Seeing is Believing: 3D-Printed Boundary Objects for the Additive Manufacturing Twin Transition

Trond Halvorsen, Raymond Andreas Stokke and Gunnar M. Lamvik
SINTEF Digital, Trondheim, Norway

trond.halvorsen@sintef.no
raymond.stokke@sintef.no
gunnar.lamvik@sintef.no

Abstract: This article describes the use of 3D-printed demonstrators as boundary objects in intra-firm collaboration processes aimed at implementing additive manufacturing (AM). AM is a disruptive digital technology with large potential environmental benefits. Demonstrators are common early in the learning process to familiarize organisations with AM, and it's important to understand both their benefits and the limitations and risks involved. The results suggest that 3D-printed demonstrators can be effective in establishing a common minimum level of knowledge across diverse professions within the same organisation. Having physical objects available makes conversations about AM more engaging and legitimizes the idea of utilising AM as realistic. However, the fabrication of demonstrators can be a lengthy and costly process, and the result may not be a good representation of the final design. Negative experiences in such initial trials may turn managers away from AM prematurely. Many of the benefits of demonstrators can be obtained by producing low-cost miniatures and/or polymer parts that will mitigate the risks.

Keywords: 3D-printing, additive manufacturing, boundary object, twin transition.

1. Introduction

Additive Manufacturing (AM) has been proclaimed as a paradigm shift in the production landscape, offering a range of benefits that promise to redefine manufacturing processes (Mehrpouya et al, 2019). AM's ability to produce customized, complex components swiftly and with reduced material waste positions it as a pivotal technology in the ongoing industrial modernisation (Gibson, Rosen, and Stucker, 2014). Despite its potential, the assimilation of AM into the intricate structures of large organisations is fraught with challenges. For example, a lack of collective understanding and acceptance of AM's capabilities and benefits across diverse business units, often hinder its widespread adoption (Ford and Despeisse, 2016).

In addressing these challenges, the concept of boundary objects, particularly in the form of 3D-printed demonstrators, emerges as a useful tool for fostering cross-disciplinary collaboration and knowledge sharing (Swann et al, 2023). Boundary objects serve as physical interfaces that facilitate communication and understanding among different social worlds within an organisation, thereby aiding in the alignment of objectives and the harmonisation of efforts towards a common goal (Star and Griesemer, 1989). In the context of AM, 3D-printed demonstrators not only provide tangible examples of AM's potential, but may also act as catalysts for discussion, exploration, and learning across various departments (Bosch-Sijtsema and Postma, 2010).

This paper delves into the utilisation of 3D-printed demonstrators as boundary objects within large organisations to promote a twin transition, i.e. green and digital (Rehman et al, 2023), towards the acceptance and integration of AM. Drawing on a qualitative research design that incorporates action research and semi-structured interviews across multiple industries, this study aims to shed light on how 3D-printed demonstrators can bridge knowledge gaps and facilitate collaborative exploration and adoption of AM technologies. The empirical evidence gathered from managers, engineers, and operational staff across sectors such as shipping, oil and gas, and research offers a multifaceted perspective on the role of demonstrators in advancing organisational understanding of AM.

This paper contributes to the existing body of literature on cross-disciplinary learning in large organisations by showcasing multiple examples of designs and discussing the benefits and limitations of using 3D-printed demonstrators as boundary objects. By building on use cases and developing a strategic roadmap for exploring business opportunities with AM, organisations can navigate the complexities of integrating this disruptive technology into their operations.

2. The use of Demonstrators When Integrating AM in Manufacturing Processes

The integration of AM into established value chains represents potential for a significant shift towards more agile, and customized production methodologies. AM production processes, characterized by their ability to add material layer by layer to create objects, offers unprecedented flexibility in design and manufacturing, challenging traditional manufacturing paradigms (Gibson, Rosen, and Stucker, 2014). This technology holds the potential to revolutionize industries by reducing lead times, minimizing material waste, and enabling the production of complex geometries that are otherwise impossible to achieve through conventional methods (Ford and Despeisse, 2016).

Despite these advantages, the adoption of AM technologies within large organisations is fraught with challenges. One of the primary obstacles is the disparate understanding and acceptance of AM across various departments and business functions. The novelty of the technology, combined with its perceived complexity, often leads to resistance or scepticism among stakeholders (Rogers, 2003). This challenge underscores the importance of effective intra-firm collaboration and knowledge sharing to foster a conducive environment for AM integration.

The concept of boundary objects, introduced by Star and Griesemer (1989), offers a valuable framework for facilitating such collaboration. Boundary objects are artifacts that serve as points of reference that different social worlds within an organisation can understand and use, despite holding divergent viewpoints or expertise. In the context of AM, 3D-printed demonstrators have emerged as potent boundary objects, enabling diverse stakeholders to visualize, discuss, and explore the potential applications of AM technologies (Carlile, 2002; Swann et al, 2023). In our study we posit demonstrators as a form of prototype or final product which offer a tangible solution to showcasing the potential of 3D-printed parts in large organisations.

Research on the use of prototypes and demonstrators in industrial design and innovation highlights their role in enhancing communication and collaboration among interdisciplinary teams. Prototypes enable stakeholders to tangibly interact with a concept, fostering a shared understanding and facilitating consensus-building (Thomke and Fujimoto, 2000). This interaction is particularly critical in the early stages of technology adoption, where abstract concepts need to be translated into concrete examples to gain organisational support (Bosch-Sijtsema and Postma, 2010).

3D-printed demonstrators have emerged as essential tools across various organisational functions, notably for sales and design purposes (Gao et al, 2015; Robinson, Lagnau and Boon, 2019; Schniederjans, 2017). In sales, these demonstrators serve as tangible representations of AM's capabilities, allowing sales personnel to distinctly showcase the potential of AM to clients and stakeholders. The physical presence of 3D-printed parts can significantly enhance customer engagement and comprehension, providing a concrete example of abstract AM benefits, thereby facilitating a more effective sales process.

Within the design phase, 3D-printed protypes enable a hands-on approach to product development, fostering a collaborative environment among designers, engineers, and other stakeholders (Swann et al, 2023). These items act as boundary objects that facilitate communication and understanding across disciplinary divides, allowing for rapid prototyping and iterative design processes. This not only accelerates the design phase but also ensures that the final product is more attuned to the practical requirements and constraints, embodying a collective vision shaped by diverse inputs.

However, the production of 3D-printed demonstrators is not without its challenges. The process can be time-consuming and costly, and the resulting artifacts may not always accurately represent the final product. This discrepancy can lead to misunderstandings or misplaced expectations regarding the capabilities and limitations of AM technologies (Thompson, 2012). Despite these challenges, the benefits of using 3D-printed demonstrators extend beyond mere knowledge dissemination. By providing a tangible representation of AM's capabilities, demonstrators can stimulate interest, inspire innovation, and legitimize the exploration of AM technologies within an organisation (Berman, 2012). They serve as a catalyst for engaging discussions, enabling stakeholders to envision the practical applications of AM in their respective domains (Horne and Nissen, 2006).

Organisations can build on the use of demonstrators to develop a strategic roadmap for exploring business opportunities with AM. This roadmap should encompass a thorough evaluation of potential applications, considering both the technical feasibility and the economic viability of AM. By systematically leveraging demonstrators to showcase AM's capabilities, organisations will be more likely to identify and prioritize high-value applications, aligning their AM initiatives with broader business objectives.

This underscores the important role that 3D-printed demonstrators have as boundary objects in facilitating the twin transition towards AM adoption in large organisations. By serving as tangible points of reference, demonstrators enable diverse stakeholders to collectively explore, understand, and embrace the potential of AM technologies. Despite the challenges associated with their production, the strategic use of demonstrators can significantly enhance intra-firm cross-disciplinary collaboration, knowledge sharing, and innovation, paving the way for the successful integration of AM into organisational processes (Star and Griesemer, 1989; Carlile, 2002; Gibson, Rosen, and Stucker 2014; Robinson, Lagnau, and Boon 2019).

3. Methodology

This study adopts an explorative qualitative research design to document the utilization of 3D-printed demonstrators as boundary objects in intra-firm collaboration towards the industrialization of AM within large organisations. A case-based approach (Yin, 2014) was deemed most suitable for obtaining in-depth insights into the complex processes and interactions associated with the adoption of AM technologies.

The primary data collection methods employed in this study were action research (Greenwood & Levin, 2006) and semi-structured interviews, which enabled the gathering of empirical evidence from the field. Action research was chosen for its participatory and iterative nature (Kindon, Pain, and Kesby 2007), allowing researchers to engage directly with the phenomena under study and to implement and observe the impact of 3D-printed demonstrators in a real-time organisational setting. This was carried out by providing coworkers and research managers access to various demonstrators. Semi-structured interviews provide a flexible yet structured means of capturing the diverse perspectives of individuals involved in the AM integration process. These interviews were conducted with managers, engineers, and operational staff of large organisations, ensuring a comprehensive understanding of the experiences and perceptions surrounding the use of 3D-printed demonstrators in AM adoption. The demonstrators were photographed by the authors or interview subjects.

The selection of cases for this study was guided by the objective of covering industries where AM has the potential to significantly impact large-scale manufacturing processes, and where we see that organisations are working actively to foster intra-organisational learning. As such, large Norwegian firms from the oil and gas industry, the maritime industry, and our own research organisation were included in our study. This diverse selection of cases allowed for incorporating a wider range of industry-specific challenges, opportunities, and strategies related to the adoption of AM technologies. The collected data were subjected to narrative analysis, with the aim of identifying recurring patterns, themes, and insights related to the use of 3D-printed demonstrators as boundary objects in AM adoption. This analytical approach facilitated the extraction of meaningful information from the qualitative data, enabling the formulation of conclusions and recommendations grounded in empirical evidence.

The study was carried out between October 2023 and March 2024, in the context of a three-year innovation project aiming to promote the use of AM in the maritime industry. Table 1 describes the interview subjects.

Table 1: List of interview subjects

Organisation	Role of interview subject
AM service provider 1	AM engineer
AM service provider 2	Chief Commercial Officer
Ship management	Fleet manager
Oil and gas operator	Head of AM team
Maritime OEM	AM ambassador
Research organisation	Research manager and research director

4. Examples of 3D-Prints Used as Boundary Objects

The photos below illustrate a variety of items that are 3D-printed and obtained with the purpose of illustrating unique aspects of AM production processes. Figure 1 shows metal items suitable for daily use in an office setting. Example 1a is a titanium coffee mug designed, printed and used by an engineer on from a Norwegian AM service bureau, currently working for a large oil and gas operator. In addition to the intricate pattern, the cup conveys the light weight and heat conductivity of the material. Example 1b shows two bottle openers. The one on the left is an unpolished titanium piece that illustrate the surface finish of parts as they come from the printer. At the back end is a small remnant of the support structure that fixed the item to the build plate during the printing process. The one on the right is a multi-functional stainless-steel item that combines a bottle opener with a flute and a loop for a key ring (not printed). The flute is attached to the logo and rotates freely within the cylinder. Example 1c are two pens with 3D-printed bodies made in titanium. Both display a lattice structure on large areas of the surface, and an integrated logo. The pen on the left has a two-piece body that screws together with 3D-printed threads, while the pen on the right has a solid body with an ink cartridge inserted from the bottom.

Figure 1: Metal prints for daily use

Figure 2 shows three examples of polymer card holders. The Figure 2 shows three examples of polymer card holders. These are used to hold identification cards that are common at many workplaces, exhibitions and conferences. Example 2a is made by sintering nylon powder with a laser. It has a slot on top to insert a business card, which is held in place by a clip on a lanyard. Example 2b is made with polylactic acid (PLA) filament in a fused filament fabrication (FFF) process. It displays a small boat, known as the 3D benchy, at the top to showcase the level of detail that the process can achieve. It also has varying surface textures and overhangs that can hold a paper conference badge. Lastly, example 2c is an access card holder with movable gears. The model does not require any manual assembly as it's a build-in-place design. The front is customized with text displaying four company core values.

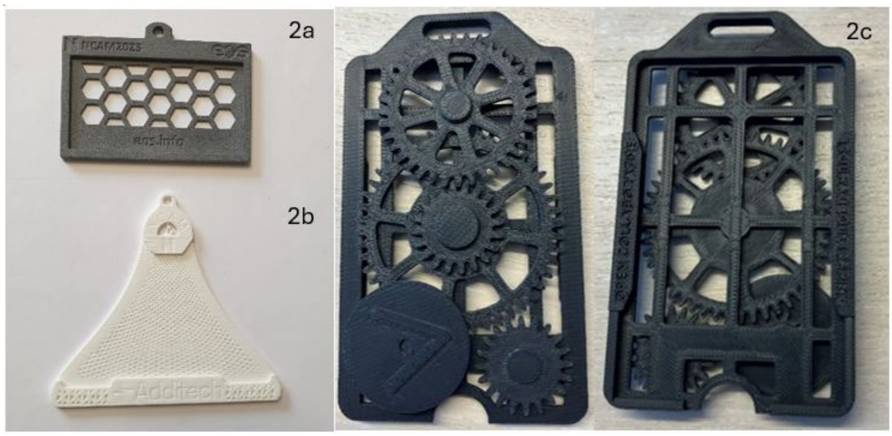

Figure 2: Polymer card holders

Figure 3 presents a few examples of items that are made for display and education, i.e. not actual use. Example 3a is a working Rubic's cube, with each small cube showing different patterns and textures. Some of them also include moving pieces, such as springs. The piece illustrates the design freedom of 3D-printing, but the polymer material is relatively fragile. Example 3b is a replacement for a PC keyboard support. It was made to illustrate the importance of part orientation during FFF-printing. The visible layer lines that are orthogonal to the length of the clips make them prone to breaking. Example 3c is a holder for tips of silicone tubes sold in hardware stores. It represents a product for which resin printing can compete economically with injection moulding for mass manufacturing. Examples 3d and 3e are made from the same digital design file. The difference is that the build process was stopped prematurely for example 3e to display the internal structures. These items are used together to illustrate the material savings that can be achieved with AM relative to subtractive manufacturing processes.

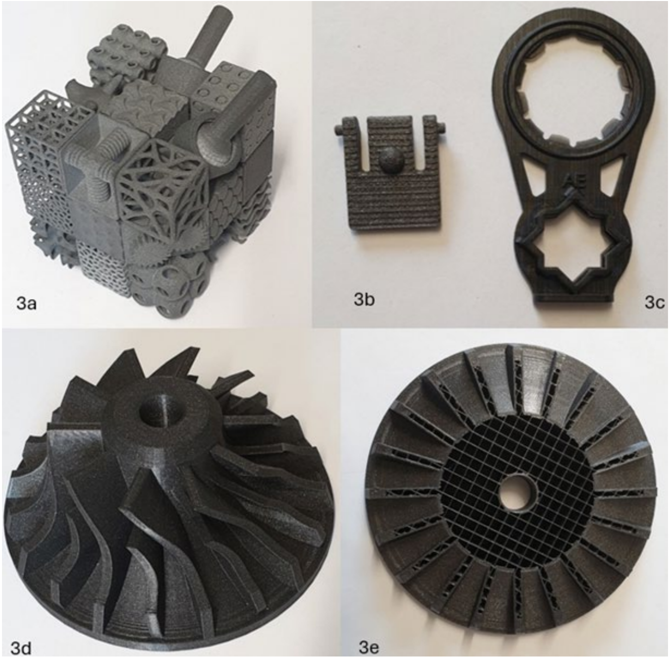

Figure 3: Illustrative polymer prints

Figure 4 shows two examples of 3D-printed products that have full production quality but are used by large organisations to create awareness about the capabilities of metal 3D-printing. Example 4a is a bike with a 3D-printed titanium frame, and an accompanying rollup with basic information about the item. The bike is painted with a company logo, and the rollup highlights some benefits. Example 4b is a pipe connector made with binder jet technology using 316L stainless steel. This item is part of a collection of 3D-printed spare parts for the maritime sector. A ball pen is included in the picture for size reference.

Figure 3: Display pieces of metal prints

5. Findings From Interviews

The interviews reflect the wide variety of settings in which the demonstrators are used, and his section summarises key findings across the subjects. Firstly, the need for and challenges of creating awareness about the value proposition of AM within large organisations was confirmed. Even though the technology is being described as sufficiently mature to produce both critical and non-critical components, the standards needed to certify the parts were not available until a few years ago. Therefore, the use of AM is not reflected in many policy documents such as maintenance plans, approved vendor lists, and project descriptions. Now there's a particular need to educate the teams responsible for renewing such documents, and those people are distributed across different departments and geographical locations.

Secondly, the organisations included in this study typically utilize more than one kind of demonstrators. Each individual item may highlight a few aspects of AM, but providing more examples is necessary to generate a better understanding of both the potential and limitations of AM production methods. Demonstrating a variety of materials and production processes is one goal. Another goal is to inspire enthusiasm and the attitude that the potential of AM is broader than one first realized. The oil and gas operator has identified “AM mindset” as a strategic concept that they refer to on this topic. “AM awareness” is another term that is used with similar connotations.

Thirdly, the knowledge level that is generated with these demonstrators is not deep, and it doesn’t have to be. Each organisation has some experts on AM, and the job of designing and producing the demonstrators, such as examples 1a and 4b, provided them with additional in-dept knowledge. But as a boundary object, the function of the demonstrator is to provide opportunities for discussing 3D-printng with non-experts and inspire questions.

Fourthly, the impact of the demonstrators can be enhanced if it’s tailored to a specific context. The bike in example 4a was acquired in relation to a bike race that the company sponsored and was used in promotional posts on social media. The card holders of examples 2a and 2b were made for AM conferences. If they were to be used in other settings, people seeing them may not realize that they are 3D-printed. The organisation that provided example 2c also make this access card holder in a separate colour for their AM experts team. This helps to build a sense of shared identity across geographical and organisational locations.

Fifthly, the tangible aspect of demonstrators is seen as important. In the interview with a ship services employee and a fleet manager, the fleet manager asked specifically for AM parts that could be shown to other officers within his company. Seeing and touching actual parts is thought to provide additional realism compared to seeing a picture of the item on a presentation slide, or just hearing about it. The research director noted that particularly holding the pens in example 1c was inspiring to him. This changed his perception of AM from being useful for making cheap plastic copies (e.g. prototypes) to seeing it as a viable alternative for making actual functional items of good quality.

The interviews also uncovered some important challenges of inter-organisational learning from demonstrators. The AM expert at the maritime equipment OEM explained that a different department than hers had experimented with making a part with a metal powder bed fusion (PBF) process and comparing it with conventional manufacturing in a low-cost country. Since PBF is a relatively expensive process and there was no redesign of the part to optimize it for AM, the head of department had concluded that AM was not a viable alternative for them. This sentiment then influenced other heads of department within the company, despite the AM expert’s opinion that another AM process would have been more cost efficient for that specific part. This story illustrates that demonstrators can also facilitate the spread of misperceptions and misunderstandings across inter-organisational boundaries.

The second challenge is that the information that is meant to be transferred between individuals is not contained, or not readily apparent, in the object itself. For example, some people may see the demonstrator without realizing that it is 3D-printed. A way to overcome this is by displaying it with signs with a short description of the item and production process. The demonstrators are also used in combination with digital presentations, such as power point slides and social media posts, that provide additional information. Thirdly, the most convincing demonstrators are typically the most expensive to produce. It makes little sense to make several identical copies of large metal parts for educational purposes. In contrast, the access card holder (example 2c) has the benefit of being very portable and visible. It is also relatively cheap and can be distributed to many employees within an organisation.

6. Discussion

The findings suggest that the use of 3D-printed demonstrators contributes significantly to the advancement of AM. By facilitating knowledge sharing, enhancing interdisciplinary collaboration, and providing tangible proof of AM's potential, these objects play a crucial role in convincing stakeholders of the value of AM, securing necessary resources, and fostering a culture of innovation. The interview subjects emphasize the role of these demonstrators in offering a hands-on learning experience, which is instrumental in building a foundational understanding of AM processes, materials, and capabilities across large organisations.

In the context of anchoring AM within organisational processes, 3D-printed demonstrators serve as concrete examples of the technology's potential impact on product development, supply chains and maintenance strategies. Physical models can significantly enhance the persuasive power of internal presentations, enabling innovators and advocates of AM to communicate the potential applications and benefits of the technology more effectively. This can lead to a stronger buy-in from senior management, crucial for securing the necessary resources and attention for AM initiatives. Moreover, demonstrators can play a pivotal role in the acquisition of resources for AM projects. By showcasing the functional and economic benefits that can be achieved with AM, these models can stimulate interest and curiosity among different departments.

The utilisation of demonstrators as boundary objects represents a collaborative approach to adopting AM technologies. These demonstrators appear as important in bridging the some of the knowledge gaps between various departments, facilitating a shared understanding of AM's capabilities and potential applications (Halvorsen and Lamvik, 2022). This study's findings resonate with the concept introduced by Star and Griesemer (1989), highlighting the importance of boundary objects in fostering interdisciplinary collaboration. The tangible nature of 3D-printed demonstrators catalyses discussions around AM, making the technology's abstract concepts more accessible and engaging to diverse professional groups within the organisation. This also aligns with the observations made by Bosch-Sijtsema and Postma (2010), who emphasized the role of tangible prototypes in enhancing intra-firm communication and collaboration.

The challenges associated with the production of 3D-printed demonstrators, such as the time, cost, and potential inaccuracies in representing the final product, necessitate a careful consideration of their design and development. These challenges, if not managed effectively, could deter interest in AM and impede its integration within organisational processes. This is in line with Thompson's (2012) findings, which pointed out the importance of physical prototypes in mitigating risks associated with new product development. It underscores the need for a strategic approach to the development of these demonstrators, as suggested by Berman (2012), to ensure that they accurately convey the capabilities and limitations of AM technologies, thus preventing misconceptions and misplaced expectations.

7. Recommendations

Considering the findings from this study on the use of 3D-printed demonstrators in facilitating the adoption of AM within large organisations, several recommendations can be posited to enhance the effectiveness of AM integration processes:

- Organisations should consider starting small with plastic prototypes. This approach allows for the exploration of AM's capabilities without incurring significant costs or committing extensive resources.
- Organisations are encouraged to actively explore redesign opportunities and demonstrate the unique opportunities that AM presents. Demonstrators don’t need to have the same size, shape or material as original models.
- Demonstrators should be presented in connection to an information source, explaining the process and benefits of AM for each item.
- Knowledge sharing sessions, workshops, and regular discussions centred around the learnings from initial demonstrator efforts can catalyse a collective understanding of AM's potential and limitations. The physical demonstrators should be brought to these arenas.
- The establishment of a structured roadmap for AM integration, informed by the insights gained from prototyping, testing, and verification efforts, is recommended. This roadmap should outline clear milestones, objectives, and strategies for scaling AM capabilities within the organisation. It should also lay out a strategy for using demonstrators for intra-organisational knowledge sharing.

The strategic use of 3D-printed demonstrators, coupled with a focused approach to knowledge building, redesign exploration, and rigorous testing, can significantly enhance the adoption and integration of AM within large organisations. These recommendations provide a pragmatic framework for organisations to leverage AM's transformative potential, driving innovation and efficiency across their operations.

8. Conclusions, Limitations, and Future Research

Our study show that 3D-printed demonstrators serve as tangible intermediaries that not only bridge the knowledge gap across diverse professional domains but also facilitate an environment conducive to collaborative innovation and exploration. Our study highlights that, by embodying the capabilities and potential of AM, demonstrators can effectively stimulate discussions, facilitate learning, and drive the twin transition towards more sustainable and digitalized manufacturing processes. Despite the challenges associated with their production, such as time and cost implications, the strategic deployment of these demonstrators has been shown to significantly enhance intra-firm communication, knowledge sharing, and ultimately, the integration of AM technologies into organisational processes.

This research is not without limitations. The case-based, qualitative nature of the study, focusing on selected industries within the Norwegian context, may restrict the generalisability of the findings to other sectors or geographical regions. Moreover, the production and utilisation of 3D-printed demonstrators are contingent upon the specific AM technologies, designs and materials employed, which may introduce variability in their effectiveness as boundary objects. For example, confidence in the use of AM processes for critical parts may be negatively influenced by only seeing AM used for demonstrations of non-critical parts (e.g. a pen). This makes the case for also making demonstrators of critical parts that are subjected to rigorous quality tests. Future research should aim to address these limitations by expanding the scope of investigation to include a broader array of industries and geographical contexts, thereby enhancing the generalisability of the findings. More research is also needed on optimizing the design and development process of these demonstrators to maximize their effectiveness while minimizing associated costs and challenges.

3D-printed demonstrators can also help in capturing the attention of key stakeholders outside the organisation. Bringing these tangible models to stakeholder meetings and industry conferences to demonstrate the organisation's commitment to innovation and technological advancement is a common practice that was outside the scope of this study. The benefits of this activity include positioning the organisation as a leader in AM adoption but also attracting customers, talent, partners, and investors who are interested in cutting-edge manufacturing technologies. Evaluating this behaviour in light of the literature on knowledge management would be valuable from both an industrial and academic standpoint.

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