”. Moreover, it is comprehensible by all staff members and promotes consensus in the team for the need to adopt VAM-R. The final version of VAM-R transformation framework to guide the identification of opportunities to across product and service lifecycles is presented in Figure 7.


	Lifecycle stage 1	Lifecycle stage 2	Lifecycle stage N
					
Strategic imperative	Regulations, Quality improvement, Cost, Differentiation, ...				
Physical materiality	Product, Plant, Resources (equipment), Site				
Reality-virtuality assessment	For each physical element described in the previous line of the lifecycle, identify the actual and the desired level of digitalization and the potential benefits to the system users (a graphical representation can be used for a position between 0% - purely physical and 100% - purely virtual)				
Digital materiality	For each physical element described in the previous line of the lifecycle, identify the synergies that both physical and digital materialities can provide. Examples: Traceability, Training, Simulation, Product information, Product quality inspection, Assembly and deconstruction procedures, Product authenticity, Complaints (interaction), Entertainment (increase product value), Safety, Sustainability				
Information value	Identify the added-value information that should be provided in physical or virtual mediums to each lifecycle phase of the product/service. Examples: Characteristics, Design, Price, 3D model, How to implement, New layers (entertainment), Deconstruction procedures, Recycling information				
Project portfolio	Define information system development projects to implement the desired state of the reality-virtuality continuum				

Figure 7. VAM-R transformation framework.

The VAM-R framework reflects the different phases of the product lifecycle along the top (Finnveden et al., 2009; Zomerdijk and Voss, 2010) and six aspects of analysis for each: strategic imperative, physical materiality, reality-virtuality assessment, digital materiality, information value, and project portfolio (López et al., 2014; Porter and Heppelmann, 2017).

7 Discussion

Our CAR was assessed for rigor and validity according to the five principles of Davison et al. (2004): *Principle of the Researcher–Client Agreement*; *Principle of the Cyclical Process Model*; *Principle of Theory*; *Principle of Change through Action*; and *Principle of Learning through Reflection*. First, the organizations and the researchers agreed that CAR was a suitable research approach to contribute to science and improve the organizational practices. We have conducted the three CAR cycles (two concluded and one with preliminary findings) according to the dual interest of problem solving and research (McKay and Marshall, 2001). The findings were constantly compared with the guiding theory, aiming to extend the body of knowledge in VAM-R transformations. Finally, there was a joint intervention to (1) change the development of the VAM-R strategies of the organizations, (2) develop concrete VAM-R solutions in the two initial cases, and (3) summarize lessons learned for the development of VAM-R strategies.

There were two main sources to evaluate possible VAM-R solutions to adopt in each case. First, the literature review identified VR/AR candidate applications in the target sectors. Second, the insights collected during our field interventions, namely, interviews with experts and meetings with the project participants. Yet, the examples presented in our paper – physical or digital – are indicative. The main purpose of our research is to assist each company to build their VAM-R strategy.

The results for our first CAR cycle address the initial questions that companies must answer to formulate their VAM-R strategy. We explored VAM-R opportunities in our action taking phase, for exam-

ple, product traceability, ceramic products simulation, and marketing strategies using VAM-R. Communication with external stakeholders is a priority for this industry.

The practical outcome of our second CAR cycle is a leading example of VAM-R in the glass industry. We found three main benefits with the experiments made in CAR#1 and CAR#2: first, facilitate the acceptance of VAM-R technologies by managers, proofing the concept in the context of use; second, study the cost-benefit of the AR development process with marker-based and markerless identification; and third, improve communication with the industry experts. It was during a discussion about AR in museums that we have identified the opportunities for global fairs, the importance of reducing the number of physical products in the showroom, combining the physical and the digital as it happens with multiple colour/decoration simulation or even with 100% digital product exhibitions.

Finally, we have created a guiding framework to assist VAM-R strategies for the provision of products and services. Our framework can be used in the early stages of identifying VAM-R opportunities involving different domain experts, complementing the López et al. (2014)'s proposal for the design of augmented objects and including support to strategy monitoring. We have demonstrated the use of the VAM-R transformation framework in two real situations. The main benefit found is to evaluate VAM-R in the entire lifecycle of the product/service, identifying priorities that are consistent with strategic imperatives of the organization.

8 Conclusions

Using three CAR cycles, we meant to devise ways to support the development of comprehensive VAM-R strategies that intertwine digital and physical forms of materiality, along the reality-virtuality continuum and across lifecycles of products and services. Based on the lessons learned, we (1) showed the potential of VAM-R for the lifecycle of traditional materials (ceramics and glass); (2) tested the benefits of VAM-R for glass products, innovating with e-labelling AR solutions that are aligned with the construction sector priorities, and (3) proposed guidance to the VAM-R transformation processes, with two distinct approaches to lifecycle analysis, namely, LCA (Finnveden et al., 2009) and customer journey mapping (Zomerdijk and Voss, 2010). A comprehensive VAM-R strategy should not be a result of unrelated efforts with objects and their digital instantiations. It should be an opportunity to assess and transform the reality-virtuality continuum across the entire lifecycle of each product or service that intertwines the social and material realms (Orlikowski, 1992; Barad, 2007; Orlikowski and Scott, 2008). A participative approach to VAM-R strategy is suggested.

There are limitations and opportunities for future research. First, the technologies and application cases identified are restricted to the selected sectors. Other examples to use VAM-R could potentially be applicable for materials manufacturing and healthcare, offering the possibility to create a VAM-R canvas for each sector of the economy. Second, the VAM-R artefact quality and efficacy can be improved, particularly, in the identification of priorities for IS developments. One possibility is to include a voting system to improve the feedback about the intended strategy (planned) and realized strategy (evaluated results). Third, we used basic tables to support the adoption of the framework, which is an advantage in making VAM-R accessible to SMEs, but future work should include the creation of a tool to support the approach. For example, the preliminary results of the third cycle suggested the need to identify projects associated to each VAM-R transformation – each one addressing a specific set of elements in VAM-R strategy, a specific project team, and management requirements. We have considered that aspect in the final version of VAM-R, but we did not yet apply it in the hospital case, since their purpose at this stage was just to outline the intended strategy and investments plan. Therefore, future research is necessary to deeply evaluate the performance of the proposed framework for the deployment of VAM-R projects in the healthcare case and obtain additional details about the physical and digital transformations that emerge in the practice of innovative IS strategies. We hope that our work may inspire new IS studies that address lifecycle opportunities in organizations, exploring the sociomaterial nature of VAM-R transformation that is so crucial to the success of digitalization.

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