

# Technological trends in digital agriculture and their impact on agricultural machinery development practices

## Tendências tecnológicas no cenário da agricultura digital e seus impactos nas práticas de desenvolvimento de máquinas agrícolas

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**ABSTRACT** - As the world's population grows, agriculture is facing an increasing demand for productivity, efficiency, and sustainability to ensure food security. The adoption of a production system similar to that of Industry 4.0 is considered to be a way to address this problem in agriculture. This approach can be seen in precision agriculture. This new technological trend has an impact on agricultural machinery and the way it is designed. Therefore, the objective of this article is to provide an overview of digital systems in agricultural machinery and their impact on equipment design processes in a developing digital agriculture scenario. Digital devices are already present in several types of equipment, performing or supporting tasks such as automatic steering and variable-rate applications. In addition, a large number of sensors monitor the crops, environment, production losses, and operational parameters in real time. Technological breakthroughs, however, are the adoption of emerging alternatives such as IoT, electric power vehicles, and small autonomous machines, which are already being implemented in other areas. Consequently, the development process of agricultural machines now involves several specialty domains besides the usual mechanics, compelling companies to employ the transverse concurrent engineering of several specialties at the same design situation and moment.

**Key words:** Agriculture 4.0. Product development process. Embedded systems. Design collaboration.

**RESUMO** - À medida que a população mundial cresce, a agricultura enfrenta demandas cada vez maiores com relação à produtividade, eficiência e sustentabilidade para garantir segurança alimentar. A adoção de um sistema produtivo semelhante ao da Indústria 4.0 é considerada uma forma de enfrentar esse problema na agricultura. Esta estratégia pode ser observada na agricultura de precisão. Essa nova tendência tecnológica tem um impacto nas máquinas agrícolas e na maneira pela qual elas são projetadas. Assim, o objetivo deste artigo é fazer um apanhado dos sistemas digitais nas máquinas agrícolas e a maneira que eles afetam o processo de projeto desses equipamentos num cenário de agricultura digital em desenvolvimento. Dispositivos digitais já estão presentes em muitos equipamentos, desempenhando e dando suporte a tarefas como piloto automático e aplicações em taxas variáveis. Também uma grande quantidade de sensores monitoram a cultura, o ambiente, as perdas e parâmetros operacionais em tempo real. O avanço tecnológico, no entanto, é a adoção de alternativas emergentes como a IoT, veículos elétricos e pequenas máquinas autônomas, que já estão sendo empregadas em outras áreas. Consequentemente, o processo de desenvolvimento de máquinas agrícolas envolve agora diversos domínios do conhecimento além da mecânica comum, levando as empresas a empregarem engenharia simultânea transversal entre inúmeras especialidades ao mesmo tempo e para uma mesma situação de projeto.

**Palavras-chave:** Agricultura 4.0. Processo de desenvolvimento de produto. Sistemas embarcados. Projeto colaborativo.

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## INTRODUCTION

The use of digital technologies, including information and communication technologies, in agriculture and livestock has a broad spectrum of aspects. They comprise the widespread use of sensors for monitoring soil, crop, weather, location, and machinery states; collection of market information (costs, prices, suppliers, and consumers); data transmission; big data; artificial intelligence (AI) data analysis and decision-making; and customized operations employing typical agricultural machinery, drones, robots, and autonomous vehicles, spreading the use of the Internet of Things (IoT) in farming (KLERKX *et al.*, 2019; KUNISHI, 2016; NAVARRO *et al.*, 2020; ZAMBON *et al.*, 2019). Although the multiple objectives underlying this technological trend include more efficient systems for operator and environmental safety and reductions in process operating costs (ZAMBON *et al.*, 2019), the ultimate goal is related to food security, as stated by the Food and Agriculture Organization of the United Nations (FAO) in a briefing paper, highlighting the need for more productive, efficient, sustainable, inclusive, transparent, and resilient food systems to face the challenge of a 'world with zero hunger' by 2030 (TRENDOV *et al.*, 2019).

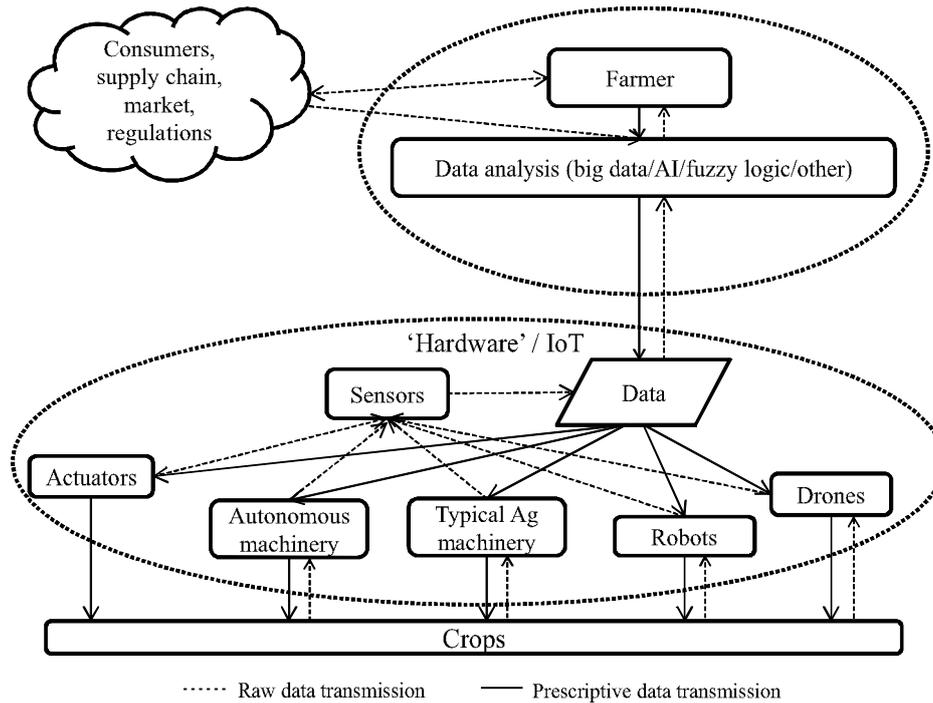
Klerkx *et al.* (2019) summarized a variety of terms used to describe the increasing adoption of digital technologies in agriculture: smart farming, precision agriculture (PA), precision farming, decision agriculture, digital agriculture, agriculture 4.0, and numerical agriculture. For the sake of clarity, the authors decided to employ the term digital agriculture to express this new technological wave. Looking at the key words in the papers cited in the present review, we found other terms such as robotic farming, intelligent agribusiness, and precision farming. Although discussing the formal definition of digital agriculture is beyond the scope of this article, it can be stated that it presents itself when two technologies merge together: PA and the Internet of farming. The interaction of both has the potential to improve crop yield and sustainability, develop better working conditions, and improve the quality of production and processing (ZAMBON *et al.*, 2019).

Some features of PA have a relatively long timeline in farm equipment. Examples of the adoption of electronics in one major agricultural machinery player typify this concept (HORVÁTH; SCHMITZ, 2019): on-board tractor computers for calculating the diesel consumption by hour or area (1984), yield monitor on combines (1991), automatic steering systems, application rate control based on prescription maps (in the 1990s), operational telemetry systems demonstrated in tractors (1999), and automatic steering systems offered by all major manufacturers (early

2000s). Agricultural machinery and other 'hardware' play an important role in the implementation of digital agriculture and new technological developments in this area. This has already been seen in PA with the use of tractor guidance systems, variable rate applications, and drones for data collection. Another key trend in agriculture is the application of robots for a multitude of tasks (TRENDOV *et al.*, 2019). In Figure 1, a schematic representation of this 'hardware' is shown along with other digital agriculture features. The data transmission components cannot be seen directly; however, they are present in every connection between elements in Figure 1, playing a prominent role in the entire system.

Global agricultural machinery manufacturers practice a formal design process within a greater context, usually called the product development process (PDP). Agricultural machine companies start developing their products after deciding to engage in a certain market for their intended product - for instance, a grain sowing machine could be designed for the sowing needs of the US, Brazil, and Latin American markets - as a result of a series of activities called the pre-development process (ROZENFELD *et al.*, 2006). Once the new product is aligned within the strategy plan, the organization undertakes the planning of the design process, thereby considering issues such as the project scope, schedule, team allocation and resources, budget, risk, acquisitions, and quality goals. This project planning activity usually becomes the first PDP stage for the agricultural machinery, delivering a project proposal to a steering committee that oversees the decision to proceed with the project (BERGAMO; ROMANO, 2016).

When the project plan is approved by the steering committee, the organization authorizes the work to start with contributions by all organizational areas with an interest in developing the intended machine and whose members cooperate during the project lifetime under a concurrent engineering approach. The design process of the agricultural machine takes place during the product development process along with the manufacturing design and marketing development, among other processes, to enable the commercial viability of the product (FACCO *et al.*, 2017). The design process constitutes part of the work that comprises the definition of the design requirements to translate farming needs into engineering characteristics, establishment of a design concept that includes the required functions and their working principles so that the machine will perform the expected operation, development of a product architecture with a layout of subsystems and components, and detailing the components with the bill of materials and respective part specifications, including the materials, geometry, and manufacturing process (ROMANO *et al.*, 2005).

**Figure 1** - Agricultural machinery-related digital agriculture. Source: own elaboration

Regarding design construction and prototyping, the industry has been engaging with digital design environments to enable a co-designing among their teams, partners, and suppliers and the virtualization of construction and testing with virtual prototypes (KARKEE *et al.*, 2011). Design teams now make extensive use of virtual collaboration environments with several design resources to increase the agility of development projects and to postpone the use of physical prototypes in the design process (GUTIERREZ; ARANGO, 2017; GRAIGNIC *et al.*, 2013). Virtual environments streamline the tasks of the manufacturing process and production design as well, supporting the implementation of manufacturing facilities that will produce the certification prototype and product to be launched.

The objective of this article is to provide an overview of digital systems in agricultural machinery and their impact on equipment design processes in a developing digital agriculture scenario in an attempt to envision possible changes in design practices, requirements, and techniques and to identify the challenges ahead. Although mechanization is usually present in greenhouses and other indoor farm activities as well as in livestock work, the machines involved in these sectors have different characteristics and mobility. Therefore, this paper concentrates on outdoor machinery.

First, we identify the mechanized farming operations and systems already working under the assumptions of a digital agriculture such as PA, including tractors, planters, sprayers, mechanical weeders, and harvesters (grain and forage). Then, we identify emerging technologies that can affect agricultural machinery functionalities, leading to the study of strategies for the agricultural machinery design process, considering this new paradigm. Lastly, we comment on the main findings related to machinery design and the design process itself.

## AGRICULTURAL MACHINERY AND SYSTEMS ALREADY WORKING UNDER DIGITAL AGRICULTURE

As we mentioned earlier, the use of electronics in farm machinery, especially tractors, began in the 1980s. Since then, the application of digital systems to improve functionalities in mechanized agricultural operations has become widespread. The reasons for this trend include agricultural input savings, operations timeliness, increased yields, safety, and environmental protection. However, these benefits will not be discussed here because they are well established. Instead, we will describe the digital technologies already in use in agricultural machinery to assess the challenges design teams are presently facing.

The machines employed for the planting and fertilization of annual crops have benefits from variable-rate application (VRA) technologies, automatic section control, and performance monitoring (VIRK *et al.*, 2020; ALAMEEN *et al.*, 2019; KEMPENAAR *et al.*, 2017; MANGUS *et al.*, 2017). With VRA, agricultural inputs are distributed according to the specific needs of different sites across fields. Two different approaches enable this technology: the most common relies on previously made prescription maps, and the other is based on real-time feedback from onboard sensors (ALAMEEN *et al.*, 2019). The use of VRA goes beyond grain crops; for example, modern potato planters can vary planting density based on soil maps, and fertilizer applications (base or N top dress) can be adjusted according to NIR sensor readings or biomass maps (KEMPENAAR *et al.*, 2017). In row-crop planters, manufacturers have adopted electronic drive seed metering systems to increase performances in irregularly shaped fields, which makes it possible to achieve individual row unit control, enabling many VRA techniques without additional hardware, including contour farming, overlapping control, and prescription seeding rates (MANGUS *et al.*, 2017). The combination of PA displays on tractors and VRA planter capabilities enables the precise real-time monitoring of planting operations as a means of managing risks and maintaining profitability (VIRK *et al.*, 2020).

The control of weeds by chemical or mechanical means is a complex issue that requires working with many technical, environmental, and social factors; perhaps this is one of the reasons why it has been greatly impacted by digital agriculture with its implementation of systems and equipment (SHAMKUWAR *et al.*, 2019). In chemical and mechanical weed control, the use of RTK-GPS systems for positioning the machine and avoiding pass overlapping (MACHLEB *et al.*, 2020), automatic pressure and nozzle flow control systems based on travel-speed variations, and weed identification through laser (LiDAR - light detection and range) and machine vision systems (WANG *et al.*, 2019; KUNZ *et al.*, 2018) have allowed for the controlled and specific application of pesticides in the necessary place or mechanical action of the cultivation tool where needed. A variety of sensors and electronically driven actuators have enabled the development of systems that act intra-row of plants in mechanical weeding, which was previously difficult to achieve (PERUZZI *et al.*, 2017). Furthermore, the development of AI, machine learning, and neural network systems has enabled the design and use of autonomous machines for chemical and mechanical weed control, and several companies have researched and developed these machines (MACHLEB *et al.*, 2020; SHAMSHIRI *et al.*, 2018).

Many of the improvements provided by digital agriculture in grain harvesters are dependent on understanding the relationships among the main functions of the machine, its energy source, and the data management and control system (PANG *et al.*, 2019). The crop cutting height control prevents equipment impacts against the soil and guarantees a more uniform cutting action performance with lower loss rates. The verification of reel rotations allows the adjustment of this setting based on the work situation and volume of harvested material. In addition, this control can also be used to unblock the feeding system when it is overloaded by reversing the reel spin, as the feeding rate may be affected by many factors, such as harvesting parameters, operating status parameters, and working conditions (CHAAB *et al.*, 2020; ZHANG *et al.*, 2018). Furthermore, along with the information obtained by speed sensors, it is possible to determine the covered distance and thus calculate the harvested area.

The threshing and separation system must be adjusted according to the grain moisture at harvest time, and the use of a sensor to measure this information, integrated with a decision-making system and hydraulic actuators, allows automatic adjustments of the cylinder rotation (ZHAO *et al.*, 2011). In addition, the cylinder opening control in relation to the concave through mass flow data interpretation also enables an optimization of the process in conventional and hybrid harvesters (OMID *et al.*, 2010).

Loss sensors installed at the end of the sieves section are another set of technologies used to improve the performance of the cleaning and driving systems. These tools present low measurement errors in comparison to what can be verified manually, requiring adjustments in the mathematical model for improvement (LIANG *et al.*, 2016; ZHAO *et al.*, 2011). Another possibility is the use of image processing along with decision algorithms to accomplish this task, seeking to differentiate the grains from other materials, detecting impurities, and monitoring the quality of the cleaning process (CHEN *et al.*, 2020).

After the separation activity, grains are conveyed to the bulk tank. The amount of grain mass transported is monitored and correlated with the information of the harvested area from the cutting system, allowing an estimation of the yield. In addition, by integrating this information with the geographical position, it is possible to develop a history of yield variability, which is usually presented in a map format (SAKAMOTO, 2020).

In addition, monitoring hillside levels is another viable alternative for improving the harvesting process. In short, two functions that use the information obtained by this system can be highlighted. First, they allow an

adequate balance of functioning systems, mainly in the threshing and separation and in the cutting and feed, through the integration of electronics and hydraulic cylinders for actuation. Second, they allow a regulation of the airflow at the fan by means of the mathematical modeling of the data, changing the drag force of the particles in the cleaning process (BADRETDINOV *et al.*, 2019), as an increase in cleaning loads reduces the air flow speed (LIANG *et al.*, 2020).

Furthermore, the workload monitoring of the harvester systems can be integrated with the monitoring of engine loads. In this sense, it is possible to search for rotation zones in such a way that the necessary energy is available for the load required with the minimum fuel consumption for the situation. Many of these technologies are based on electronic fuel injection control, widely used in other pieces of equipment such as agricultural tractors (KHANDAL *et al.*, 2017).

All these technologies present in grain harvesters require an electronic control based on mathematical modeling and artificial intelligence so that they operate in an integrated manner (YIN *et al.*, 2018). In addition, the instantaneous connectivity of the equipment to databases to assist this process becomes increasingly necessary, especially for fast error diagnosis and the online mapping of grain production (MAERTENS *et al.*, 2001). The use of telemetry systems for remote data collection and sharing is also dependent on this access (OKSANEM *et al.*, 2016). Additionally, the optimization of the harvesting process is based on the constant monitoring of the environment and machinery park involved in the process (MAERTENS *et al.*, 2001), ensuring the rapid generation of information for decision making, often presented to the operator through in-cabin displays. On the other hand, annual calibration is needed for most electronic systems; however, technological improvement and the integration with new solutions, based on 'auto-feedback' functions, will eliminate this practical problem (CHANGHUA *et al.*, 2018).

Forage harvesters already have increasingly consolidated electronic systems that optimize machine use and operator comfort by displaying relevant harvest data. These features use a header optical sensor that measures the plant's maturity to automatically adjust the cut size. Another system automatically adjusts the machine speed to the engine power and then the rotation to the material being harvested (FERREIRA *et al.*, 2020). A 3D-view system recognizes the position of both the discharge spout and forage wagon deposit, allowing automatic unloading (MIAO *et al.*, 2019).

Undoubtedly, the design of large rectangular or cylindrical balers and forage harvesters have experienced

great technological developments in recent years. One of these is the travel speed automatic control in large rectangular balers and windrowers based on the material feed (GUO *et al.*, 2019; FOSTER *et al.*, 2005), and another is the use of baling chamber sensors to monitor the baling task flow (YIN *et al.*, 2017). Displays for balers are also available that monitor its operation, such as the adjustment of the tractor speed to the mass of the collected material, bale density and length adjustment, individual performance of the knotting mechanism, cameras that track bale ground or accumulator deposition in real time, frequency-controlled automatic lubrication of the lashing mechanisms, and collection of data such as the individual bale weight, water content, efficiency, location, and harvested quantity (ALONÇO *et al.*, 2020).

## EMERGING TECHNOLOGIES IN AGRICULTURE

The agricultural production chain has been technologically improved through resources supporting the control of field operations, such as embedded electronic devices and AI systems. When the results obtained using traditional agricultural machinery are compared with those obtained from autonomous machines in operations such as seeding, fertilization, spraying, and harvesting, they suggest, in many aspects, that the latter may be an economically viable alternative if the inclusion of AI is cost-effective (SHOCKLEY *et al.*, 2019). Over the years, a tendency has become more evident with the use of large agricultural machinery to increase economic gains and reduce costs per hectare. As the size of agricultural machinery continues to increase, some undesirable consequences have arisen, not only for the operator but also for the environment. Therefore, there is a trend in new designs to favor smaller and lighter agricultural machinery as an option to perform field operations. The replacement of manually operated large agricultural machinery by smaller, autonomous machinery is a paradigm change that will lead to changes in the structure of agriculture with implications in many areas (SHOCKLEY *et al.*, 2019). An example is the concept of the autonomous XAVER (Mobile Agricola Robot Swarm) vehicles, smaller interconnected robotic units that use data analysis to plan, monitor, and document the seeding process with precision (HORVÁTH; SCHMITZ, 2020).

However, for the adoption of interconnected autonomous machines, the generation of a large amount of information and data is still necessary. The emergence of the IoT in association with other technologies, such as cloud computing, allow real-time data processing and

analysis, making the decision-making process easier (GUERRERO-IBAÑEZ *et al.*, 2017). It is important to consider a wireless sensor and actuator network (WSAN) structure, which consists of a group of self-fed sensors and actuators that acquire data in real time about the crop, climate, and soil, thus enabling physical and adequate actions within the farm, even if it represents an extra challenge due to the large amount of heterogeneous raw data acquired. However, IoT technology allows for a more efficient agricultural management with increased production and profitability in many farm sectors (SYMEONAKI *et al.*, 2020). In outdoor IoT, strategically positioned sensors may automatically detect and transmit data to the cloud for additional recording, prediction, or app control. By doing this, the control is the result of active monitoring in an automated system, in which the monitored variables are automatically adjusted. These systems also help in the monitoring and control of environmental conditions, such as temperature, humidity, pressure, wind, and luminescence (VILLA-HENRIKSEN *et al.*, 2020).

For this technology to advance worldwide, new methods using renewable energy are emerging. From this perspective, there is evidence that the use of electric motors, replacing internal combustion engines in agricultural machinery, leads to increased energy efficiency, high torque, low maintenance, low operational cost, and zero emissions, while bringing versatility to rural activities (MELO *et al.*, 2018; MAGALHÃES *et al.*, 2017; POULLIKKAS, 2015). However, some difficulties are expected, such as the high production cost of electric vehicles and the convenience of the use of fossil fuels, making this replacement difficult to implement. In addition, one of the main hindrances for this advance is energy storage, which is directly linked to batteries and accumulators that are still costly and are associated with the autonomy of electric vehicles, thus affecting their operation in any environment. This may indirectly stimulate the study of hybrid vehicles (MAGALHÃES *et al.*, 2017).

In the near future, information systems will make their way into the management of rural properties, thus helping farmers make decisions and serving as a support for financial analyses, business processes, and supply chain-related functions. In addition, the introduction of autonomous vehicles and robotics in agriculture will increase the importance of optimizing field operations using sensor-based route planning and specific site use (VILLA-HENRIKSEN *et al.*, 2020). However, technology developers need to ensure that the solutions generate a real benefit for farmers and that these are available and suitable for both large and small properties.

## MACHINERY DESIGN PROCESSES FOR DIGITAL AGRICULTURE

The adoption of technologies in agriculture is driven by the ability to gather profit-linked information in agricultural operations. Precision agriculture, which involves the linkage between prescription maps and individual control systems in specific machine functions, is evolving in connectivity and intelligence to digital agriculture. This new paradigm requires the involvement of several disciplines to leverage knowledge about site-specific field properties for the benefit of cultivation productivity; at the same time, any extra data resource needs to provide information that creates a revenue increase that is higher than its cost (BULLOCK *et al.*, 2007).

Digital innovation under the PA paradigm is clearly influenced by the age of smart technologies in the design and manufacturing of new agricultural machines. The European Agricultural Machinery Association states that machines are 4.0-enabled when they carry the following features: (a) connected machines can communicate with each other and with remote service portals, including storage, processing, and visualization facilities; and (b) smart machines can recognize and adapt to variable cultivation properties by working with data. These machines implement a wide bandwidth connectivity and distribute information resources as the edge of a farm management system (HOSTENS, 2020).

While this is similar to the wave of development in driving assistance systems seen in road vehicles, scale economies as practiced in the vehicle industry are challenged in agricultural applications. Agribusiness works under significant seasonal weather variations leading to income uncertainty for farmers and resulting in cyclic economic patterns between productivity growth and product shortage. In addition to a fragmented supply chain, the pressure for scale economies in increased cultivation capacity and the shrinking customer base due to rural flight and farm consolidation makes for a market in which scale economies are inaccessible to manufacturers of agriculture-specific platforms (DRYANCOUR, 2016).

Furthermore, procedural design and development models approach activities and their dependencies in a global development practice; a formal development process model exists in support of agricultural machine design (Reference Model for the Agricultural Machinery Development Process: RM-AMDP (ROMANO *et al.*, 2005). Extensive research on development practices in the agricultural machine industry shows that global manufacturers adopt formal development processes driven by the scale and complexity of their products (ROMANO,

2013); smaller agricultural machinery companies are following suit with the adoption of systematic, yet tailored, approaches to designing and obtaining a solution to the field based on their business needs (BERGAMO; ROMANO, 2016).

This means that the academy and industry cannot meaningfully engage in digital agriculture without acknowledging that research, design, and development processes entail several practical viewpoints across context levels of agricultural machine design, from project follow-up to individual tasks in design practice; there, procedural models make up the starting point for exploring the universe of design methods (WYNN; CLARKSON, 2018). The idea embedded in the RM-AMDP as a procedural development model is to enable a shared perspective on the activities and dependencies in the product development process (ROMANO, 2013) that defines roles for the aggregation of digital resources and novel collaboration methodologies. While global manufacturers can leverage their scale economies to engage in automotive-level complexity, specialist agricultural machine companies need to take advantage of other digitalization economies such as standard communication protocols and open software platforms to ramp up their development practices of novel agricultural machines (CEMA, 2017; DRYANCOUR, 2016).

Industry usually follows stage-gate processes to ensure better performance in project management, which drives the formalization of design and development practice. In addition, engineering teams are developing an awareness of knowledge interchanges between organizational disciplines (product design, dependability, and aftersales) during the development process. When compared to other sectors, agricultural machines present a unique set of specifics to enable the traceability and interchange of requirements and information across engineering disciplines with the involvement of agronomists and agricultural engineers. For that purpose, the Brazilian industry is paying attention to hiring these professionals and investing resources toward their involvement in the agricultural machine design process. In this context, the establishment of design requirements for agricultural machines requires the assessment of influencing factors in agricultural machine design that comprise field, market, and project scope characteristics (MARINI; ROMANO, 2009). While project planning requires less integration due to its goal-setting nature, design phases involve more teamwork due to the relevance of design work and its effect on later development task decisions in which other organizational disciplines, such as manufacturing and aftersales, are in charge of supporting the farmer/operator (FACCO *et al.*, 2017).

In this context, early phases first involve setting the design specifications for the new solution in collaborative CAD/CAE/CSCW cloud environments such as 3DXperience, Windchill, and Fusion 360 with geometry and simulation design, product lifecycle management, and online interaction features (WU *et al.*, 2015) that support the critical-mass knowledge needed to establish an agricultural machine design. The development proceeds by embodying the product architecture of the agricultural machine, including engineering domains such as fluid power, mechanics, electricity, electronics, and software. This phase works through the development and iterations of engineering features, starting from the system architecture, its elements, and the measures of effectiveness (BERGAMO; ROMANO, 2016). This enables the generation of subsystem assemblies and component geometries and the working of single- and multi-body numeric geometry simulations with finite and discrete element models (GUTIERREZ; ARANGO, 2017; HORABIK; MOLEND, 2016) to interoperate through multi-level FMI and hardware-in-the-loop models (RAIKWAR *et al.*, 2019).

In the context of digital agriculture, manufacturers need to be aware of agronomic subjects that describe fieldwork interactions and their effects on cultivation along with homologation and quality regulations. Therefore, physical prototypes are required in addition to simulations in the virtual realm to carry out functional, performance, and standardized tests on laboratory test benches and field dynamic experiments (MARINI; ROMANO, 2009; CORRÊA; SCHLOSSER, 2011). After being approved through field experiments, agricultural machine organizations freeze the agricultural machine design and associated dispositions related to safety, quality, marketing, manufacture, supply chain, and production for the purpose implementing it in the production line. A pilot production run enables the testing of process equipment and its quality alongside the dynamic field performance of the final machine, the approvals of which enable the full series production and launch of the machine into the market (BERGAMO; ROMANO, 2016).

As digital agriculture comprises real-time perception, cognition, communication, and decision-making abilities, it involves a departure from the product viewpoint to an integrated system viewpoint involving physical, logical, and human technologies (CORALLO *et al.*, 2018). Successful endeavors involve planning and designing solutions with allowances for the freedom to evolve in performance and solutions, for integration of partners with rapid decision making, and for constant innovation and experimentation (BOSCH, 2016). These principles drive the creation of technology partnership ecosystems aimed at a flexible, modular solution to be

developed in an agile, ever-evolving approach (SHEARD, 2018) that engages parallel domains in fulfilling the needs of cultivation operations (mechanics, electricity, fluid power, electronics, real-time perception and controls, algorithms, telematics, predictive maintainability, and safety). Here, development processes and design practices in cooperation with agricultural design properties - and industry practice in the design of agricultural machinery – play an outsized role in technology scouting and development to field operations (DOS SANTOS *et al.*, 2020). A multidisciplinary involvement in digital agriculture programs is essential to understanding the features and information brought by smart agricultural systems to ensure profits for the producer (BULLOCK *et al.*, 2007), at the same time providing a fair ecosystem environment with data-sharing conditions that will allow novel profit-driving solutions (HOSTENS, 2020). There is a benefit in the convergence of development initiatives in agricultural machinery toward digital agriculture: longstanding academy-industry partnerships in consolidated innovation testbed programs (AMADO *et al.*, 2015; CORASSA *et al.*, 2018); initiatives in techniques and procedural models to improve the design and development processes (ROMANO *et al.*, 2005; MARINI; ROMANO, 2009; BERGAMO; ROMANO, 2016; FACCO *et al.*, 2017; DOS SANTOS *et al.*, 2020); and projects performing system and technology development aimed at small-farm, horticultural, and orchard applications (STEFANELLO *et al.*, 2014; LAMBRECHT *et al.*, 2017; SPAGNOLO *et al.*, 2019).

While manufacturers and system suppliers consider newly dedicated digital-ready machines, legacy machinery in current service could also be supervised by smart farming devices. A policy paper (VALENTE, 2017) supported by the European Agricultural Machinery network (CEMA), with inputs from academic and industry experts and policymakers, states that retrofitting existing agricultural equipment is a way of rationally introducing digital features. This would reduce the economic impact for farmers arising from purchasing new equipment with embedded digital features, as most agricultural machinery still uses analog technologies and are of a considerable age (average of 27.5 years for tractors) in the EU. This article presents the system requirements for retrofitting to ensure the integration into a total farm management system: independent of the manufacturers and age of machinery; rational linking with operating data and work specifications; smart analyses and interpretation within an individual farm management system; capable of networking with other parts of the farm; compatibility with other applications; targeted capture of relevant data (machine/POI, location, persons, times) on a platform/program compatible with other farm applications; data protection and data security ensured; support/services

for users; and international usability. Designing systems to work with agricultural machines using previous technologies requires specific design expertise, including methods and teams, which may be substantially different from what is needed to develop a product from scratch.

As mentioned above, the requirement for compatibility between the machine hardware and generated data is an essential issue, not only for retrofitting but also for new development. Device compatibility is well addressed by the ISO 11783 standard; however, the data format is a challenge yet to be resolved during design because it generates the need for different interfaces for data transfer, which is both complex and requires expensive maintenance (VILLA-HENRIKSEN, 2020; HORVÁTH; SCHMITZ, 2019). In the application of IoT devices in agricultural machinery, the design team should also be aware of other requirements, the most relevant of which are costs, communications issues (range, wireless quality, latency, throughput, and rate), and power consumption (VILLA-HENRIKSEN, 2020). The presence of additional accurate sensors and data transmission under a common standard in agricultural machinery will also allow for data collection for product development and technological research purposes as well (BACKMAN *et al.*, 2019). Although the tractor is a major source of data, available through the ISOBUS system, the design of other machinery can also benefit from this approach. For example, planter downforce, a dataset already collected by modern planters to control furrow depth on-the-go, has the potential to improve the quantitative characterization of agricultural field soil strength for management purposes (BRUNE *et al.*, 2018) and could be used to enhance the finite element analysis of planter frames to obtain optimized designs.

## CONCLUSIONS

1. This work presented a literature review of arable land agricultural machinery currently working under the premises of digital agriculture, emerging technologies that may be adopted in the future, and the way all these affect agricultural equipment design processes. The review included an analysis of the digital technologies already used in tractors, harvesters, planters, sprayers, and mechanical weeders; a search for new or not yet well-settled technologies such as small autonomous machines, IoT, and electric powered machines; and how these new trends influence agricultural machinery design, including issues such as the customization of development processes, scale economy effect, design influencing factors, teamwork, decision-making, academy-industry partnerships towards R&D

- ecosystems, design requirements, and data collection for product development;
2. In relation to the development process of agricultural machines, the change process occurs in both directions; digital agriculture comes of age from the digitalization of everyday life as well as in other sectors of the economy, including engineering and industry. Digital agriculture solutions also have an impact on changes in development and design practices in industry. With digitalization involving wide area telematics for enhanced communication and connectivity and control-based mechatronic systems for behavior processing and intelligence among other technologies, agricultural machines now involve several specialty domains in addition to the usual mechanics, some of them unheard of until very recently;
  3. This domain complexity has a significant impact on design and development practices, forcing a paradigm shift to a pervasive collaboration. Those companies already employing concurrent engineering practices between upstream and downstream development competences - engineering and manufacturing, for instance - are now forced to employ transverse concurrent engineering among several specialties at the same design situation and moment, such as mechanics, electronics, electromechanics, telematics, fluid power, algorithms, software, user interfaces, and virtual collaboration, among other areas of interest. It also requires a change in organizational integration relationships, forcing a transition from a supplier-to-buyer to a partner-to-partner approach, in which command-and-control gives place to collaboration among willing partners with complementary knowledge and assets toward implementing a beneficial solution with knowledge economies in connectivity and intelligence;
  4. This transverse dialogue between specialty areas requires design tools with capabilities to bridge knowledge differences between apparently disparate knowledge areas that interact in the same function or device within a machine. A systemic perspective is required to enable this engagement among several specialties working in different functions of the digital agriculture system in a common knowledge framework, which also drives the need to engage knowledge integration disciplines applied to the design and development processes. Systems engineering enables the architecting of solutions based on several specialties to assess how the elements of the digital agriculture solution will work together, and this provides a basis for virtualizing the development of the elements of the system based on a simulation supported by function definitions and their governing equations;
  5. The systems understanding of digital agriculture is also experiencing transformations of its own, as design complexity reaches a degree in which behaviors can only be identified and managed through interoperable simulation models, meaning that several simulation tools need to work together in a traceability/implementation chain linked by parametric relations. This indicates a need for companies in all positions of the agricultural machinery supply chain to invest in improving their development processes and the resources committed to it. This can be achieved through the acquisition of collaborative and interoperable digital design tools for implementing a multidimensional concurrent engineering approach and through the integration and sponsorship of universities for educating new engineers who will practice the design and development of digital agricultural machines in such environments.
  6. Digital-enabled agricultural technologies are already present in the field, performing or supporting tasks such as automatic steering with the aid of RTK-GPS systems in planting, spraying, weeding, fertilizing, and harvesting; variable-rate application technologies using yield maps, soil data, and prescription seeding rates in fertilization and planting; and real-time weed identification in pesticide application and mechanical weeding. In addition, a large number of sensors fitted in these machines and working along with RTK-GPS systems are used to monitor the crops, environment, production losses, and operational parameters in real time to provide data for future use or to automatically optimize machine performance, adjusting system settings without operator interference. Some typical examples include harvester header height, machine speed control according to crop parameters, reel speed control, position of the discharge spout relative to the wagon, yield mapping, automatic section control in planters and sprayers, and overall performance monitoring.
  7. Automation seen in traditional machinery will properly achieve a digital agriculture status when all these sensors are integrated under specific goals set by the farmer or manager. This breakthrough is beginning to occur in farming with the adoption of emerging technologies, such as IoT, in this case supported by widespread, fast, and reliable information and communications technology, use of electric power vehicles, and small autonomous machines to perform various types of operations. As a consequence, these new technological trends will impact both the agricultural production chains, as expected, and the way the new equipment ought to be developed.

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