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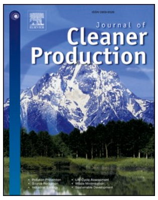

The relationships between digitalization and ecosystem-related capabilities for service innovation in agricultural machinery manufacturers

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ABSTRACT

Manufacturers seeking to provide smart product-service systems require new sets of capabilities such as digitalization and ecosystem-related capabilities. Studies have investigated these capabilities separately, although it seems to have an unexplored convergence between them. Therefore, this article aims to identify the digitalization and ecosystem-related capabilities of manufacturers in the agricultural machinery industry that are seeking digital servitization and offering smart product-service systems. Moreover, it aims to uncover the relationships among these capabilities to determine their driving and dependence power. A combination of methods was employed to achieve this result. First, a systematic literature review was conducted to define key digitalization and ecosystem-related capabilities. Next, the Interpretive Structural Modelling and fuzzy MICMAC analysis were employed to define the capabilities' driving power and dependence power. By combining these analyses, we propose a conceptual framework that integrates these two sets of capabilities, which is comprised of three macro-layers: driving, linkage, and dependent. This article contributes to the literature by showing the interrelationships between digitalization and ecosystem-related capabilities. Also, it proposes a conceptual framework that groups capabilities based on their contributions to the development of digital service innovation.

1. Introduction

Over the past decades, manufacturers have invested in service-oriented business models (Chen et al., 2021; Paschou et al., 2020; Tronvoll et al., 2020). More recently, manufacturers have also been influenced by digital technologies (Frank et al., 2019b; Verhoef et al., 2021). As a result, manufacturers in industries such as IT (Xerox), heavy machinery (Caterpillar), turbines (Rolls-Royce), elevators (Otis), and transportation (Scania) have transformed their business models due to servitization and digitalization. In the agricultural machinery industry, these two trends are reinforced by the advances in precision agriculture, or Agriculture 4.0 (Kaňovská and Tomášková, 2018; Ozdogan et al., 2017). Manufacturers in this industry are developing smart products that enable digital services such as real-time data collection, product remote reconfiguration, and predictive analytics (Kovács and Husti, 2018). For example, John Deere collects data on crop yields through its farming equipment and sells it to DuPont, which, in turn, sells seeds and agricultural consulting for the same customer. As these instances illustrate, John Deere and other manufacturers are aligning their transformations toward digital servitization.

Digital servitization refers to the shift from offering pure products and complementary services to offering smart PSSs or solutions based on product and services integration (Chen et al., 2021; Paschou et al., 2020). Moreover, due to the infusion of digital technologies, changes in manufacturers' business models are necessary for digital servitization (Sjödin et al., 2020), and to integrate PSS with digital technologies (Pirola et al., 2020). A remarkable aspect of this shift is that the offering of smart PSSs goes beyond the traditional supply chain to encompass an entire ecosystem perspective (Chen et al., 2021; Sjödin et al., 2020; Sklyar et al., 2019). Inter-firm collaboration and ecosystem approaches

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are considered important sources of service innovation for manufacturers (Lütjen et al., 2019). Therefore, digitalization and the ecosystem approach are central to the digital servitization strategy (Chen et al. 2021; Sklyar et al., 2019).

To take advantage of the benefits of digital servitization, manufacturers also require new sets of capabilities besides those already emphasized by traditional servitization (Chen et al., 2021; Kolagar et al., 2020; Paschou et al., 2020). They need to develop digitalization capabilities, which refer to the company's ability to implement solutions and improve its processes based on digital technologies (Lenka et al., 2017; Ritter and Pedersen, 2020). Additionally, manufacturers also need ecosystem-related capabilities to align and stimulate the collaboration between the ecosystem actors (Immonen et al., 2018; Kolagar et al., 2020). In general, studies have already investigated these two sets of capabilities—digitalization and ecosystem-related—separately (e.g., Lenka et al., 2017; Lütjen et al., 2019; Ritter and Pedersen, 2020).

The isolated identification of digitalization and ecosystem-related capabilities is ineffective due to the convergence between the two sets of capabilities. In this sense, Tronvoll et al. (2020) suggest that it might not be possible for a focal firm to transform digitally without the collaboration of other ecosystem actors. This becomes more important in complex contexts (e.g., digital servitization) based on collaborative networks since more actors might be required to interact due to the complexity of their innovative solutions and advanced services provided to customers (Kahle et al., 2020; Kohtamäki et al., 2019; Kolagar et al., 2020). Lastly, digitalization draws on increasingly available resources that arise from the collaboration and integration between different ecosystem actors (Sklyar et al., 2019). This is a noteworthy gap in the research (Chen et al., 2021; Paschou et al., 2020) because the interrelationships between digitalization and ecosystem-related capabilities can uncover mutual influences that might support the development of smart PSSs and, thereafter, the digital servitization strategy.

In response to this gap, this study was conducted to model and analyze interrelationships between digitalization and ecosystem-related capabilities using an approach that integrates Interpretive Structural Modeling (ISM) with fuzzy Matrices d'Impacts Croises Multiplication Appliqué à un Classement (MICMAC) analysis. The ISM method assesses the interrelationships among elements involved in a complex system based on data collected from industrial and academic experts, whereas the MICMAC method provides the fuzzification of the intensity of the relationship between two elements, clustering each one according to its driving and dependence power (Muruganantham et al., 2018). Several studies have used these two methods in different research contexts such as quality management (e.g., Muruganantham et al., 2018), supply chain (e.g., Bhosale and Kant, 2016), Industry 4.0 (e.g., Kamble et al., 2018), and capabilities (e.g., Mota et al., 2021). For this study, a group of experts from industry and academia linked to the Brazilian agricultural machinery industry was interviewed. This industry was chosen for two main reasons: (i) agricultural machinery manufacturers are heavy users of digital servitization motivated by precision agriculture (Kaňovská and Tomášková, 2018; Ozdogan et al., 2017); and (ii) Brazil is one of the world's largest exporters in agribusiness, which has generated conditions for high investments in the agricultural machinery industry (da Silva et al., 2007; Bolfe et al., 2020; Mantovani et al., 2019).

This research adds to existing knowledge in the digital servitization field in several ways. First, this study demonstrates the interrelationships between digitalization and ecosystem-related capabilities. Second, based on a capability-based perspective, we propose a conceptual framework that establishes that the interplay between digitalization and ecosystem-related capabilities can progress throughout three macro-layers (i.e., driving, linkage, and dependent). Therefore, this study contributes to bridging the research gap on the development of capabilities by manufacturers seeking digital servitization (Raddats et al., 2019), and on the alignment of digital servitization strategy and collaboration within an ecosystem (Rabetino et al., 2018). Third, we focus on the context of the Brazilian agricultural machinery sector, expanding the servitization research through a quantitative investigation of a scenario with inadequate exploration in the digital servitization literature. Thus, this paper answers calls for studies on digital servitization outside developed Western countries (Rabetino et al., 2018), as well as calls for investigations from other manufacturing sectors (Paschou et al., 2020). Finally, the use of a multi-method approach with the ISM and Fuzzy MICMAC is important to broaden the range of methods applied in the digital servitization literature, which predominantly consists of exploratory qualitative studies (Paschou et al., 2020; Rabetino et al., 2018).

2. Conceptual background

2.1. Digital servitization

Digital servitization is defined as "the transformation in processes, capabilities, and offerings within industrial firms and their associate ecosystems to progressively create, deliver, and capture increased service value arising from a broad range of enabling digital technologies" (Sjödin et al., 2020, p. 478). It encompasses the convergence of servitization and digitalization (Frank et al., 2019b; Paschou et al., 2020). While servitization emphasizes the provision of services by manufacturers, digitalization refers to the use of digital technologies (e.g., Internet of Things, cloud computing, big data, among others) to alter and improve existing business processes and offerings (Verhoef et al., 2021). In particular, digital technologies support the digitization of information and tasks as well as the digital transformation of the company's business logic (Verhoef et al., 2021).

Digitalization is an enabler of servitization (Paschou et al., 2020). In this regard, digitalization changes the back-end or the front-end service activities performed by manufacturers (Coreynen et al., 2017; Tronvoll et al., 2020). It benefits back-end operations by increasing their efficiency through task automation. In the same vein, digital service centers or digital platforms enable the centralization of front-end service activities and create new types of customer interactions (Coreynen et al., 2017; Kohtamäki et al., 2019; Tronvoll et al., 2020). The use of digital technologies also stimulates the development of new services. For instance, the Internet of Things (IoT) allows remote monitoring services, and predictive analytics relies on big data analytics (Ardolino et al., 2018). Besides, the digitalization of supply chain and distribution networks changes manufacturers' relationships with suppliers, customers, and other actors in the ecosystem (Chen et al., 2021; Tronvoll et al., 2020). In short, digitalization contributes to service innovations in the value propositions as well as in the service processes, increasing the number of digital-enabled services, digital services, and smart services due to product visibility, data availability, information exchanges, ecosystem approaches, and deep knowledge of the customer's processes (Sjödin et al., 2020; Tronvoll et al., 2020; Zheng et al., 2018).

Digital servitization requires a new set of capabilities (Chen et al., 2021; Tronvoll et al., 2020). A capability refers to a firm's capacity to repeatedly perform a certain activity that directly or indirectly determines its ability to create value, by transforming inputs into outputs (Grant, 1996; Ritter and Pedersen, 2020). Notably, in digital servitization, manufacturers must advance in digitalization and ecosystem-related capabilities (Chen et al., 2021; Sklyar et al., 2019; Tronvoll et al., 2020), which should be added to the extant portfolio of other capabilities (e.g., service and dynamic capabilities). This study focuses on these two newer sets of capabilities—digitalization and ecosystem-related.

Lenka et al. (2017) emphasize that digitalization capabilities enable value co-creation, resulting in new digital offerings. Capabilities related to the generation, transmission, storage, access, and security of data are logically essential for manufacturers seeking digitalization (Ritter and Pedersen, 2020; Verhoef et al., 2021). The literature also highlights other capabilities such as digital technology selection (Ardolino et al., 2018), intelligence (Lenka et al., 2017), analytics (Lenka et al., 2017;

Schroeder et al., 2020), predictive (Ardolino et al., 2018), and reasoning capabilities (Lenka et al., 2017). Although we recognize that digitalization involves regulatory, contractual, and ethical capabilities (Ritter and Pedersen, 2020), our focus is on the technical and analytical capabilities due to their central role in the exploitation and exploration of innovations.

Another set of capabilities encompasses the relationship between the servitized manufacturer and other ecosystem actors (Kohtamäki et al., 2019; Tronvoll et al., 2020). Digital servitization calls for intensive collaboration and co-creation (Kamalaldin et al., 2020; Sklyar et al., 2019), and requires the alignment and integration of other actors (Kohtamäki et al., 2019). Collaboration with ecosystem actors is important for data integration, which in turn enables the manufacturer to increase its supply chain responsiveness (Opresnik and Taisch, 2015; Pagoropoulos et al., 2017). Thus, the manufacturer can meet customers' needs in real-time (Chen et al., 2021; Opresnik and Taisch, 2015; Sjödin et al., 2020). In this sense, ecosystem-related capabilities are necessary to stimulate collaboration and innovation (Immonen et al., 2018). For instance, collaboration with actors (Lütjen et al., 2019; Nenonen et al., 2018), trust management coordination (Ruokolainen et al., 2011), and understanding of actors' resources (Nenonen et al., 2018). Therefore, digital servitization exists in the relationship between ecosystem actors, requiring communication, collaboration, and shared knowledge for service innovation and the provision of advanced digital solutions (Kohtamäki et al., 2020; Tronvoll et al., 2020).

Although several studies have indicated the mutual relationship between digitalization and ecosystem-related capabilities (Kohtamäki et al., 2019; Tronvoll et al., 2020), the extant literature has addressed both capabilities separately (Lenka et al., 2017; Lütjen et al., 2019; Ritter and Pedersen, 2020). However, an isolated identification of these capabilities is inadequate because more complex contexts of digital servitization require greater collaboration with actors in the ecosystem given the complexity of the solution offered (Kahle et al., 2020; Kohtamäki et al., 2019; Kolagar et al., 2020). Thus, it is important to unveil how these capabilities influence each other, which addresses the research gap regarding the interrelationships between digitalization and ecosystem-related capabilities to support a digital servitization strategy.

2.2. *Digital servitization in the agricultural machinery industry*

The main focus of past digital servitization research has been on original equipment manufacturers (OEMs) catering to a wide variety of sectors, such as industrial machinery (Sklyar et al., 2019), automotive (Ciasullo et al., 2021), telecommunications (Kamalaldin et al., 2020; Sjödin et al., 2020), and mining (Kamalaldin et al., 2020; Sjödin et al., 2020). One relevant sector is the agricultural sector, including crop and animal production (e.g., farming and livestock), forestry, fishing, and aquaculture (Kaňovská and Tomášková, 2018; Ozdogan et al., 2017). Two main factors have driven agricultural machinery manufacturers towards digital servitization. The first factor is precision agriculture (Agriculture 4.0), which refers to the application of new technologies to provide, process, and analyze multisource data of high spatial and temporal resolution for decision-making and operations in the management of crop production (Kaňovská and Tomášková, 2018; Ozdogan et al., 2017). The second factor is the change in the farmers' needs: (i) to increase productivity to compete with countries where legislation is less restrictive and costs are lower (Matheny and Leahy, 2007); (ii) to continually invest in facilities to remain efficient (Lee and Cappellazzi, 2017); (iii) to comply with new environmental standards (Lichtenberg, 2019); and (iv) to reduce the uncertainties of agricultural activity (Kaňovská and Tomášková, 2018).

As a result of the technology-push and demand-pull factors, agricultural machinery manufacturers are offering new advanced solutions to farmers, which are tailored to their specific needs (Kaňovská and Tomášková, 2018). From an equipment perspective, tractors or harvesters, for instance, are equipped with sensors and data systems that allow equipment optimization, remote diagnosis, remote maintenance, predictive maintenance, and real-time simulations for prototyping and testing (Cedeño et al., 2018; Kaňovská and Tomášková, 2018). From an operations perspective, smart PSSs allow harvest monitoring in real-time and predicting resource consumption (e.g., seeds, fuel, fertilizers) based on historical data (Cedeño et al., 2018; Kaňovská and Tomášková, 2018). For instance, John Deere is offering a management system that connects all of its tractors in the field, helping the farmers to monitor and control their operations (Kaňovská and Tomášková, 2018; Porter & Heppelmann, 2014). Moreover, the service platform provides equipment monitoring and maintenance services to farmers.

To provide smart PSSs, agricultural machinery manufacturers are also strengthening their relationships with ecosystem actors, especially with their users (Kaňovská and Tomášková, 2018). For this purpose, front-end digital technologies are essential for data collection and monitoring of agricultural production (Cedeño et al., 2018; Kaňovská and Tomášková, 2018). At the same time, communication and platform technologies support provided services, advising the farmers on how to operate the equipment or how to increase its productivity (Cedeño et al., 2018). In this way, the interplay between digitalization and the ecosystem in the context of agricultural machinery manufacturers stands out.

The efforts to provide new advanced solutions can be seen in emerging countries. For instance, agribusiness is one of the main economic activities in Brazil, which has generated high investments in the agricultural machinery sector to maintain the country as one of the world's largest suppliers of grains and animal products (Mantovani et al., 2019). Although the diffusion and adoption of digital servitization in the country have not yet reached the expected competitive levels, the national industry has invested in new technologies to equip tractors and harvesters with tools that enable digital machine integration and that offer digital solutions (Bolfe et al., 2020; Mantovani et al., 2019). Thus, because research on digital servitization has focused on advanced Western economies (Rabetino et al., 2018), analyzing it in the Brazilian agricultural machinery manufacturers landscape offers new insights.

3. Research methods

Considering the article's objectives, a systematic review was conducted to identify key digitalization and ecosystem-related capabilities. Next, a combination of ISM and Fuzzy MICMAC analysis was used to categorize these capabilities. The joint usage of these analyses is very common (Bhosale and Kant, 2016; Muruganantham et al., 2018) because the ISM enables the identification of the existence of the relationship between two elements (Muruganantham et al., 2018), while the Fuzzy MICMAC analysis overcomes this binary approach by providing the fuzzification of the intensity of these relationships based on expert opinions (Bhosale and Kant, 2016; Muruganantham et al., 2018). Thus, a multi-method approach for the systematic literature review was adopted. Fig. 1 depicts the methods used in this study.

3.1. *Systematic literature review (SLR)*

We developed a systematic literature review (Tranfield et al., 2003) to identify a preliminary list of digitalization and ecosystem-related capabilities. Searches were performed in the Web of Science (WoS) database, which is a database that offers noteworthy publications from influential journals and research scholars (Zhang et al., 2016). The keywords used are shown in Table 1. These keywords were searched in the titles, abstracts, and keywords of the articles. Two inclusion criteria were also adopted: type of documents (only "articles" and "reviews") and language (English). Thus, documents included in the *grey literature* (conference papers, etc.) were not considered as they had not passed through rigorous evaluation processes. Based on these procedures, we obtained an initial sample of 1620 articles linked to digitalization and 620 articles linked to the ecosystem. The searches were conducted in

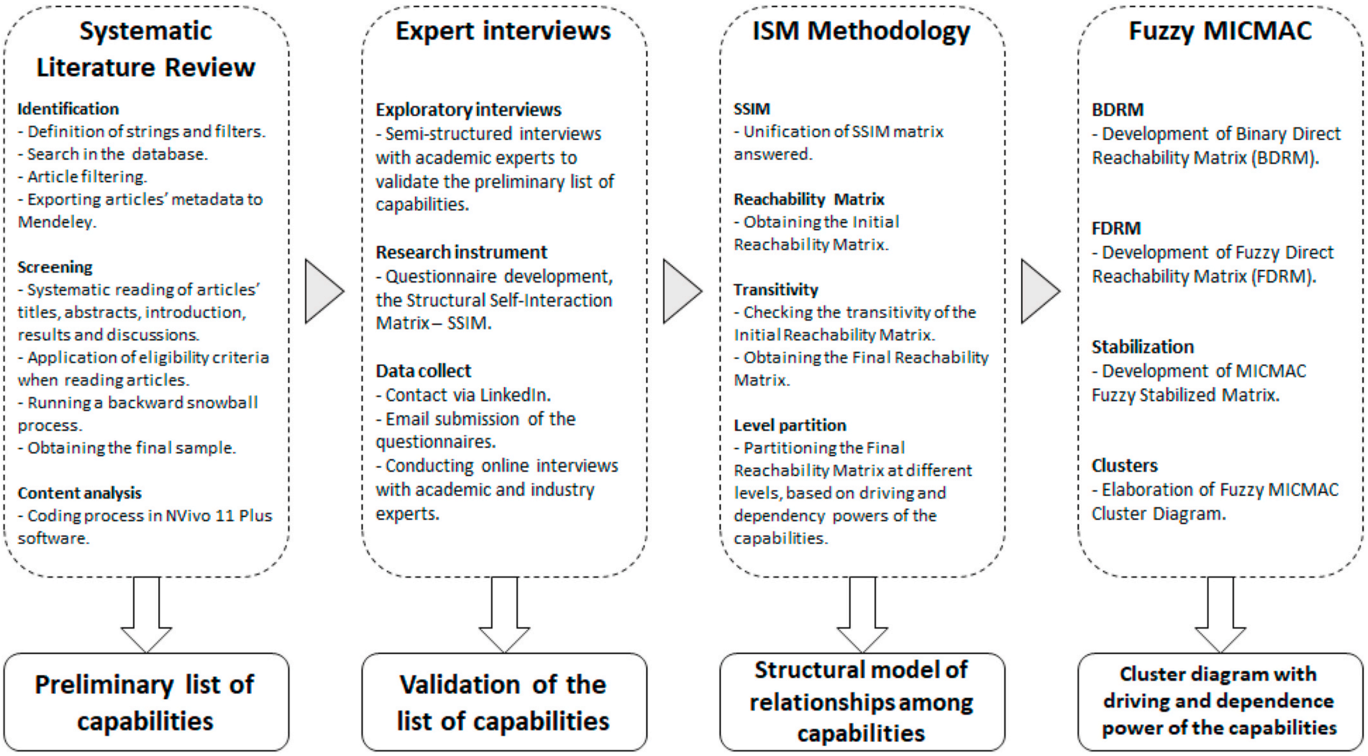


Fig. 1. Research method.

Table 1
Constructs and keywords.

Constructs	Keywords	References
Digitalization	(digitali*ation OR digiti*ation OR "digital manufacturing" OR "digital technology" OR "digital transformation" OR "industry 4.0″)	(Kohtamäki et al., 2020; Paschou et al., 2020)
Ecosystem	("innovation ecosystem*" OR "innovation network*" OR "business ecosystem*" OR "business network*")	(Aarikka-Stenroos and Ritala, 2017; Desmarchelier et al., 2020; Yin et al., 2020)
Capabilities	(capabilit* OR competenc*)	(Egbunike et al., 2018; Wang and Rajagopalan, 2015)

February 2021.

As our focus was to identify a preliminary list of capabilities, we considered articles published in journals that are widely perceived to be the top-ranked, according to their JCR impact factors, and that were representative of the investigated themes. The full list of journals is shown in Appendix A. Thus, the new samples that resulted from this last procedure were comprised of 259 digitalization-related articles and 153 ecosystem-related articles. The article's metadata was then exported to Mendeley. The screening process began with the reading of article sections (e.g., abstracts, introductions, results, discussions, etc.). The objective was to identify if the articles presented or discussed digitalization and ecosystem-related capabilities. Two authors of the research team were involved in this screening process. When a consensus was not reached, a third author was involved. Finally, to overcome the potential limitations of the search strings, a backward snowball process was performed, which resulted in the selection of seven additional digitalization-related articles (e.g., Ardolino et al., 2018; Lenka et al., 2017) and eight ecosystem-related articles (e.g., Ritter and Gemünden, 2003), most of which were highly cited references. After this procedure, the final sample of digitalization-related articles consisted of 162 articles, whereas the final sample of ecosystem-related articles consisted of 102 articles.

Lastly, a content analysis (Seuring and Gold, 2012) was performed to identify a list of the most frequent digitalization and ecosystem-related capabilities. This process was done, in parallel, in the two samples with the support of NVivo 11 Plus software. Two authors of the research team were more involved with the process of identifying the capabilities, but the final categorization was discussed among all the authors.

3.2. *Expert interviews*

Firstly, two members of the research team and another invited researcher whose research interests are digital servitization and Industry 4.0 made a first assessment of the identified capabilities to refine them and proceed with the study. Secondly, we developed a research instrument that encompassed three sections: (i) expert information; (ii) the *Structural Self-Interaction Matrix* (SSIM); and (iii) additional information (e.g., qualitative feedback). A pre-test was conducted with two other academics to examine the accuracy and completeness of the research instrument. They suggested only small modifications (e.g., wording).

In the following, we identified new potential experts that could participate in our research. In this case, new academic and industry experts were invited to participate in a survey. The academic experts were identified based on their involvement with digital servitization and Industry 4.0 research (e.g., solid academic background, active research, and publications in top-ranked journals related to the areas explored in this study). We also identified potential experts from the agricultural machinery industry based on the following eligibility criteria: senior management positions in Brazilian agricultural machinery manufacturers; work experience; experience in engineering, and operations areas, and participation in innovation processes in their respective companies. Invitation e-mails were sent to the selected experts, explaining the research objectives and asking for their participation. If they agreed to participate, a second e-mail was sent with the research instructions, the list of the capabilities (including their descriptions), and the research instrument.

In total, we received completed answers from 12 experts. The practitioners were top managers with more than 10 years of work experience in leading Brazilian agricultural machinery manufacturers, whereas the academic experts had more than 10 years on average of academic experience and were researchers in the digital servitization area (see Appendix B for their profiles). Considering the number of experts, our sample is in line with other recent articles using a similar research design such as Kumar et al. (2015), Kamble et al. (2018), and Mota et al. (2021), varying from 12 to 14 expert responses. Additionally, we also requested interviews with the industry experts (who had responded to the questionnaire) to gather empirical evidence about the service innovation practices in their companies and to discuss the relationships between digitalization and ecosystem-related capabilities. In total, six interviews were conducted, lasting between 60 and 90 min each. The data collection and interviews were conducted in March and April 2021.

3.3. *ISM method*

Initially introduced by Warfield (1974), Interpretive Structural Modelling (ISM) allows measurement of the interrelationships among elements involved in a specific problem, having been widely used to establish order and direction in the complex relationships among the elements of a system (Sage, 1977). Given that the ISM represents a finite set of n elements in a system represented by $S = (s_1, \ldots, s_i, \ldots, s_n)$, the SSIM encompasses pair-wise comparisons of elements (s_i and s_j) of the system under consideration, evaluating whether one element leads to achieving another (Muruganantham et al., 2018). In this study, the SSIM contained 18 capabilities (digitalization and ecosystem-related capabilities). We were also interested in uncovering how these capabilities can contribute to manufacturer performance (mainly, service innovation performance). Therefore, we included the other three elements related to performance; which resulted in a 21 × 21 matrix, and the experts were asked to fill in each pair of elements in this matrix using the following codes:

V: the element i will lead to the achievement of the element j;
A: the element j will lead to the achievement of the element i;
X: the elements i and j will lead to the achievement of each other; and.
O: the elements i and j are unrelated to each other.

After collecting the experts' responses, we unified the 12 SSIM matrices obtained based on the recommendations made by Muruganantham et al. (2018), generating a unified SSIM in which each matrix entry is given by the most frequent code in the experts' responses. Next, the unified SSIM matrix was converted into a binary matrix (Initial Reachability Matrix)—in which it is possible to verify the type of relationship between each pair of elements—according to the following steps:

(1) If the entry (i, j) in SSIM is V, then, in the reachability matrix, the entry (i, j) is 1 and the entry (j, i) is 0;
(2) If the entry (i, j) in SSIM is A, then, in the reachability matrix, the entry (i, j) is 0 and the entry (j, i) is 1;
(3) If the entry (i, j) in SSIM is X, then, in the reachability matrix, the entries (i, j) and (j, i) are 1;
(4) If the entry (i, j) in SSIM is O, then, in the reachability matrix, the entries (i, j) and (j, i) are 0; and
(5) The elements of the main diagonal are assigned a 1, since i and j are equal.

In the following, we verified the *Initial Reachability Matrix* transitivity to develop the *Final Reachability Matrix* according to Muruganantham et al. (2018). Transitivity occurs when: if A is related to B and B is related to C, then A is necessarily related to C. In the *Final Reachability Matrix*, the pairs of elements marked with the symbol 1* represent those obtained from the transitivity condition. Lastly, the *Final Reachability Matrix* allowed the verification of the *driving power* and *dependence power* of each element, by adding the values of rows and columns, respectively, in the matrix. Driving power reflects how much one element (e.g., capability) drives the ones it relates to; whereas the dependence power reflects how much one element (e.g., capability) depends on other elements it relates to. Thus, it was possible to group the elements into different partition levels, establishing a hierarchy of the investigated elements. Noteworthy, the elements that have the same level of reachability and intersection are placed at the same level of the ISM hierarchical model (Muruganantham et al., 2018).

3.4. *Fuzzy MICMAC method*

In conjunction with the ISM, the Fuzzy MICMAC method has been used because it enables the fuzzification of the intensity of the relationship between two elements based on the experts' response frequencies (Bhosale and Kant, 2016), thus being an alternative to overcome the binary approach of the ISM (Bhosale and Kant, 2016; Muruganantham et al., 2018). Due to this reason, it was used in this paper.

First, we replace all diagonal entries (where i and j are equal) in the Initial Reachability Matrix with zero to develop the initial *Binary Direct Reachability Matrix* (BDRM), keeping the other matrix values. Next, we analyzed the strength of each relationship between elements. In this sense, the strength of the investigated elements is not only represented in a binary way but on a 0–1 scale, as shown in Table 2. It also presents the assignment rules that were used for establishing the fuzzy-based relationships as suggested by other studies (Kamble et al., 2018; Mota et al., 2021). Then, we determined the *Frequency Direct Relationship Matrix* based on the experts' response frequency. For each matrix entry, we counted how many experts answered that element i leads to the achievement of element j, and we multiplied by the value of the respective entry in BDRM.

In sequence, we defined the *Fuzzy Direct Reachability Matrix* (FDRM). For this, the Frequency Direct Relationship Matrix and the fuzzification rules in Table 2 were used. Thus, to define the FDRM, each Frequency Direct Relationship Matrix entry was transformed into the values present in the second column of Table 2, according to the rules of the third column. Finally, we used the max-min function determined by Equation (1), proposed by Kandasamy et al. (2007), to determine the *Fuzzy MICMAC Stabilized Matrix*. With the help of a MATLAB program, this function was used to repeatedly multiply the FDRM until the hierarchies of driving power and dependence were stabilized, enabling its conversion to the Fuzzy MICMAC Stabilized Matrix.

$$T = U.V = \max n \left[\min(x_{in},\ y_{nj})\right] \tag{1}$$

where, $U = x_{in}$ and $V = y_{nj}$.

Similar to the ISM technique, to obtain the driving power of each element, the entries in the corresponding row in the Fuzzy MICMAC Stabilized Matrix were summed; then, to obtain the dependence power of each element, the entries in the corresponding column were added. The analysis with the aid of the MICMAC approach is depicted with the support of a cluster diagram (Bhosale and Kant, 2016; Muruganantham et al., 2018). Thus, the capabilities and performance measures were classified into four clusters (autonomous, dependent, linkage, and independent), based on their driving and dependence power.

Table 2
Fuzzy scale and assignment rules to define the strength of the antecedents.

Strength	Value assigned	Number of experts agreed that element *i* enables/ enhances element *j*
No	0	0–6
Weak	0,25	7–8
Average	0,5	9–10
Strong	0,75	11
Very strong	1	12

4. Results

4.1. Digitalization and ecosystem-related capabilities

A preliminary list of capabilities contained 32 digitalization and 24 ecosystem-related capabilities. This list was further refined by three academic experts (not included in the final group of experts). Based on their judgments, similar capabilities were merged since they represented the same competence (e.g., monitoring of processes, products, and services), and less frequently cited capabilities (e.g., financial transaction, mass customization, and collaboration with financial agents) were not considered. Exclusion of these capabilities was motivated by two main reasons: (i) to focus on the main capabilities and (ii) to keep a manageable set of elements to perform the ISM and Fuzzy MICMAC methods. Three additional performance measures (mainly, service innovation measures) were also included to evaluate their relationships with digitalization and ecosystem-related capabilities. As a result, a final list of 21 elements (11 digitalization capabilities, seven ecosystem-related capabilities, and three service innovation performances) was considered for investigation using the ISM technique. These elements, respectively, are shown in Tables 3–5.

4.2. ISM results

Twelve SSIMs were obtained from the experts' responses. In this subsection, we present the unified SSIM (Table C1), the Initial Accessibility Matrix (Table C2), the Final Accessibility Matrix (Table C3), and the Level Partition (Table C4). All ISM tables are shown in Appendix C.

4.3. Fuzzy MICMAC results

Following the procedures shown in subsection 3.4, we present the Binary Direct Reachability Matrix (Table D1), the Frequency Direct Relationship Matrix (Table D2), the Fuzzy Direct Reachability Matrix (Table D3), and the Fuzzy MICMAC Stabilized Matrix (Table D4). All Fuzzy MICMAC tables are shown in Appendix D.

5. Discussion

Initially, the ISM and Fuzzy MICMAC results are discussed separately and, later, a conceptual framework integrates all of the findings.

5.1. The ISM results

Fig. 2 presents the ISM model, which depicts the investigated elements into five levels (see Table C4). At the lowest level (Level V), we have the majority of the digitalization capabilities and two ecosystem-related capabilities (*collaboration with service partners - EC3,* and *research institutions - EC4*). This result shows a strong interrelationship among the digitalization capabilities because they were placed at the same level. Thus, they can be considered as *base capabilities* encompassing technical digitalization aspects. In particular, they allow connectivity (e.g., *automation - DC6*, *real-time operations - DC3*, *data collection - C1*, *data transmission - DC2,* etc.) and intelligence (e.g., *monitoring - DC4*, and *security - DC11*) for the system. Noteworthy, the two ecosystem-related capabilities at this level refer to the collaboration with knowledge and technology developers such as universities/research centers (Kahle et al., 2020) and knowledge-intensive business services (Gebauer et al., 2013; Sklyar et al., 2019). Thus, agricultural machinery manufacturers rely on collaborations with these ecosystem actors to gather and enhance their digitalization capabilities.

Capabilities such as *predictive analysis (DC8)*, *collaboration with suppliers (EC2),* and *servitization (EC7)* are placed at Level IV. Interestingly, *incremental service innovation (SI1)* is also at this level. These results indicate that the capabilities at Level V led to the predictive analysis capacity and collaboration with suppliers, which are necessary to improve the final product availability, cost reductions, and the development of product-related service innovations (Feng and Ma, 2020; Markovic et al., 2020; Pagoropoulos et al., 2017). The servitization capability also suggests the opportunity to invest in product- and customer-related services enabled by the infusion of digital technologies (Bustinza et al., 2019). Therefore, this bottom-up second level encompasses capabilities that support the provision of services and the integration of the value chain (Gölgeci et al., 2021). Thus, agricultural machinery manufacturers can predict future failures in their products in advance, enabling preventive maintenance and availability (Bueno

Table 3
Digitalization capabilities.

Capabilities	#	Description	Key representative references
Data collection	DC1	Capability to collect real-time data from different types of sources such as products, customers, processes, etc.	Al-Jaroodi et al. (2020); Barlette and Baillette (2020).
Data transmission	DC2	Capability to transmit data, facilitating data flow, information sharing, and knowledge exchange.	Fatorachian and Kazemi (2021); Miranda et al. (2019); Ritter and Pedersen (2020).
Real-time operations	DC3	Capability to perform real-time operations such as the interventions in processes, products, and data access.	Bueno et al. (2020); Mohamed et al. (2019).
Monitoring of processes, products, and services	DC4	Capability to monitor the performance of processes, products, and services.	Ardolino et al. (2018); Fatorachian and Kazemi (2021); Miranda et al. (2019).
Data analysis	DC5	Capability to analyze data and extract information to support the decision-making process and establish competitive advantage.	Al-Jaroodi et al. (2020); Barlette and Baillette (2020).
Automation	DC6	Capability to automate production and standardize operations or assign automatic functions to machines, increasing their repeatability and reducing human errors.	Al-Jaroodi et al. (2020); Ardolino et al. (2018); Frank et al. (2019a).
Interoperability	DC7	Capability to interconnect different physical objects (e.g., devices, machines, and systems), facilitating data exchange without human intervention.	Al-Jaroodi et al. (2020); Bueno et al. (2020); Miranda et al. (2019); Mohamed et al. (2019).
Predictive analysis	DC8	Capability to employ advanced analytics to make predictions about unknown future events.	Ardolino et al. (2018); Bueno et al. (2020); Fatorachian and Kazemi (2021).
Virtualization	DC9	Capability to transform physical elements into virtual reality, facilitating the visualization of the process and product performance.	Frank et al. (2019a); Mohamed et al. (2019).
Human-machine interaction	DC10	Capability to facilitate interaction between people and machines.	Miranda et al. (2019); Pacaux-Lemoine et al. (2017).
Data security	DC11	Capability to protect the privacy of data and ensure security in data management.	Lohmer et al. (2020); Mohamed et al. (2019); Redelinghuys et al. (2020).

Table 4
Ecosystem-related capabilities.

Capabilities	#	Description	Key representative references
Collaboration with customers	EC1	Capability to collaborate and co-create with customers to understand their needs, reduce uncertainties, develop cooperative activities and contribute to their performance.	Gebauer et al. (2013); Yin et al. (2020).
Collaboration with suppliers	EC2	Capability to collaborate with suppliers in the supply and distribution chain (e.g., suppliers, distributor, and other partners).	Gebauer et al. (2013); Kaufmann and Tödtling (2001); Yin et al. (2020).
Collaboration with service partners	EC3	Capability to collaborate with service providers, (i. e., partners specialized in distribution, consulting, installation, maintenance, IT, security, and logistics, among others).	Gebauer et al. (2013); Kaufmann and Tödtling (2001).
Collaboration with research institutions	EC4	Capability to collaborate with research institutions and technology centers/ universities that provide scientific and technological knowledge for service innovation.	Kahle et al. (2020); Yin et al. (2020).
Risk management	EC5	Capability to identify, mitigate or share risks involving in the provision of smart solutions.	Bustinza et al. (2019); Kahle et al. (2020).
Collaboration with governments	EC6	Capability to collaborate with government agencies, which act as legislators (policymakers) influencing institutional norms.	Planko et al. (2017); Xie and Wang (2021); Yin et al. (2020).
Servitization capability	EC7	Capability to seize and provide advanced services and service solutions based on smart products.	Weigel and Hadwich (2018); Windahl and Lakemond (2006).

Table 5
Service innovation performance.

Performance measures	#	Description	Key representative references
Incremental innovation	SI1	Capability to develop incremental service innovations.	Gallouj and Weinstein (1997).
Radical innovation	SI2	Capability to develop radical service innovations.	Gallouj and Weinstein (1997); Snyder et al. (2016).
Financial performance	SI3	Capability to achieve financial performance based on digital servitization (e.g. increased sales of services, revenues, etc.).	Wang et al. (2018).

et al., 2020; Fatorachian and Kazemi, 2021).

Two ecosystem related-capabilities (i.e., *collaboration with customers - EC1*, and *risk management - EC5*) and *radical innovation (SI2)* are placed at Level III, suggesting that the prior capabilities (focused on capturing value through efficiency and incremental service innovations) contribute to the provision of advanced services, which, in turn, require proximity with customers and a capacity to assess different types of risks (e.g., operational, relational, and financial). Thus, manufacturers seeking the development of advanced services (e.g., customer-support agreements, risk-and-reward-sharing contracts, and revenue-through-use contracts) should focus on customer knowledge and underpin accurate risk management to achieve customer value (Bustinza et al., 2019; Tronvoll et al., 2020).

Level II is composed of the ability to collaborate with governments, reinforcing that the ecosystem approach comprises the three dimensions of the innovation triple helix: (i) the knowledge sector, (ii) private sector, and (iii) government sector (Frank et al., 2019b). Government agencies can provide subsidies for innovations by implementing regulations (Planko et al., 2017), or by creating the necessary infrastructure (e.g., high-speed internet) for industry 4.0 (Xie and Wang, 2021). At this stage, the government would act as an external supporter, providing funds and policies for the consolidation of the innovation ecosystem. Nevertheless, ecosystem capabilities related to other ecosystem actors (e.g., research centers, service partners, suppliers, and customers) seemed more important to the interviewed experts.

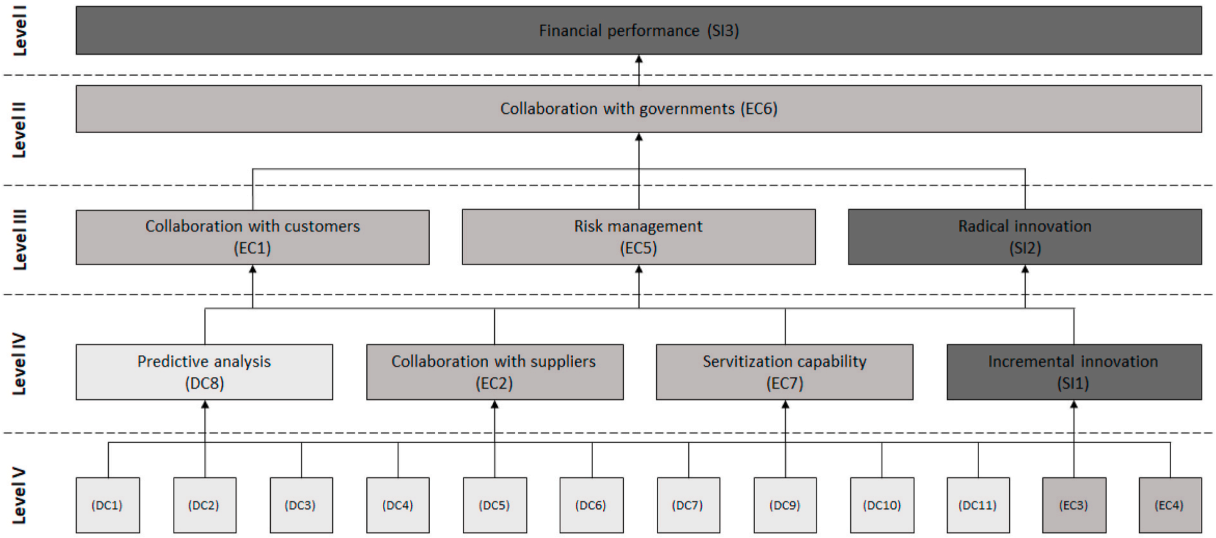
Finally, at the highest level (level I) is the expected financial performance achieved by the development of prior capabilities. Indeed, several studies (e.g., Gebauer et al., 2021; Kohtamäki et al., 2020) discuss the called digital servitization paradox, in which product companies invest in digitalization and servitization, but fail to enhance their revenue accordingly. Therefore, our results show that, according to the experts, the development of the previous capabilities would be necessary to achieve financial returns with digital servitization.

5.2. *Fuzzy MICMAC results analysis*

Based on the results presented in section 4.3, Fig. 3 shows the driving and dependence power of digitalization and ecosystem-related capabilities. In a fuzzy MICMAC analysis, the capabilities were classified into four clusters: independent (I), linkage (II), dependent (III), and autonomous (IV).

Quadrant I clusters eight capabilities that show high driving power and low dependence power: the independent elements. They have a driving nature and capacity to significantly affect other capabilities (Muruganantham et al., 2018). Based on the proximity of these capabilities, we can split them into two sub-clusters. The first one includes capabilities such as *data collection (DC1), data security (DC11),* and *collaboration with research institutions (EC4)*, which have lower dependence power (i.e., they are less influenced by other elements). Among the capabilities placed at level V of the ISM model (see Fig. 2), they represent primary capabilities (Andres et al., 2021). In particular, they allow raw data integration (Al-Jaroodi et al., 2020; Barlette and Baillette, 2020) as well as ensure cybersecurity to address customer concerns (Redelinghuys et al., 2020). Collaboration with universities and research centers provides scientific knowledge to implement precision agriculture, which helps smart product manufacturers that collect raw data (Ozdogan et al., 2017). One of the interviewed experts, a CEO (e9), stated, *"Innovation does not exist without this interaction. We are talking about technological development, [and] bringing all [of] this intellectual capital into the company is unfeasible. If you want to follow, you only have one path: don't disconnect from the university."*

Other capabilities placed at Level V of the ISM model are in the second group of Quadrant I (*data transmission - DC2*, *automation - DC6*, *interoperability - DC7, virtualization - DC9*, and *collaboration with service partners - EC3)*. These capabilities relate to data processing, which requires data-driven applications such as virtualization, transmission, and interoperability of data, and which supports more advanced digitalization capabilities. For instance, the virtualization capability drives remote monitoring and control of agricultural operations, enabling the real-time identification of potential problems (Pylianidis et al., 2021). As the senior designer in product development (e4) illustrated, *"You can map the field. For example, if you are going to fertilize a certain area or correct the soil, you can collect data in various regions of that area where you are going to plant: soil pH, what is needed to treat the soil, [and] what fertilizer is missing. You can put this data into a program and your machine, when applying fertilizer or soil correction, can apply it there, via satellite."* Furthermore, manufacturers can rely on service partners that provide



Notes

(DC1) Data collection
(DC2) Data transmission
(DC3) Real time operations
(DC4) Processes, products and services monitoring
(DC5) Data analysis
(DC6) Automation
(DC7) Interoperability
(DC9) Virtualization
(DC10) Human-machine interaction
(DC11) Data security
(EC3) Collaboration with service partners
(EC4) Collaboration with research institutions

Fig. 2. ISM model.

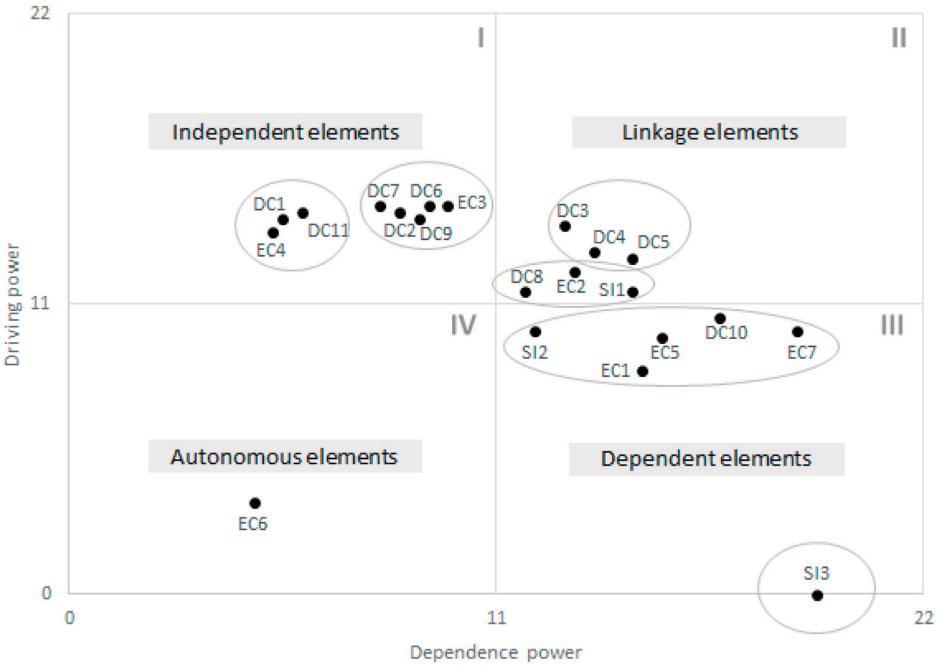


Fig. 3. Cluster diagram of the fuzzy MICMAC.

specialized knowledge-intensive services for developing precision agriculture (Zhang, 2016) and, for that reason, this capability is placed at this cluster. On this topic, the CEO (e9) commented, *"One of our partners works with highways, counting cars and tires, and measuring their speed. What he knows is useful for me in agriculture. I know about agriculture, he knows about his area, and we put this knowledge together to create another [area]. It's a co-created product."*

Quadrant II clusters six capabilities showing high driving power and high dependence: the linkage elements. They are strongly interconnected, meaning that any change occurring to these capabilities will affect the other ones (Muruganantham et al., 2018). Based on their driving power, we can split them into two sub-clusters (see Fig. 3). The first one (higher driving power) includes capabilities such as *real-time operations (DC3), process, product, and service monitoring (DC4),* and *data analysis (DC5).* These capabilities were also placed at Level V (see Fig. 2). Together, they allow real-time monitoring of agricultural equipment operations (Cedeño et al., 2018; Kaňovská and Tomášková, 2018). Moreover, it is possible to perform advanced data analysis to increase product availability and performance (Kaňovská and Tomášková, 2018). Regarding this, one expert (e5) noted, *"Today, some products have embedded electronics that can transmit a lot of information to the company itself in real-time, the so-called telemetry. For a self-propelled* *machine, for example, you can monitor its operation: engine rotation, oil pressure, temperature. The company can monitor the product for the customer in real-time and get a lot of information.*"

The second group is formed, mainly, for capabilities that were placed at Level IV of the ISM model (e.g., *predictive analytics - DC8*, and *collaboration with suppliers - EC2),* which reinforces that they are influenced by lower-level capabilities (see Fig. 2) and by other linkage elements as well. Specifically, through monitoring and data analysis, services based on prediction, adaptive control, and optimization of the product/system in the field can be provided (Bueno et al., 2020; Fatorachian and Kazemi, 2021; Frank et al., 2019b; Pagoropoulos et al., 2017; Zheng et al., 2018). Furthermore, collaboration with suppliers is necessary to achieve vertical integration and to support smart solutions (Chen et al., 2021; Sklyar et al., 2019). Thus, these two capabilities contribute to the development of *incremental innovations (SI1)*, improving the manufacturing firm's product and process performance (Chen et al., 2021).

Quadrant III also clusters six capabilities: the dependent elements, showing low driving power but high dependence power. By nature, they are more performance-oriented elements and highly dependent on other capabilities included in the system (Muruganantham et al., 2018). Based on their driving power, we can split them into two groups (see Fig. 3). The larger of the two groups consists of customer-oriented capabilities: *collaboration with customers (EC1)*, *risk management (EC5)*, and *servitization (EC7)*. Digitalization facilitates new types of interaction with customers, which, in turn, enables the offering of advanced services (Cenamor et al., 2017; Shah et al., 2020). In doing this, manufacturers assume activities and, hence, risks that were usually internal to the customer (Cenamor et al., 2017). Thus, how to evaluate and mitigate risks refers to an essential capability for digital servitization, mainly for radical service initiatives (Chen et al., 2021; Tronvoll et al., 2020). This reasoning would explain the customer orientation of these capabilities and their connection with *radical service innovation (SI2)*. Interestingly, *human-machine interaction (DC10)* is the only digitalization capability in this group. In precision agriculture, constraints (e.g., bad connectivity in agricultural scenarios, harsh field conditions, lack of users' digital competencies, etc.) make the interactions between users and interfaces (e.g., machine visual boards, digital platforms, and mobile applications) a concern for manufacturers (Bowen and Morris, 2019). For instance, *"In Brazil, usually the large production areas are the most distant places, where there is not a good cell signal, thus limiting the service provided,"* as the senior designer in product development (e4) reported. Thus, the human-machine interaction capability seems to be important for innovative solutions, which might justify its position in this quadrant.

The *financial performance (SI3)* is found in Quadrant III, positioned in an isolated position due to its lower driving power. This is an outcome-oriented element, resulting from the offer of advanced service solutions by manufacturers. By offering customer-focused solutions, agricultural machinery manufacturers aim to create customer loyalty, and, mainly, new sources of revenues and profitability. However, the results indicate that they require all of the other capabilities to achieve the economic viability of precision agriculture and overcome the digital servitization paradox.

Finally, quadrant IV clusters those capabilities with low driving power and low dependence: the autonomous elements. Thus, they are disconnected from other elements (Kumar et al., 2015; Muruganantham et al., 2018). Based on the results, only one capability appears in this quadrant. In the Brazilian context, the ability to *collaborate with governments (EC6)* has a low impact on the practices of digital servitization, indicating that the policies and incentives provided by this stakeholder have little influence on the development of digitalization and advanced services.

5.3. *Conceptual framework*

Fig. 4 integrates the previous results into a conceptual framework. The investigated capabilities that we display are based on their position in the ISM hierarchy and their driving and dependence power in the Fuzzy MICMAC diagram. In doing so, the capabilities are presented as a progressive journey that can guide the implementation of digitalization and ecosystem-related capabilities. We are not proposing this framework as the ideal stages of capability development, but rather as a potential roadmap based on the experts' opinions. Moreover, the model considers expected results during the capability progressive development. Next, we discuss the capabilities present in the framework according to each stage.

The *driving layer* comprises capabilities possessing higher driving power and, therefore, they can influence other capabilities. We split

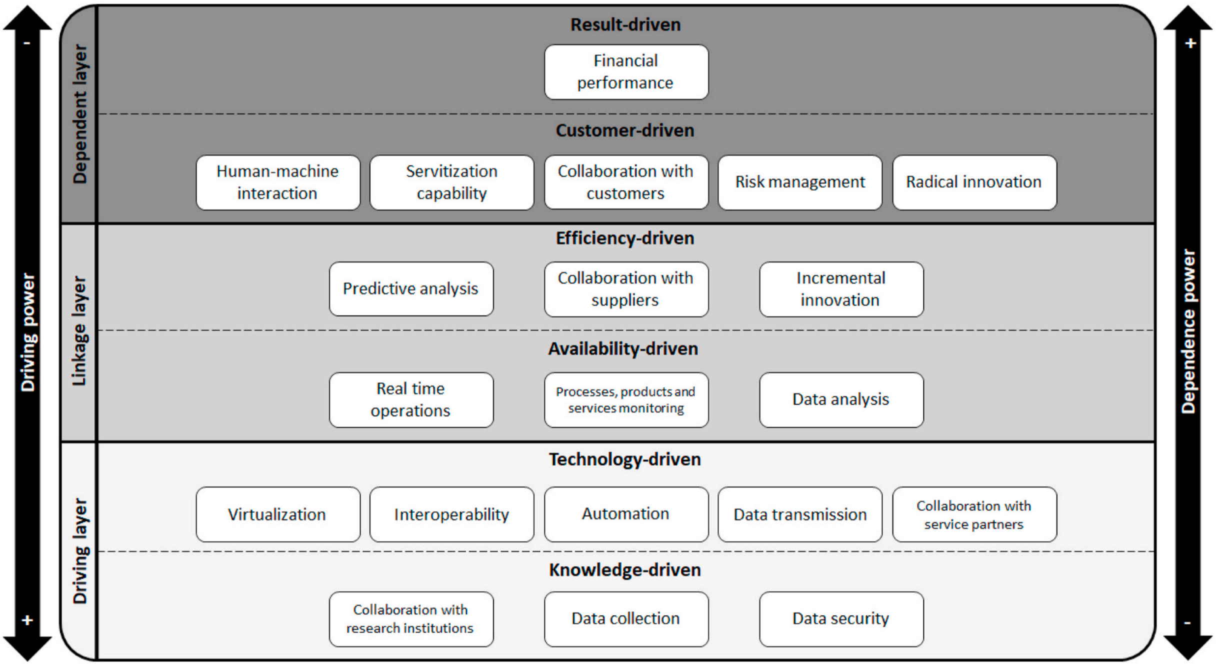


Fig. 4. Framework of the journey to innovation in digital services.

them into two sub-layers based on their progression: a knowledge-driven and technology-driven sub-layer. This result is aligned with Andres et al. (2021) who argue that the data integration between actors is also divided into two levels: the first one is based on raw data and the second on processed data. The knowledge-driven sub-layer represents the ability of agricultural machinery manufacturers to configure smart products to capture data with low human intervention, and to ensure security aspects (e.g., trust, ethics, and data ownership) on data collection (e.g., Al-Jaroodi et al., 2020; Barlette and Baillette, 2020). These capabilities require investment in IoT technologies (e.g., sensors and other connectivity artifacts) and close collaboration with knowledge developers that help the manufacturers to implement the digitalization capabilities (Kahle et al., 2020). In the technology-driven sub-layer, capabilities advance from value-based on information and knowledge towards value-based on technological capabilities related to Industry 4.0 solutions. Thus, virtualization, interoperability, automation, and data transmission capabilities appear at this level, calling for the most advanced technologies (e.g., big data analytics in machinery, cloud computing, machine-to-machine communication, smart services, etc.). In particular, these capabilities emphasize the ability to exchange data and coordinate activities with other digital assets/partners (Frank et al., 2019a). Moreover, they allow the integration of physical and virtual objects (e g., machine vision, digital manufacturing, virtual commissioning, virtual or augmented reality, etc.) to form the so-called Cyber-Physical (Frank et al., 2019a). Virtualization is also an effective digital tool for smart products development because it enables manufacturers to carry out many simulations to assess product maintainability, which improves the machine's performance throughout its lifecycle (Guo et al., 2018). To support the development of these capabilities, agricultural machinery manufacturers should interact with service partners due to their expertise in knowledge-intensive services and technologies (Zhang, 2016).

The *linkage layer* encompasses capabilities that leverage the agricultural machinery manufacturer's strategy to become an availability provider (Ardolino et al., 2018; Chen et al., 2021; Pagoropoulos et al., 2017). This layer is also split into two more sub-layers: an availability-driven and efficiency-driven sub-layer. First, the provision of availability requires effective monitoring, control, optimization, and data analysis to support products and product-related services, which result from the capabilities (e.g., real-time operations, monitoring, and data analysis) placed at the first, information-driven sub-layer. For instance, agricultural equipment with real-time data transmission makes it possible to monitor its operation conditions and predict future breaks (Kaňovská and Tomášková, 2018). In line with Chen et al. (2021), our findings also suggest that the development of these capabilities lays the foundation for more advanced product-related services and improving efficiency across the supply and distribution chains. This is represented by the second, efficiency-driven sub-layer. Here, analytical algorithms support the performance of predictive diagnostics, allowing the optimization of smart products and, therefore, the improvement of their performance. To support the value proposition expansion, collaboration with suppliers has to be expanded since they provide complementary knowledge to achieve availability (Feng and Ma, 2020; Markovic et al., 2020). Moreover, this expansion also involves new partners in the ecosystem due to the diverse set of components, services, and digital interfaces that are required for smart solutions (Chen et al., 2021). As a result, data generated by the digitalization capabilities and collaboration with partners can shorten innovation cycles and trigger incremental innovations.

The *dependent layer* includes capabilities that are strongly dependent on other capabilities, separated into two more sub-layers. The first, customer-driven sub-layer emphasizes higher digitalization and ecosystem-related capabilities (e.g., servitization, collaboration with customers, and risk-management) that enable manufacturers to provide customer-oriented smart solutions (Cenamor et al., 2017; Tronvoll et al., 2020). This requires increased proximity, trust, and relationship with the customers to understand their broader needs (Tronvoll et al., 2020) and, hence, shows a more strategic nature that drives radical service innovation (Kamalaldin et al., 2020). By collaborating with customers, the manufacturer can make them solution co-creators, enabling market segmentation and the opportunity to offer more customized services (Sjödin et al., 2020). Our findings are in line with Shah et al. (2020), suggesting that the provision of advanced services demands stronger collaboration with customers, while collaborating with suppliers leads more to the provision of basic services. In the precision agricultural sector, this represents smart products that act as a platform for advanced customized services such as spatial and longitudinal analysis to evaluate regions for agricultural operations, data management systems, digital platforms for sharing information, autonomous machines, and performance-based contracts (Ozdogan et al., 2017). Therefore, digitalization capabilities foster collaboration with customers and servitization capabilities, which, in turn, lead to more services. Ultimately, this increases financial performance results, shown by the result-driven sub-layer at the top of the framework. Here, the agricultural equipment manufacturer ensures greater product loyalty, an increase in its market value, revenues, and profitability by seeking digital servitization (Kaňovská and Tomášková, 2018).

6. Conclusions, limitations, and recommendations for future research

This study aimed to investigate the relationship between digitalization and ecosystem-related capabilities for seeking digital servitization among agricultural machinery manufacturers in Brazil. A multi-method research approach based on the systematic literature review, ISM technique, and MICMAC fuzzy analysis was employed. As a result, digitalization and ecosystem-related capabilities were identified and validated by experts. Moreover, we also demonstrate the relationships between these capabilities as well as their driving and dependence powers. Finally, we developed a conceptual framework that shows levels of adoption of the investigated capabilities and their implication for the implementation of service innovations in digital servitization. These results offer important contributions to digital servitization literature, and they provide valuable orientation for managers on the path to digital servitization.

6.1. Theoretical contributions

The present study has four theoretical contributions. First, prior studies have emphasized separated sets of capabilities for digital servitization (e.g., Lenka et al., 2017; Lütjen et al., 2019). In the same vein, studies have highlighted the partnerships in ecosystems (Kohtamäki et al., 2019; Sklyar et al., 2019) but they have not clarified the role of each ecosystem actor in advancing the digitalization capabilities. Although inter-firm collaboration is seen as a key source for the success of digital servitization, this theme is still incipient in digital servitization literature, while in other research fields (e.g., supply chain management), it is already a mature concept (Chen et al., 2021; Kohtamäki et al., 2019). Thus, we demonstrate the interrelationships between digitalization and ecosystem-related capabilities, and we highlight that the collaboration with the ecosystem actors has different emphasis aligned with the progression of digitalization capabilities and the type of service innovation.

Second, we answer the call for holistic approaches for digital servitization implementation (Paschou et al., 2020). Thus, based on a capability-based perspective, we propose a conceptual framework which establishes that: (i) the interplay between digitalization and ecosystem-related capabilities progresses throughout three macro-layers (driving, linkage, and dependent); (ii) within each layer, the main capabilities support service innovation and, consequently, digital servitization implementation; and (iii) the distinction between the layers and their elements are made based on the nature of their driving and dependence power. Thus, our study contributes to the prior literature by describing the stages that manufacturers (i.e., agricultural machinery manufacturers) go through as they reconfigure specific digital servitization capabilities.

A third contribution refers to the investigation of digital servitization in specific contexts (Paschou et al., 2020; Rabetino et al., 2018), and in this case, focuses on the agricultural machinery industry in Brazil as a representative sector of an important emerging economy. Digital servitization diffusion and adoption in Brazil is still behind the expected competitive levels. Such a problem is corroborated with a recent survey that indicates 84% of the Brazilian farmers use at least one type of digital technology, but this percentage decreases as the level of the application's technological complexity increases (Bolfe et al., 2020). Moreover, the cost of purchasing machinery and applications, problems with connectivity in rural areas, and lack of government investments in rural infrastructure are problems that prevent the development of Industry 4.0 in Brazil (Bolfe et al., 2020; Mantovani et al., 2019). Thus, our findings aimed to understand how value is co-created in precision agriculture and how the digitalization capabilities progress, which is essential for Brazil to keep its position as one of the export leaders in several crops.

Lastly, a fourth contribution is the use of quantitative research in the field of digital servitization research, which currently primarily utilizes qualitative research methods (Paschou et al., 2020; Rabetino et al., 2018). Thus, by making use of a multi-method approach with the ISM and Fuzzy MICMAC, this study explores the driving power and dependence relationships between digitalization and ecosystem-related capabilities for service innovation in agricultural machinery manufacturers. The results help researchers to understand how these capabilities reinforce service innovation, and they can also be used for different types of abductive investigations. For example, researchers are encouraged to complement or make new integrations of the identified capabilities. Furthermore, this study reinforces the digitalization calls for an ecosystem approach in digital servitization (Chen et al., 2021; Tronvoll et al., 2020).

6.2. *Managerial contributions*

This study offers several managerial implications. First, the study identified 11 digitalization and seven ecosystem-related capabilities. Thus, managers can focus on these capabilities to better develop digital servitization in their firms. Second, the study provides the relationships between the identified capabilities in the context of agricultural machinery manufacturers, categorizing them according to their driving power and dependence. Thus, managers can understand the mutual influence of these capabilities and how certain ecosystem actors contribute to the development of digitalization capabilities and service innovations. Third, our conceptual framework serves as a guide for the development of digital servitization capabilities in agricultural machinery manufacturers. For instance, managers could: (i) build knowledge based on primary digital technologies and collaboration with knowledge developers; (ii) advance their technical capabilities to strengthen the digitalization of their value creation processes; (iii) enhance the availability strategy based on data monitoring and analysis; (iv) reinforce their digitalization capabilities and collaboration with partners to provide product-related services and trigger incremental innovations (efficiency-driven); (v) develop higher ecosystem-related capabilities focused on customer orientation and advanced services; and (vi) monitor results to overcome the digital servitization paradox. Furthermore, this systematized view may also support managers in auditing their current DS capabilities for future improvements.

6.3. *Limitations and future research*

This study presents some limitations that can be considered as opportunities for future research. First, although we tried to be comprehensive in our list of capabilities, other capabilities may have an impact on service innovation and digital servitization. Thus, future research can assess the interrelationship between different capabilities. Second, we interviewed experts from agricultural machinery manufacturers in Brazil. Consequently, our findings should be carefully considered in other contexts. Thus, future research may investigate other industrial sectors and countries. Third, the development of the fuzzy MICMAC and ISM model was based on the subjective judgment of academics and industry experts. Consequently, in this study, the final result may be influenced by any bias in the experts' judgment. However, we tried to avoid this problem by carefully selecting our group of experts. Other types of empirical research (e.g., survey) can also be employed in future works. Finally, the proposed conceptual framework can be improved based on empirical evidence regarding its contribution to digital servitization.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

CRediT authorship contribution statement

Guilherme Sales Smania: Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Glauco Henrique de Sousa Mendes:** Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Moacir Godinho Filho:** Conceptualization, Validation, Writing – review & editing. **Lauro Osiro:** Methodology, Software, Formal analysis, Data curation, Writing – review & editing. **Paulo A. Cauchick-Miguel:** Conceptualization, Validation, Writing – review & editing. **Wim Coreynen:** Conceptualization, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130982.

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