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ORIGINAL RESEARCH

Assessing industry 4.0 readiness and maturity in the dairy sector: a case study in Sardinia

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Abstract
Small and medium-sized enterprises (SMEs) in the dairy sector are under increasing pressure to adopt Industry 4.0 technologies to enhance competitiveness, operational excellence, and sustainability. The research presents a digital maturity model tailored to the dairy supply chain, encompassing both structural and operational levels. The model was derived from the DREAMY framework and adapted for application to the dairy industry, demonstrating its feasibility. Through extensive literature review and qualitative interviews with industry specialists and academics, this study examines digital readiness across four principal dimensions: monitoring and control, process execution, organization, and technology infrastructure. It has functional sectors, including production, logistics, energy management, maintenance, warehousing, and sustainability. Validating the model through implementation in two Sardinian-based dairy companies substantiated its suitability, versatility, and efficacy in measuring digital maturity and highlighted actionable pathways for improvement. The outcomes reveal industry-specific actions to connect generic maturity models with the real-world practicalities of agrifood SMEs. The previously developed maturity models have remained generic, rather than being specific to dairy SMEs. The present study makes an original contribution by using the DREAMY framework specifically and implementing it with two case studies related to the dairy sector. The model provides managers with concrete guidelines for prioritizing digitalization activities, structuring investments, and synchronizing technology implementation with available resources. By targeting dairy SMEs, the research provides a systematic, adaptable framework that facilitates digital transformation in traditional agrifood sectors and contributes to expanding maturity model theory into underrepresented sectors.

Keywords Digital Maturity · Industry 4.0 · Sustainability · Digital transformation · Dairy industry

1 Introduction

1.1 Specific issues and opportunities of industry 4.0 in dairies

Industries are increasingly accepting the need to digitalize production processes to enhance competitiveness and sustainability. Industry 4.0 can be understood as the intersection of technologies that are digital, physical, and biological, so that this shift marks a new world of production and supply chain management, which assumes significance in the agrifood sector, as the efficiency of processes with traceability and resource conservation is of utmost importance.

Traditional manual and artisanal methods have forced the dairy industry to modernize. The integration of Industry 4.0 technologies such as IoT, automation, analytics, and digital platforms has become an increasingly inescapable requirement for organizations seeking to improve product quality,

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reduce costs, and meet increasingly stringent regulatory and market requirements. The problem appears even more serious for small and medium-sized enterprises (SMEs), which lack the economies of scale of larger organizations (Sonar et al. 2024; Oreshina et al. 2025).

Specific issues arise in the dairy transformation approach. The sector faces the problems of inefficient resource use, waste generation, and the need to meet the competitive environment of the global marketplace while strictly adhering to environmental regulations (Moazzam et al. 2019; Peterson and Mitloehner 2021; Hassoun et al. 2023a; Shamsuddoha et al. 2024). Additionally, there are structural barriers that impede organizations, including inadequate infrastructure, insufficient skill sets, and resistance to new technology. As a result, organizations will need to evaluate the state of the digital environment as the first step toward encouraging the adoption of Industry 4.0 technology in the dairy industry (Forsan 2025).

Digital maturity analysis offers a systematic method for examining an organization's state of affairs with respect to its capabilities, objectively defining its shortcomings, and prioritizing investments in digital technology (Senna et al. 2023). A maturity model (MM) serves as a benchmarking tool, enabling organizations to assess their readiness for digital transformation by evaluating critical business processes and technology capabilities (De Carolis et al. 2017; Senna et al. 2023); an industry-specific maturity model for the dairy industry, given its varied production and decentralization.

This study aims to satisfy this requirement by designing and evaluating a digital maturity model specific to the dairy sector in the region of Sardinia, with SMEs accounting for the vast majority of dairy producers. A particular model focusing on the dairy sector in the region of Sardinia was developed through an iterative process combining a literature review with field interviews and pilot testing. Some of the principal business areas that were considered of utmost significance are production, logistics, energy management, sustainability, maintenance, and warehousing.

This study offers a comprehensive, contextually applicable tool that could fill the gap between generic models of digital transformation and the specific operational issues faced by food systems operating in SME and artisanal business environments. This particular model offered in the study serves simultaneously as an instrument of measurement, a decision-making instrument, and a capacity-enhancement instrument within the context of the Digital Age. However, there are maturity models that might fit SMEs on a generic scale, like DREAMY (De Carolis et al. 2017) and RAMI 4.0 (Bastos et al. 2021). There appears to be general agreement that these models are too generic and do not suit the SME environment in the agricultural food sector. Structural issues, including a lack of appropriate digital infrastructure, financial constraints, and the prevalence of artisanal culture, characterize the dairy industry in Sardinia.

1.2 Industry 4.0 and the dairy sector

The application of Industry 4.0 technology in the dairy sector offers significant potential to improve the efficiency and sustainability of the production process. This technology can intelligently manage processes and data, facilitating decision-making and reducing waste while meeting the requirements for quality products (Moazzam et al. 2019).

Within the context of the increased application of technology driven by digitalization, the first issue that arises is measuring the organization's readiness to adopt it (Markov et al. 2022). Additionally, the extent of integration may differ based on the nature of the business, size, and organizational form, as well as the rigorous regulatory policies governing food production; therefore, it is necessary to monitor various factors to meet food safety requirements continuously (Malik et al. 2024).

Under this system architecture, the Internet of Things (IoT) and sensor technology play an integral role in continuously collecting process-related data. This technology enables compliance with regulatory requirements and allows optimizing the process. The fact that the product can be traced throughout the supply chain, from the point of natural milk reception to distribution, is critical for meeting market and regulatory requirements. Furthermore, in these circumstances, cloud-based data management platforms, blockchain technology, and RFID technology can be beneficial. These technologies are highly adaptable and can be implemented across different phases of dairy production, from procurement and processing to logistics and distribution (Hassoun et al. 2024). For example, remote environment management is employed to create optimal conditions during the ripening of cheese products, and technology is used in cold chain management during the transportation of dairy products to prevent spoilage (Priyashantha et al. 2021; Eramo et al. 2025).

Besides enhancing traceability and process efficiency, technology applications play a pivotal role in addressing energy consumption and environmental sustainability issues. The natural freshness of dairy products, together with the need for proper environmental conditions during processing and storage, implies the consumption of considerable amounts of energy. The integration of intelligent energy management with wastewater reduction technology could improve sustainability indices without affecting efficiency (Cheah et al. 2022; Pandey et al. 2023).

Contemporary scientific activity focuses on developing maturity models that address the specific nature of particular industries and take into account the distinctiveness of the

agrifood industry (Arena et al. 2023; Scandurra et al. 2023; Stempfle et al. 2024). Current trends in the dairy industry reveal an increased focus on the application of machine learning and the development of digital twins aimed at improving process control and quality prediction (Caro et al. 2018; Malik et al. 2024), although the application of these technology trends necessitates the creation of implementation frameworks that account for the dairy industry's artisanal nature and regulatory requirements.

The dairy industry's growth in the modern technology age cannot rely solely on investments in technology; it also requires specific changes at the organizational and employee levels. A growth path founded on the development of custom-made maturity models could make this transition smoother and more efficient, even for regions like Sardinia that lack technology but have an essential dairy sector.

The following research questions guide this study:

- RQ1: What is the best way to align maturity models to the unique operational and organizational characteristics of dairy SMEs?
- RQ2: What is Sardinian dairy SME's current digital maturity level, and where should priority interventions be implemented?
- RQ3: What implications emerge from applying a sector-specific maturity model?

2 Assessment of maturity models

The current state of the art was analyzed in the paper 'Industry 4.0 assessment in the agrifood and dairy sector: a literature review of maturity models' (Arena et al. 2023). In conducting this analysis, 272 papers were considered, specifically those related to the presentation and explanation of a new maturity model using various criteria, including title, abstract, and keywords. Subsequently, the research focused only on the papers that presented a new structured evaluation model. In this context, 53 documents provided an MM to assess the maturity of the transition to the digital world. Among these documents, 27 general MMs pertained to the theoretical structures used to evaluate innovation and the transition of different business operations.

Besides these structured maturity models, some authors prefer criterion-based readiness assessments for digital transformations, grounded in performance or capability benchmarks. For instance, Moazzam et al. (2018) applied this approach to prepare for a transition into supply chains covering the agrifood industry, whereas Abdul Basit et al. (2024) generalized such a framework to also cover small- to medium-sized businesses with a particular focus placed on sustainability-driven practices. These studies highlight transparency-driven, criterion-based evaluations, which also contribute to developing a current framework committed to dairy-specific coverage.

Various Industry 4.0-related models have been advanced to assess Industry 4.0 adoption across different contexts. Table 1 compares some of the most cited models across the literature, ranging from high-level, broad-based models such as RAMI 4.0 and DREAMY to more recent industry-specific models. These models exhibit functional structures but either offer high generality, bias towards large firms, or focus on non-digitization themes, suggesting that it is necessary to develop a tailored model that addresses the specific challenges of dairy SMEs.

Currently, there is no ad hoc model for the dairy sector; only generic models are available, which are not suitable for the industry's specific needs. The analysis of existing

Table 1 Comparative summary of maturity models and their applicability to dairy SMEs

Model/Framework	Type	Sector/Scope	Dimensions	Gap for dairy SMEs
RAMI 4.0 (Bastos et al. 2021)	Reference architecture	Manufacturing	Layers, life cycle, hierarchy axis	Too complex; not SME-oriented
DREAMY (De Carolis et al. 2017, 2025)	Maturity model	Manufacturing	Process, Organization, Monitoring, Technology	Generic; not sector-specific
Senna et al. (2023)	Digital maturity model	Industry 4.0 (general)	TOE framework	Large-firm focus; no agrifood link
Scandurra et al. (2023)	Review/synthesis	Agrifood (circular economy)	Environmental, Resource, Organizational	The focus should be on the circular economy rather than on digital transformation
Proposed Model	Sector-specific maturity model	Dairy SMEs	Monitoring, Process, Technology, Organization	Tailored to SMEs; fills sector gap

models revealed several weaknesses that need attention. Most importantly, it became clear that the models used by small companies are not suitable for all issues in the dairy sector, whereas those used by large companies are not adaptable (Arena et al. 2023). SMEs face substantial constraints on financial and human resources, which can hinder the adoption of roadmaps developed for large organizations, making the definition of design principles a complex, tailored task (Abdul Basit et al. 2024). Accordingly, the agri-food and dairy sectors are undergoing a profound digital transformation, driven by Industry 4.0 technologies (Arena et al. 2023). Although digitalization holds the potential for greater efficiency, quality, and competitiveness, it heavily burdens SME businesses due to their limited financial and human capital. MMs have evolved into critical instruments for measuring technological preparedness and assisting organizations in implementing the Industry 4.0 paradigm (Bastos et al. 2021). Nevertheless, available MMs are designed for large companies, leaving a substantial gap for SMEs, particularly in the dairy industry. The lack of a specific model, combined with the urgent need for companies to accelerate digitalization, has highlighted the necessity of developing one that addresses the unique characteristics of the dairy sector to engage local companies and create efficient models suited to each type of business.

The goal is to help dairy companies visualize their digital journey and set priorities for process optimization. The creation of a new model will therefore be oriented toward the possibility of tackling any dairy company, starting with a standard base and branching out into the various company divisions. The expected output will therefore be a basic model that can be applied to business needs, given that each company in this sector has unique characteristics. The ultimate goal is to help companies in the dairy industry assess their level of digitization and support them in making informed decisions to enhance their position.

3 Research framework and methodology

The purpose of this study is to help dairy companies make the most of Industry 4.0's potential. To this end, the first step of the study involved an initial SLR to evaluate the status of the dairy industry in the application of Industry 4.0 (Arena et al. 2023). Recent literature reviews on the dairy industry used an analogous approach, focusing on the intersection of maturity level and technology forecasting. This technique has facilitated understanding and the extraction of information on the highest maturity level achieved by various organizations in Industry 4.0 adoption. The systematic approach offers an in-depth examination and identification of shortcomings in digital maturity, along with organizational strategic plans to position the organization as an Industry 4.0 player.

The complete research methodology is represented in Fig. 1 below. Accordingly, the integrated approach encompasses the tasks of literature analysis of maturity models and their evaluation criteria; conducting expert interviews with four academic and two dairy company representatives; adapting the DREAMY approach according to the specificities of the dairy sector; and the final validation of the strategy with the help of the case study method on dairy companies. The research methodology adopts a multi-method approach that ensures it incorporates the best of theoretical foundations and practical applicability.

The case study was carried out with strictly defined methodological approaches, as with qualitative research involving multiple cases. Walkthrough observations and interviews were conducted with flexibility to enable easy comparison. The information was gathered through walkthrough observations and interviews, and documents from the organizations were used to enhance construct validity. Thematic analysis was used to examine patterns within the cases regarding managers' actions and technology adoption.

Simultaneously, an analysis regarding the state of practice has also been conducted through a series of interviews. Specifically, two companies that are considered the most digitally advanced in the industry, based on their previous investments in digitization, were interviewed, along with four academic experts in this area. To clarify these aspects, two companies in the local sector were involved: the managers from different areas, including administration, production, and quality of Dairy A and Dairy B, who were interviewed and participated in the initial works. The two dairies differ in size and industrial approach. Dairy A is small, with fewer than four employees, has an artisanal vocation, and is oriented towards the production of excellent products, in particular Sardinian pecorino, with complete control of the supply chain from the company's livestock in the pastures surrounding the company to the final customer. Dairy B is larger and adopts an industrial approach, particularly for the production of Roman pecorino, as well as for production lines of Sardinian pecorino and other products intended for large-scale retail trade. The two dairies were selected to represent the two main categories of dairies in Sardinia: the vast majority of the 400 dairies are small, while a smaller number are large but generate significant revenue. The applicability of the coding framework to the dairy sector was ensured through iterative interaction with company managers during on-site walkthroughs, sector-specific refinement of themes, and comparison between artisanal and semi-industrial production contexts.

Both remote and on-site interviews were conducted, lasting roughly 2 h per participant, thereby permitting an

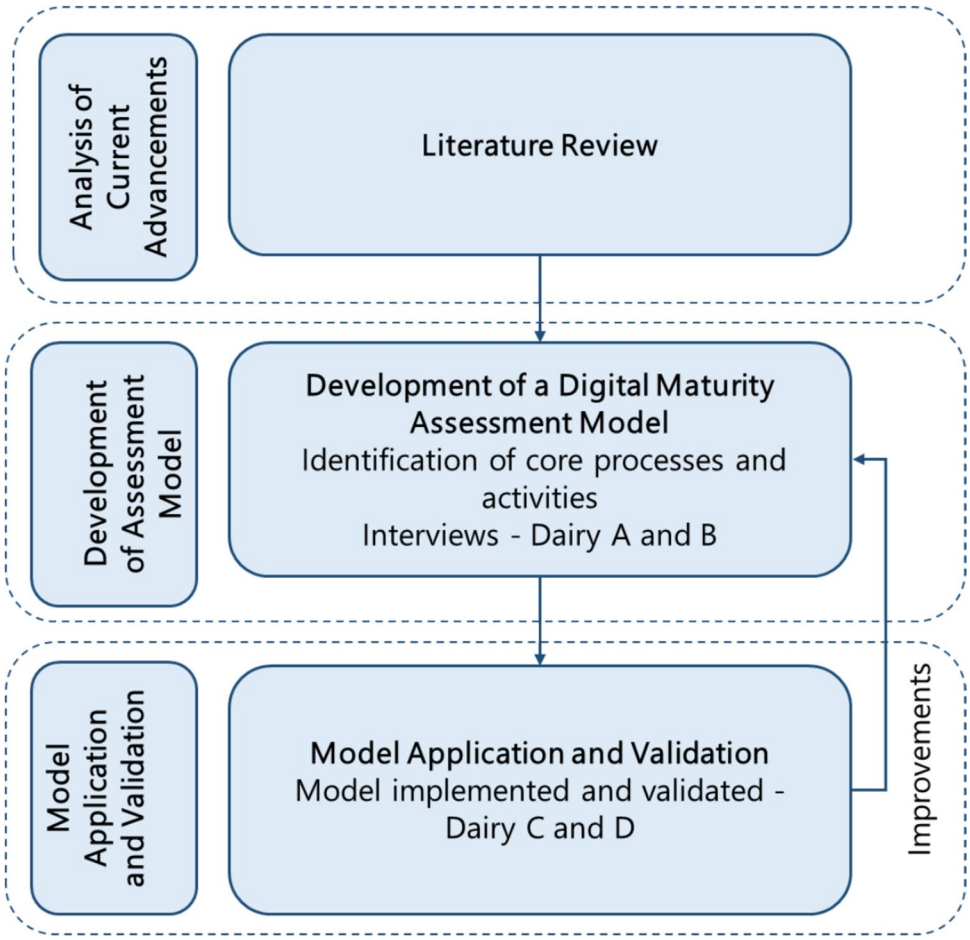

Fig. 1 Research methodology adapted from De Carolis et al. (2025)

in-depth exploration of industrial processes and the information flows that accompany them. A set of open-ended interview questions focused on production planning and supply chain organization, sustainability, and the application of technology. The interview answers were thematically coded with corresponding observations taken from the literature; thus, there could potentially be an application of information systems and Industry 4.0 technology.

Some interviews were conducted during guided factory tours, while others were conducted via video conferencing. Interviews were conducted with a senior manager who oversees the manufacturing, quality control, or administration departments. Insights were recorded live and compiled immediately after each interview. An audio recording of the interviews was made, if permitted, and observations made during the factory tours and process-mapping exercises were collated.

The combined state-of-the-art analysis and state-of-practice showed that the dairy industry shares common aspects with the manufacturing sector. Some of these aspects include handling a large volume of information and optimizing internal company operations to stay ahead of the competition. As a result, the study examined the availability of tools, models, and other guidance to help the manufacturing sector navigate the digital transformation. Of these, the DREAMY approach stood out as the most applicable due to its prescriptive nature, which allows the company to evaluate its position at different levels of maturity toward advanced digitalization (De Carolis et al. 2017, 2025). Nevertheless, because DREAMY's original development was geared toward generic manufacturing companies, it needed to be aligned with the unique characteristics of dairy SMEs. This customization of the model helps it remain both theoretical and practical. DREAMY assesses digital readiness across five levels and provides a tailored roadmap for their digital transformation.

As illustrated in Figs. 2 and 3, the proposed approach assesses the digital maturity of SMEs on four significant aspects of their operations: monitoring and control, processes, technology, and organization. The study will measure five maturity levels for each of these aspects, starting with an initial stage characterized by limited control over processes and a lack of technology application, and culminating in an advanced stage marked by accelerated and secure information transfer, which is facilitated by the

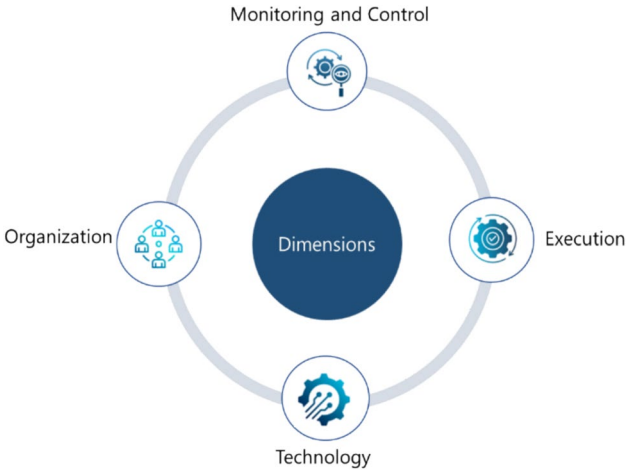

Fig. 2 The four dimensions of digital maturity

integration of technology and organizational structures through digitalization.

Additionally, the approach utilizes nine macro-areas of analysis, including new product development, production planning, cheese production, ricotta production, quality, logistics, supply chain management, energy consumption and sustainability, and maintenance, as indicated in Fig. 4 below. This modularity ensures that the requirements of small- and medium-sized dairy businesses, which may focus on semi-industrial and artisan aspects, are well captured by the assessment model.

After the model and its accompanying questionnaire were finalized, another set of interviews was conducted to validate the exhaustive nature of the assessment questions. Some refinement of the questions and then development of the final model were carried out based on the results of this second round of research. The final research questionnaire included around 200 questions, designed based on the DREAMY model and its modifications to address industry-specific practices across domains such as production, logistics, sustainability, and organizational practices, among others. The manager interviews were conducted using a structured format, but all responses were grouped into the four DREAMY themes.

A semi-structured interview design was formulated to assess the digital maturity of the four model dimensions, i.e., monitoring and control, processes, organization, and technology, and the nine operating macro-area domains, such as new product development, production planning, cheesemaking, ricotta-making, quality, logistics, supply chain, energy management, sustainability, and maintenance. It was based on knowledge gained from the literature review and was pilot-tested by subject-matter experts from academia before use.

Interviews were organized into three parts (Appendix 1): (i) general firm information and contextual factors (size, structure, technological base, market orientation); (ii) assessment of digital readiness across the four model dimensions, through open-ended questions that allowed respondents to list practices, tools, and pitfalls; and (iii) identification of barriers, opportunities, and plans for digital change. Specific questions asked included the use of the ERP/IoT tools utilized for monitoring, scheduling, and planning; quality

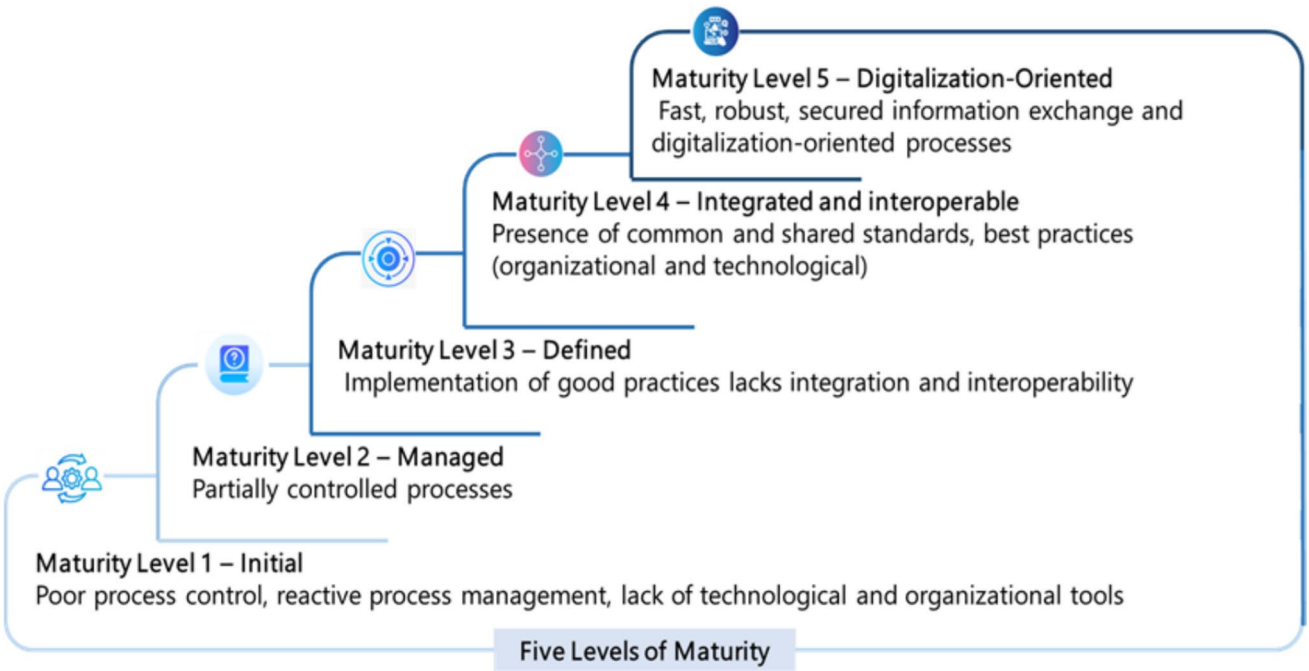

Fig. 3 Levels of maturity

Fig. 4 Analysis of company processes by key dimensions

management and traceability; energy monitoring; and sustainability initiatives.

The adaptation was undergone through a three-step approach. Initially, we maintained the four fundamental dimensions of DREAMY: monitoring and control, processes, organizations, and technology, as they represent the principal pillars of digital transition. Secondly, we ensured the content validity by aligning the indicators with the operational realities of dairy SMEs. The study was conducted through a survey of sector-specific literature, expert interviews, and value chain mapping of key processes, including cheese and ricotta production, milk logistics, and energy-intensive activities. Finally, the model was expanded to include nine macro-areas that are important for small and medium-sized dairy businesses: new product design, production scheduling, cheesemaking, ricotta making, quality management, logistics, supply chain management, energy management, sustainability, and maintenance. These were obtained by reinterpretation of DREAMY's original elements in the context of sustainability imperatives and artisanal production systems. Thus, the developed sector-specific model maintains DREAMY's structured capability assessment, with its tailored application addressing limitations and potentials faced by SMEs in the dairy sector. This sector-specific model extends DREAMY's theoretical foundations by demonstrating its feasibility across generic manufacturing and tailored agri-food sectors.

Two industrial cases were chosen to test the relevance and usefulness of the proposed approach in the dairy sector. These cases are Dairy C and Dairy D. Both chosen organizations operate in the dairy sector and are located on the island of Sardinia. An empirical study of the dairy sector on the island of Sardinia highlights that there are more than 400 small, owner-managed, artisan-type organizations. Additionally, there are a few semi-industrial organizations. This situation makes the environment an intriguing one for studying the maturity of organizations in the digital world, as they operate under a traditional production system and have highly fragmented supply chains. The industrial cases chosen are representative of the sector's majority type, consisting of a small artisan dairy organization and a semi-industrial organization. The organizations selected through purposeful sampling are relevant within the industry, as they belong to the same type but are different organizations. Both organizations chosen depict the kind of industrial dairy on the island of Sardinia. This type of dairy organization manufactures cheese specific to the sheep and goat breeders of

small- and medium-sized types situated near the industrial organization.

4 Adaptation to build a specific model for the dairy industry

4.1 Development of a digital maturity assessment model

As noted above, when creating a model for the dairy industry, it is necessary to identify the processes and operations relevant to dairy production. Industrial practitioners and dairy industry professionals have supported this process.

The research context has included not only primary business operations but also ancillary functions such as new product development and logistics. Based on its findings, this research develops a hierarchical system that distinguishes between primary and ancillary business functions. This research also explores, in greater detail, the intricate business functions involved in dairy units and develops an overall methodological framework to analyze their efficiency and IT maturity. The main business functions under this research include new product development and modification, production planning, cheese and ricotta manufacturing, quality control, logistics and warehousing, supply chain management, maintenance, energy use, and sustainability. The business functions covered by this research are.

Product development and modification: This could involve developing new dairy products, exploring new packaging technologies, enhancing existing products, and conducting research. This process involves designing products, performing cost estimates, and managing data for both new and existing products.

Production planning This business activity involves production planning and other capacity functions.

Cheese production This process consists of all operations involved in the production of finished dairy products from the source material, milk (Fig. 5), as well as those that monitor production (Rencricca et al. 2023). The operations undertaken may vary from one dairy factory to another. The operations include receiving the milk and performing initial steps such as the chemical-bacteriological test, transportation, and other methods, according to the Hazard Analysis and Critical Control Points (HACCP) system. This step involves cooling the milk before the production process begins (Lievaart et al. 2005). Next, processing firms use either a plate pasteurizer or a multipurpose boiler to heat

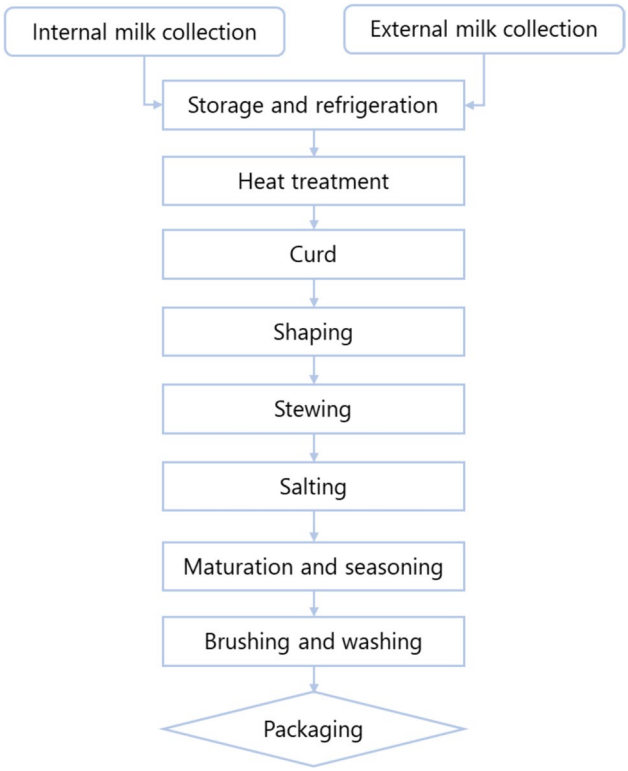

Fig. 5 The stages of the production process in cheesemaking

milk, then add culture and rennet to curdle, and thereafter shape and drain whey. Stewing is an essential part of developing the texture and acidity of the final products. Salting at this time adds the necessary flavor during ripening. Products are cleaned and rinsed according to the type of cheese produced, then packaged.

Ricotta production Ricotta is a byproduct of the cheesemaking process. The process involves heating the whey, separating the surface ricotta, molding, cooling, and packaging (Litopoulou-Tzanetaki 2007; Mangione et al. 2025).

Quality This step encompasses various processes that directly affect product quality. The operators examine milk quality, which is critical for maintaining competitiveness, particularly amid pressure from imported dairy products.

Logistics and warehousing This step encompasses all internal logistics operations, including material handling and warehousing.

Management of the supply chain It comprises functions such as supplier identification and management, procurement, transportation management, cold chain management, demand forecasting, financial management, and customer master management.

Maintenance This process covers all maintenance activities for machines and tools used in the preceding processes.

Energy consumption, sustainability, and certification This process encompasses the management of energy, water, and waste production and consumption, as well as pursuing eventual certifications.

This typology and model were then validated through 1-h interviews with academics and practitioners. Having identified the salient processes and subprocesses, it is essential to define measurement indicators for each. The operational measurement indicators were established for production, implementation forms, standardization, innovativeness within specific activity fields, and technology support. First, it was necessary to determine the measurement elements based on the interviews and an analysis of state-of-the-art expertise. These elements were subsequently described as indicators to enable measurement of their respective levels of maturity, as detailed in the previous chapter.

Following conventions for conducting qualitative case studies in operations management research (Voss et al. 2002; Barratt et al. 2011; Ketokivi and Choi 2014), an appropriate systematic coding methodology has been employed to enhance the rigor and accuracy of case analyses. A thematic coding technique was employed in this research on qualitative evidence with the aim of creating coded themes. Open coding was carried out separately by two researchers initially on the qualitative evidence according to the four DREAMY dimensions. Axial coding was then employed, and correspondences were established for each questionnaire structure based on themes that evaluate the digital maturity of each diary. Each process examined four themes used to assess digital maturity.

The research team performed a coding review to enhance reliability and clarify potential discrepancies. The construct validity was assured using triangulation to verify the research results. To add further robustness to construct validity, the findings and interpretations were reviewed by managers of both organizations for respondent validation, as well as to verify findings using member checking (Wallwey and Kajfez 2023). This process further enhanced construct validity by ensuring a clear focus on how themes represented both empirical evidence and real-world operations in dairy SMEs.

The questionnaire was partially developed and validated through a series of interactions with the team of academic experts, spanning multiple sections and totaling 6 h. Finally, the questionnaire was validated with two industrial practitioners, who were allowed to review it before the interviews, and their comments were duly addressed. After the validation phase, the final questionnaire was structured into an MS Excel survey. This format simplifies the assessment process while automating the calculation of final maturity levels.

4.2 Case study: model application and validation

The model was validated through its implementation in two Sardinian dairy firms, which we refer to as Dairy C and Dairy D. Both businesses are artisanal producers with strong ties to their region and are heavily dependent on local milk collection. They were selected because they epitomize the two prevailing typologies of Sardinian dairies: family-based artisan businesses (Dairy C) and semi-industrial SMEs (Dairy D). Their different profiles make the sample more representative. Dairy C has initiated an organizational upgrade process to enhance its brand image and implement more accurate scheduling based on demand forecasting. Milk supply is its primary bottleneck. Dairy D has a higher innovation orientation with investments in several Industry 4.0 tools, solar panels, and ongoing process optimization. Warehousing capacity is its core bottleneck, consistent with the regional report's findings. Dairy C's bottlenecks are primarily supply-side, while Dairy D faces structural barriers in storage and logistics. While the paper focuses on Sardinia, these barriers and maturity patterns don't reside uniquely in it. Similar problems affect European dairy SMEs and other agrifood sectors with artisan-based production, diffuse value chains, and limited access to digital infrastructure. In this way, the framework can be generalized to similar regional dairy sectors with appropriate local tailoring to their technological, cultural, and policy environments. It thus extends the model's range of validity as a strategic tool for diagnostic purposes in the context of SME digitalization. Both cases also represent barriers typically faced by SMEs, such as a lack of investment capital, limited digital competence, inadequate infrastructure, pressure to comply with norms and regulations, and an organizational culture resistant to technological innovation. These barriers align with overall findings from the agrifood SME literature, which indicate that digitalization initiatives are often hindered by resource scarcity, labor-force skills shortages, and dispersed infrastructure. Moreover, regulatory compliance obligations and ingrained artisanal practices usually lead to cultural resistance to adopting technology. By explicitly linking these contextual barriers to maturity levels, the model emphasizes caution in applying gradual, context-sensitive strategies rather than a straightforward use of off-the-shelf, generic models developed for large industrial companies. These observations underscore the need to adopt a milk industry-specific maturity model rather than off-the-shelf models designed for large corporations.

Both companies lack information technology infrastructure for data collection, although they have efficient manual data collection systems that could be further facilitated through appropriate digitalization and modernization. Sardinia's dairy industry has embraced long-standing, refined artisanal traditions. Its strong cultural traditions make it difficult to use modern technology, as traditional methods might clash with new initiatives like digital technology. However, such an environment offers a tremendous opportunity to develop new approaches that complement its rich heritage without undermining the genuineness or excellence of its dairy products.

Preliminary interviews with managers at each dairy were conducted to map production process dynamics, sector practices, and key dimensions for measuring digital maturity. Visits to these dairies to understand production, administrative, and other areas enabled analysis of operational dynamics, strengths, and weaknesses, as well as coordination between departments.

During these visits, the interviewees walked the researchers through the production process. Conducting these interviews in a semi-structured manner enabled an in-depth understanding while also gathering the information needed to complete the questionnaire on digital maturity at a later stage. These interviews highlighted the importance of having in-depth familiarity with the questionnaire to guide the process.

Critical production stages have been identified, and a questionnaire was used to evaluate the adoption of digital applications across production, quality, logistics, monitoring and control, organization, and digital transformation readiness. Following each guided tour, more customized questions, especially those related to quality, have been added to address any gaps. Both case studies have assisted in validating the overall structure of the questionnaire, thereby confirming its appropriateness in the dairy industry. However, some items, particularly those related to artisanal production, were deemed unsuitable for their intended purpose, despite their potential suitability in more heavily industrialized environments. A modified scoring approach, therefore, has allowed for zeroing in on those items not fit for purpose, thereby omitting them in the overall scoring. During the back-office stage, answers were processed and evaluated. From these results, more crucial elements were identified, especially in the 'organizational section.' For instance, whether an activity is in-house or outsourced does not necessarily affect a company's maturity level. It's illogical to rate companies lower, for example, if they choose to outsource an activity to a more expert company. It was crucial to align with the company's ability to supervise such an activity, whether in-house or not.

5 Results and discussion

5.1 Case study results and cross-case comparison

A qualitative analysis was performed following the conventional guidelines of thematic analysis that are commonly employed in operations and management studies. An assessment of interview transcripts and observations was initially carried out on recurring themes that were then grouped into broader themes on the basis of the four dimensions of DREAMY.

As shown in Figs. 6 and 7, the case study analysis of the two Sardinian dairies proves the applicability of the proposed methodological framework. The proposed methodological approach accurately identifies the levels of digital maturity and the key areas requiring management attention. As expected from the literature on digital transformation in the agrifood SME sector (Cannas 2023; Ciasullo et al. 2025), this study's results confirm that technology readiness, data management capabilities, and system integration remain significant constraints on the development of dairy enterprises.

The evaluation of Dairy C and Dairy D involved six production areas: new product development, cheesemaking, logistics and storage operations, production planning, energy management, and maintenance, at four levels of maturity: process maturity, technology maturity, control and monitoring maturity, and organizational maturity. Dairy C exhibits an unbalanced state of maturity, specifically low levels of technology and monitoring. This aligns with European observations that dairy SMEs apply artisanal knowledge but lack integrated digital monitoring systems (Wójcicki et al. 2025). Process and organizational maturity are relatively strong; however, the underdevelopment of IoT technologies and predictive quality systems hampers the possibility of optimization. This particular state corresponds to the overall status of food SMEs that adopt incremental, disconnected forms of digitalization.

Dairy D demonstrates greater maturity in the production of both soft and rigid cheese. It exhibits excellent workflow management and collaboration capabilities, aligning with the argument that the efficiency and coordination of internally offered services enable successful digital transformation (Trenerry et al. 2021; Sagala and Őri 2024). However, Dairy D still requires more advanced analytics capabilities, live observation, and automation to form the backbone of growing Industry 4.0 implementation.

In comparison, both dairies appear to have highly formalized structures; therefore, this issue of organizational readiness may not pose a problem. On the other hand, the lack of technological capabilities appears to be a significant

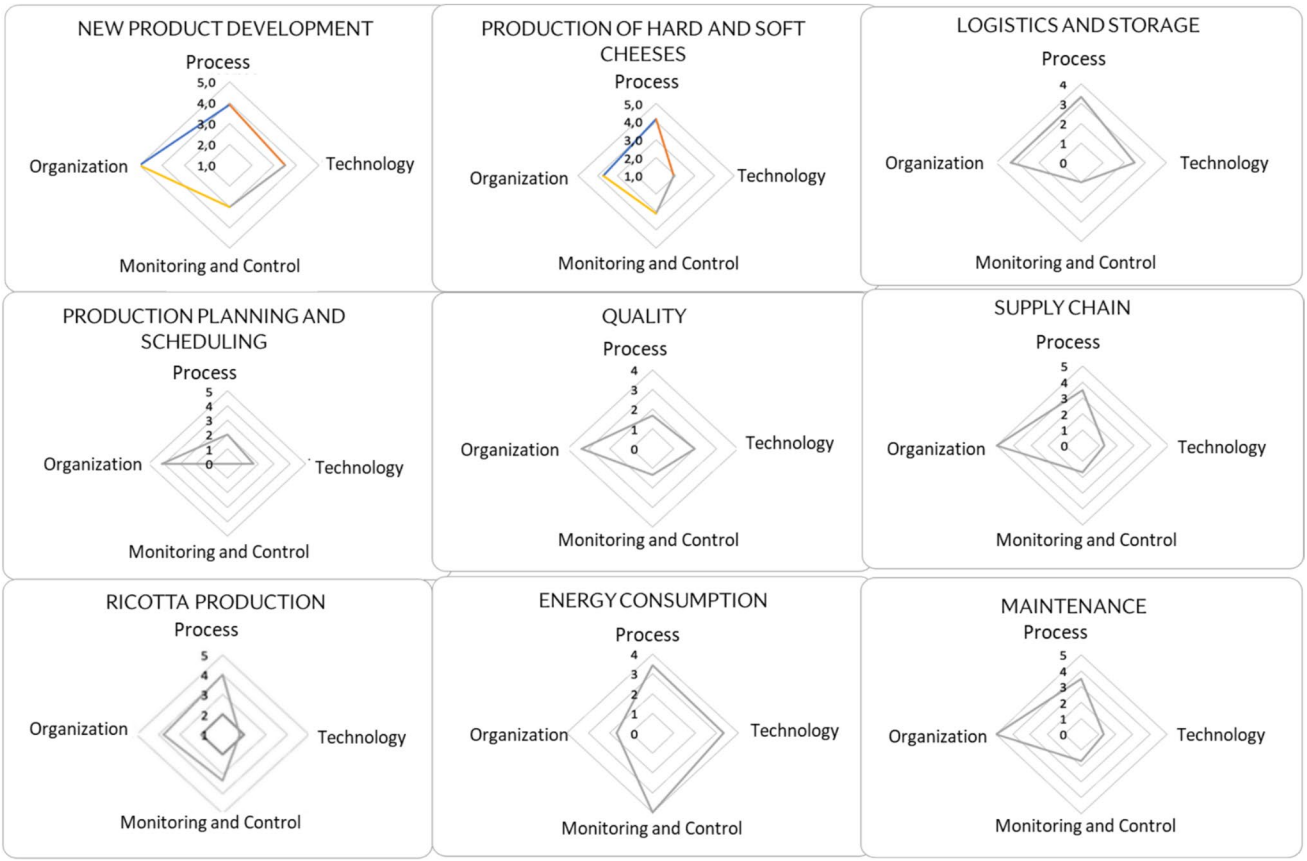

Fig. 6 Dairy Producer C maturity levels

constraint, similar to that faced by the dairy industry more broadly (Kaushik et al. 2024; Tadele et al. 2025).

For Dairy C, the transformation process should begin with base-level projects, such as simple IoT sensor setups, entry-level ERP/MES implementations for tracing and scheduling solutions, and energy management software. These proposed implementation strategies align with the literature promoting step-by-step, affordable technology development within low-maturity SMEs. Dairy D can more effectively implement advanced technologies such as predictive maintenance, digital energy consumption management, and RFID-enabled automated warehouses due to its relatively more industrialized business setup, which aligns with the literature emphasizing the performance benefits of analytics-based integrated technology platforms in well-prepared food processors (Hassoun et al. 2023b; Gowrishankar et al. 2023).

The results confirm the relevance of aligning the organizational readiness of dairy SMEs with the focus of investment on specific technologies that satisfy their unique requirements. Although the best artisanal procedures and well-structured workflows form the backbone of a solid platform, it is still necessary to adopt the right approach for applying data analytics and automation to achieve increased levels of digital maturity.

5.2 Managerial Implications

The maturity model serves as an operational decision support tool The proposed maturity model serves as a useful decision-support tool and not only a descriptive benchmarking device. It has been found that the maturity level related to digitalization in dairy SMEs varies across different business processes and their respective dimensions. In less developed environments, it has been observed that, despite expert artisan knowledge and organizational discipline, effective operational management in the dairy sector is challenging without oversight from contemporary digital systems. Concerning operational management, it has been made clear that initial investments in the dairy sector must initially target the development of a foundational level of data visibility, such as temperature, processing time, and production volume, prior to the implementation of other advanced automation and analysis tools. Such an approach allows a smoother transition mechanism from expert-operational management to data-driven management, without disturbing the already established dairy sector operations. In other technologically superior dairy SMEs, the management's main emphasis migrates from data collection to data integration and utilization. After the initial data-monitoring

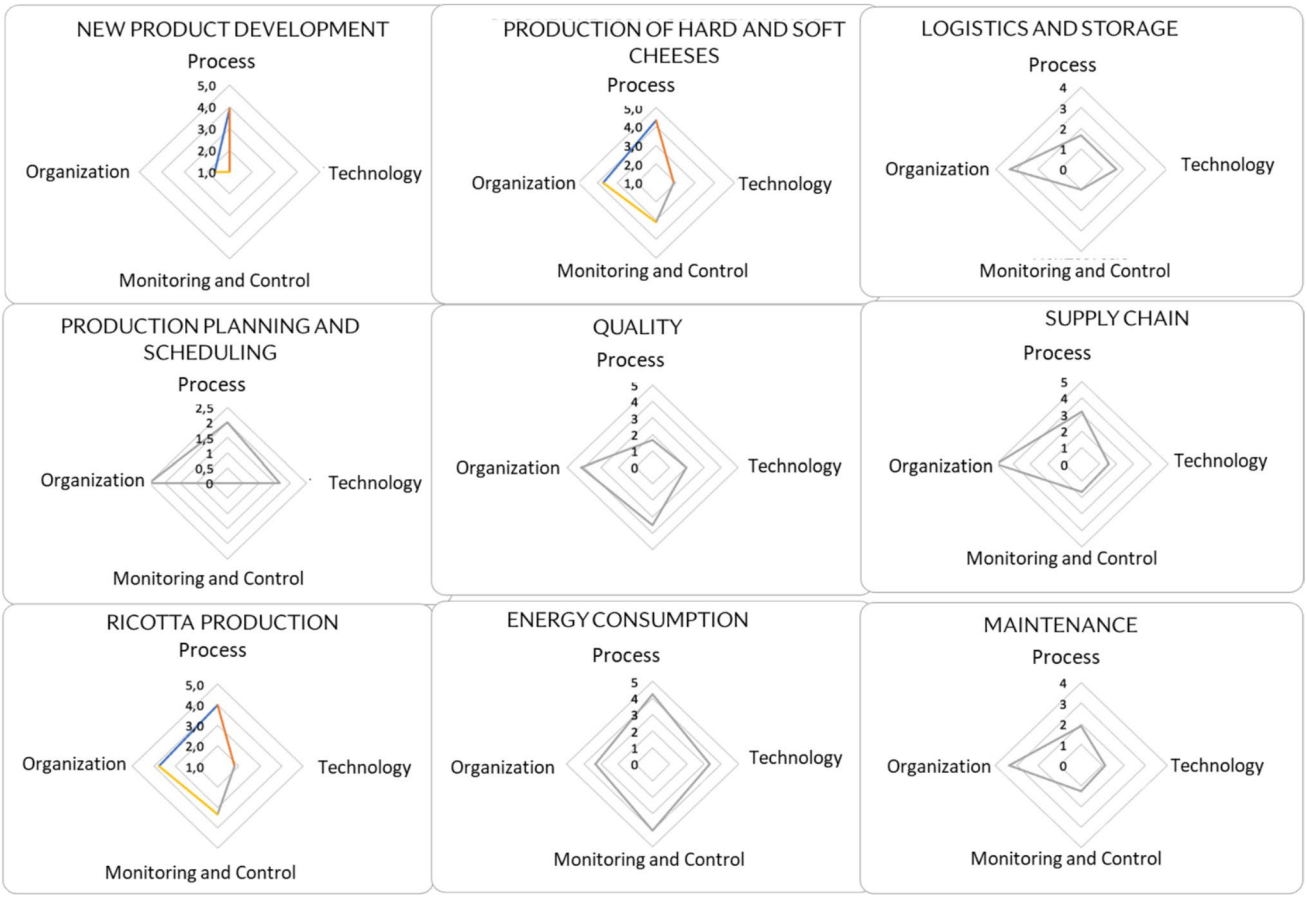

Fig. 7 Dairy Producer D maturity levels

infrastructure has been established, the enhancement of dairy sector management, on a progressive basis, depends on data-linking capabilities concerning different production, logistics, maintenance, and energy management tasks. As such, this particular maturity profile enables dairy management to determine the appropriate timing of implementing predictive analytics tools, enabling anticipatory management decisions rather than post-event management.

Prioritization of digital investments is based on process orientation The results of a process-oriented approach are of higher value compared to a technology-oriented approach in facilitating a successful transformation of dairy SME enterprises through digitization. Resource limitations in the enterprises hinder the wide adoption of digitization, thereby causing companies to prioritize the process of making digital investments. Based on the maturity model, the significant bottlenecks in specific macro-processes such as product manufacture, cheese making, warehousing, and energy-driven processes are identified, thereby enabling the prioritization of digital investments. Arranging digitization initiatives around production constraints is relevant in the dairy industry due to the risks associated with production variability and government regulations, which significantly increase the likelihood of making improper digitization investments.

Organizational readiness and capability management It becomes apparent from the research that there is a gap between the technological and organizational levels in the dairy SME sector regarding the decision-making system and the intra-organizational coordination. These measures should help facilitate an effective organizational process that allows concrete digital projects to be assigned to coordinators in SME firms, regardless of the presence of organizational structures in the IT sectors. This means that outsourcing digital solutions would not affect the digital maturity level.

Relating digitalization to sustainability and compliance The maturity model helps in the integration of digitalization with the sustainability agenda and the concept of regulatory compliance. By digitally monitoring the management of energy, water, and waste, the managers can improve their expenditure controls in addition to the monitoring of food safety laws and regulations. This analysis proves the integration of

sustainability in the digitization process, rather than treating it as a decentralized activity. As far as the dairy SMEs are concerned, energy consumption, traceability, and the monitoring of the food safety law are major issues.

Supporting strategic planning and transformation The model will provide a solid foundation for strategic planning and investment governance, facilitating the long-term transformation and development of a firm. By looking at the maturity scores, companies can identify important areas to improve, and these scores can help communicate their plans for increasing digital investments to owners, cooperatives, or public funding agencies, ensuring that no company remains at a medium maturity level.

6 Conclusions

This study implemented and validated the Model for Digital Maturity Assessment, a custom-developed model specifically for the dairy industry, thereby establishing it as a strategic tool to support digital transformation among SMEs. The model identifies key areas of digital preparedness across fundamental business processes (i.e., production, logistics, energy management, and sustainability) under four dimensions: monitoring and control, processes, organization, and technology. Through a structured framework for measuring and improving digital competence, the model helps SMEs better understand their level of maturity and design effective strategies to improve. An application to Sardinian dairy companies demonstrates its practicality and relevance to industry sectors. It identifies both current areas of weakness and future possibilities for digital development.

However, there are certain limitations to this study, including the small sample size, geographic focus, and the need to apply the framework to specific production environments and technological setups. These present opportunities for future work, including expanding the scope of analysis to encompass a more representative selection of dairy SMEs, subjecting the model to tests across other subsectors of the agrifood industry, and evaluating its transferability across various adoption scenarios for technologies. Future research should examine the economic ramifications of digital adoption and explore adaptable models that can respond to swiftly evolving technologies and changing regulatory demands. Thus, this research offers a starting-point framework that can aid the dairy sector's digital transformation, easing organizations' efforts to address digital transformation challenges and helping them build resilience, innovation, and sustainability. Theoretically, this research extends existing studies on maturity models by formulating how generic models like DREAMY can be applied to artisanal small and medium-sized enterprises within the agrifood industry, thereby contributing to operations management theories with sector-level insights. Subsequent research can be conducted by covering broader domains beyond a single region, implementing quantitative validation, and focusing on next-generation technologies such as digital twins and AI-driven, data-driven benchmarking.

Appendix 1 Semi-Structured Interview Guide

Table 2 Structure, themes, and guiding questions of the interview

Section	Content/Themes covered and guiding questions
1. General Information and Context	Themes: Company size and organizational structure; product typology and market positioning; existing certifications; description of the production process; technological base; and currently used ICT tools Questions: • How are processes executed and controlled in this area? • Which data are monitored (e.g., time, temperature, energy, waste)? • How is data collected (manual recording, sensors, enterprise software)? • What is the level of automation and digital support? • Are roles, responsibilities, and skills adequate to manage digital systems?
2. Digital Readiness Assessment (Four DREAMY Dimensions)	Dimensions applied to all macro-areas: • Process execution • Monitoring and control • Technology • Organization Guiding questions: • How are processes executed and controlled in this area? • Which data are monitored, and how are they used? • What is the level of automation and digital support? • Are roles, responsibilities, and skills adequate for managing digital systems?
Macro-Areas Evaluated	1. New product development and product modification • On what basis does the company decide to develop a new product or modify an existing one (customer input, market trends, internal initiatives, and regulatory requirements)? • Which departments are involved? • Is digital support used in product design (simulations, digital models, data analysis)? 2. Production planning and scheduling • How is production planning currently carried out? • Which criteria define production volumes and schedules? • Are processes standardized or frequently adapted? • What are the main sources of variability or uncertainty? 3. Cheese production • How is the cheese production process managed and monitored? • Which digital tools support this process? • What bottlenecks or manual activities affect production? 4. Ricotta production • How is ricotta production organized and controlled? • Which data are collected during this process? 5. Quality management • What quality control procedures are in place? • What monitoring or traceability systems are used? 6. Logistics and warehousing • How are logistics and storage activities managed? • How is information exchanged across departments? 7. Supply chain management • How is coordination with suppliers and distributors managed? • Are digital tools used for supply chain visibility? 8. Energy consumption, sustainability, and certifications • Are sustainability or energy efficiency objectives formally defined? • Which indicators are used to evaluate sustainability performance? • Are digital tools used to support sustainability goals? 9. Maintenance • How is maintenance currently managed? • Are digital tools or monitoring systems used?
Questions Across All Areas	• Which digital tools (ERP, MES, IoT systems, spreadsheets) support this process? • How is data collected, stored, and shared (paper-based vs. digital)? • What type of monitoring or traceability systems are used? • How is process performance measured (KPIs)? • What bottlenecks or manual activities affect this process? • Which tools or improvements would be most beneficial?

Table 2 (continued)

Section	Content/Themes covered and guiding questions
3. Barriers, Opportunities, and Plans for Change	Themes: Barriers to digital adoption (skills, budget, infrastructure); sustainability and energy constraints; priorities for digital improvement; planned or ongoing investments; opportunities identified by managers Questions: • What are the current challenges that are limiting the integration of digital technologies (e.g., skills, cost, infrastructure)? • How do sustainability and energy issues affect operational decisions? • What digital initiatives are being prioritized in the short term, in the longer term, or in both? • Are technological investments being planned or presently implemented? • How have the improvement opportunities been determined by management?
4. Closing Questions	Themes: Completeness and clarity of the questionnaire; validation of mapped processes; missing aspects; willingness to adopt further digital solutions or participate in follow-up discussions Questions: • Does this questionnaire accurately represent your processes? • Are there relevant aspects not covered? • Would the company be willing to adopt further digital solutions or participate in follow-up activities?

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Declarations

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