LANDTECHNIK 74(4), 2019, 69–80
DOI:10.15150/lt.2019.3209

Variability and specificity as determinants of mobile machinery performance in agricultural processes

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Agriculture is characterized by the fact that machinery used there has one of the lowest levels of utilization in comparison with other sectors. The performance achieved under real conditions differs significantly from the maximum possible performance. The factors influencing this performance gap, machine specificity and environmental variability are systematically derived in the article. This leads to approaches to optimizing machinery and technical systems.

Keywords
process, performance, variability, specificity

Performance gaps in agricultural processes

In agricultural processes, three systems typically are of paramount importance: environmental systems, technical systems and social systems. For the purpose of conducting processes properly, it is necessary to understand these subsystems accurately. These include identifying and describing conditions and behavior, including prediction, and the ability to manage and regulate. Increased system understanding and the ability of situational behavior allow better achievement of goals in terms of time, cost and quality defined in the process objectives.

As with every complex system, a deeper understanding of the three above-mentioned subsystems is important in agricultural systems.

In this article, we discuss the performance degradation caused by interrelation of environmental parameters and technical capabilities that can be designated as performance gap. The agricultural environment differs significantly from other sectors such as semiconductor production, car manufacturing or textile processing. The main reasons are the high level of environmental exposure, high complexity of technical systems and the low division of labor due to family employment. In principle, it can be said that there is much higher variability in the environmental parameters than for example in closed workshops. Many successfully industrialized processes are characterized by explicitly excluding individual influences (e. g., environmental exposure through buildings) or by effective mechanisms to control them (e. g. specialization of labor for certain installations) (Figure 1).

received 17 December 2018 | accepted 27 May 2019| published 24 July 2019
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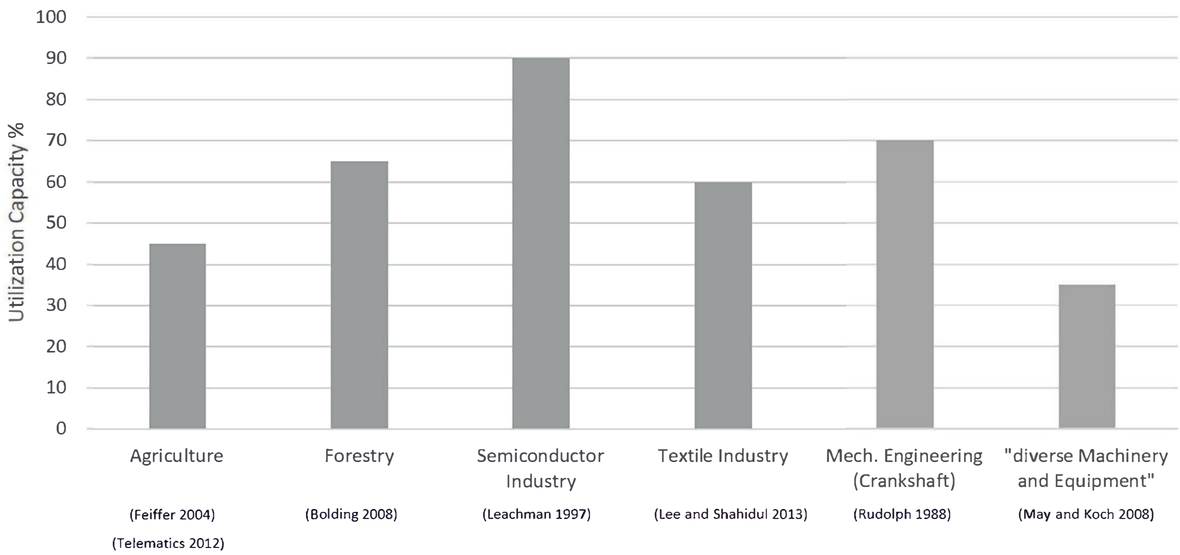

Figure 1: Typical load levels of production machines in different domains

Agriculture is characterized by the fact that adjustments to the environment or full definition are impossible or at least difficult to achieve. This difference has significant consequences, in particular the ratio of intermediate performance to machinery and its best performance. In order to illustrate the specificity of agriculture, the metrics of overall equipment effectiveness (OEE), as used in industries, can be applied (Nakajima 1988). OEE is defined as:

$$OEE = availability\ x\ performance\ x\ quality \quad \text{(Eq. 1)}$$

and can also be understood as the ratio of the factual error-free output to the expected result (Nüßer and Steckel 2018). It is therefore an approximation of the above-described performance ratio. Figure 1 shows typical values for OEE in different domains.

Agricultural values derive from direct performance measurements by (Feiffer 2004). It is evident that in typical agricultural processes only about 45 percent of the output can be realized when comparing with best-case scenarios. As expected the realized performance in agriculture is well below those of industrial sectors. The figures show that the customer does not use more than half of the machine's capacity. The difference with forestry seems remarkable, despite the similarity of the working environment. It is mainly caused by strict sequential execution of sub-processes, in other words avoidance of performance limiting parallel tasks with continuous need for synchronization. Main enabler of sequential processing in forestry is the timber insensitivity to moisture.

The following sections examine in more detail this performance gap within a new framework. For this, sections 1 and 2 define the core terms. Section 3 then discusses the key concepts of specificity and variability based on examples before some indications of possible optimization are derived.

Installed and realised performance

The performance gap (ΔL) resulting from the difference between potential and real performance and can be approximated as a difference of installed (L_{inst}) performance and real performance (Lreal):

$$\Delta L = L_{inst} - L_{real} \quad \text{(Eq.2)}$$

It is therefore directly linked to the abovementioned OEE characteristic (Nüßer and Steckel 2018). The installed power can be modelled on a mathematical basis. Technical systems follow physical principles, such as combustion engines, that follow rules of thermodynamics. They can be calculated precisely for idealized environments. In many cases, the installed power can be described in sufficient detail on that basis. Examples are power plants or agricultural machinery on test stands. If a derivation of the installed performance is impossible, a fall back on empirical identified indicators makes sense. This may include, for example, benchmarks for measuring the performance of a machine or a whole process in well defined environments.

In real operation, the level of installed performance is never achieved for multiple reasons that are in the focus of this article. All users confronted with complex systems can confirm the derivation of observed performance (L_{real}) from reported figures. These include computer users, drivers and agricultural companies alike. The factors of influence and the size of the difference between empirical evidence and models clearly have to be explained.

Determinants of the output gap

The determinants of the output gap can easily be deduced if the concept of performance is more closely investigated. Performance is defined as work per time and measured in this way as well. However, the relevant work done is often fixed, as the performance of the whole process is sought. Therefore, the time needed is the critical measure in this approach. A typical example is the determination of the performance of a machine for processing an entire field by measuring the time required. The more time the machine needs, the lower the performance.

So the central question is under which conditions and why the required times are not always the same. The basic answer is simple: the time needed will be longer if the machine cannot run at maximum power. The causes of this can be traced back to necessary adaptations to changing environmental conditions (Nüßer and Steckel 2018). Any adjustment, e.g. to varying soil moisture, will cost time and also raises the question whether the machine can continue to operate in the new environment with its maximum power.

Consequently, there are two factors that determine the performance gap:

- The variability of the working environment. The degree of variation is generally associated with the environment and, for example, in test benches or clean rooms significantly lower than in the field.
- The ability of the machine to adapt to changing environments. This specificity includes, on the one hand, the time needed to adapt and, on the other, resulting losses in case of incomplete adjustments. A highly specific machine needs either long time to adapt to new environmental situations and/or does fails to adapt. The choice of this term is motivated by transaction cost theory, where it uses the ability to reuse objects in - modified - environments (Williamson 1985). In this context, specificity is sometimes called a quasi-rent (Monteverde and Teece 1982).

Figure 2 and Figure 3 show examples of environments of high and low variability or specificity. Variability is indicated by probability distribution P (x) for a typical parameter x, e. g. soil moisture. Similarly, specificity is given as the maximum power L (x) for a given parameter value x.

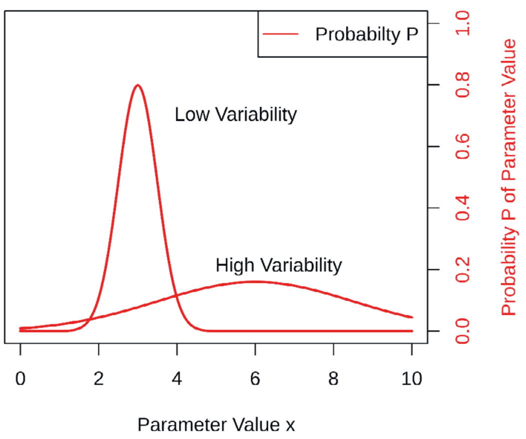

Figure 2: Variability of environment

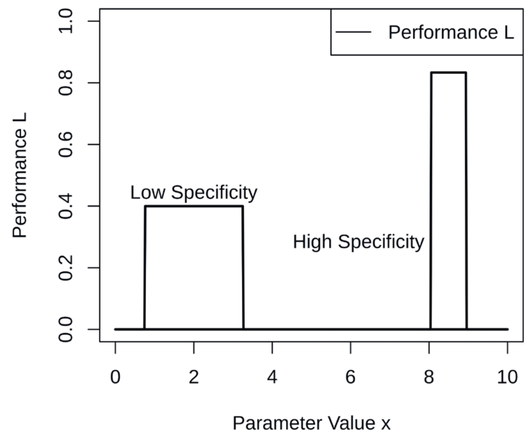

Figure 3: Specificity of machines

In order to achieve the highest possible performance, two conditions must be met. First of all, the machine performance must be as high as possible in different characteristics of the environment. Thus, the curves in Figure 2 and 3 shall be as convergent as possible. This means, the integral

$$Lp = \int L(x)P(x)dx \quad \text{(Eq 3)}$$

should be maximal (Figure 4). This can be considered as a necessary condition because otherwise the maximum performance cannot be achieved.

In addition, the variation in the surrounding environment must be as small as possible; otherwise, the machine will have to make a certain amount of adjustment work. By averaging all executions, an approximation for Lreal occurs. In this article, we primarily consider the first condition, since a precise analysis of the second condition requires a more extensive mathematical approach.

In discussing the condition that L_P should be maximum, we first consider – due to the unknown functional form of P(x) and L(x) – extreme cases for high and low variability and specificity. Extremes of variability are achieved when the environment is very closely controlled or uncontrollable. The specificity varies between technical systems which can provide good performance only under very defined conditions and those that show acceptable or good performance over a wide range. It cannot be concluded that an increase in the width of the scope must be accompanied by a generally reduced maximum performance.

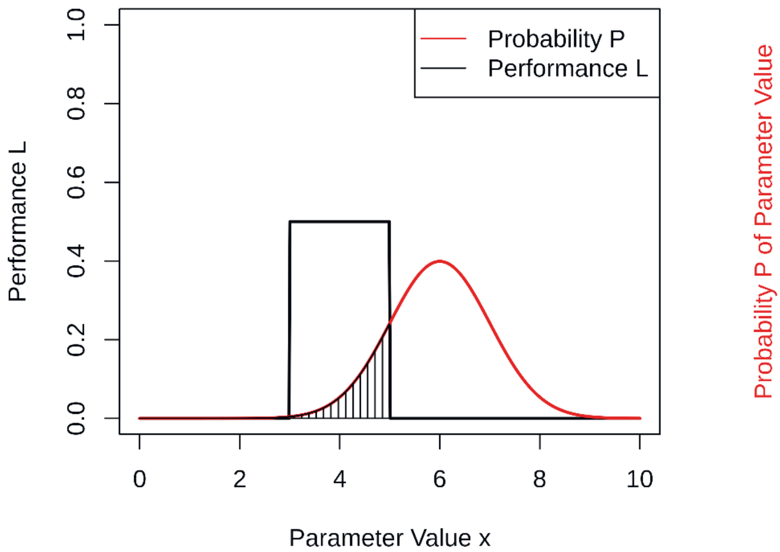

Figure 4: Integral both curves as the average performance. The power curve is described by the left vertical axis, the probability of occurrence by the right vertical axis.

Four simplified combinations can be derived:

- Machines with high specificity operating in environments with high variability
- Machines with high specificity operating in environments with low variability
- Machines with low specificity operating in environments with high variability
- Machines with low specificity operating in environments with low variability

These combinations are presented in Figure 5, starting line by line from the top left with a high variability and high specificity situation. These images show that high specificity (distinct peak for L (x)), is the position of maximum power for the mean achieved performance. The best possible result is achieved when systems can provide the maximum, in other words installed performance in their particular environment. Moreover, the curves also show that very flexible and therefore non-specific machines can provide very good average performance if they also provide a good maximum performance. An increase in the maximum performance alone does not necessarily result in an improvement for the average of scenarios.

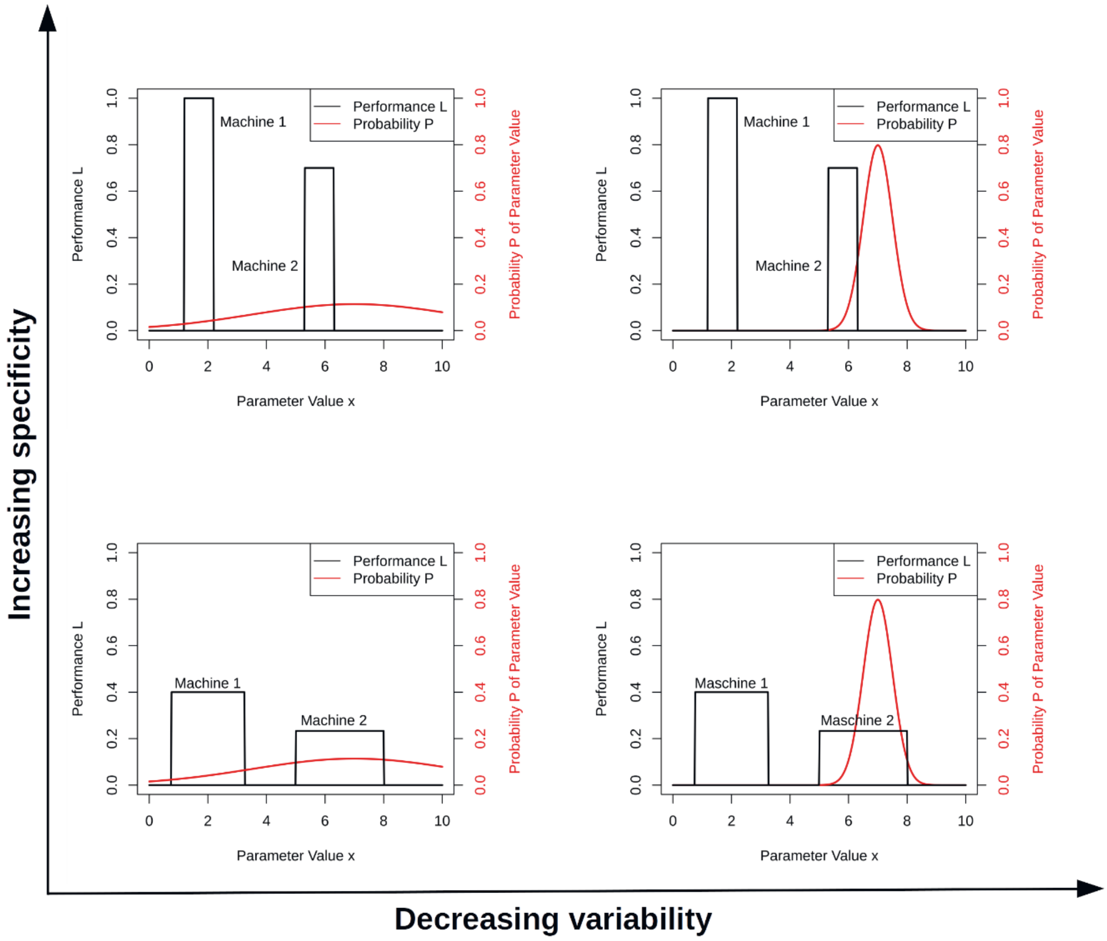

Figure 5: Scenarios for the combination of variability and specificity. Left column: high variability. Upper line: high specificity.

System boundaries for the design of variability and specificity in agricultural processes

As described, the specificity of the systems and the variability of the environment are the key determinants of the feasible performance and thus of the performance gap. Consequently, the process result is determined by the ability of the technical system to adapt to and/or adapt the environment to the capabilities of the technical system. In order to clarify the limits of adaptation, we first discuss the two core concepts based on the constellations shown in Figure 5.

High specificity with high variability (upper left)

<u>Example:</u> Self-propelled plant protection sprayer in a heterogeneous area structure

Self-propelled plant protection sprayers are designed precisely for a specific use case, the application of pesticides, and thus low configurable. These machines are particularly suitable for operation on large farms because of their size. If such a machine is used in a region with a heterogeneous area structure, the better the field size complies with the machine's specificity, the better it can deliver a high performance. An ideal environment consist of large, uniform surfaces and rectangular border structures. If these conditions are not available, the machine will show low average performance. In an extreme peculiarity, such machinery can be considered completely unsuitable.

High specificity of low variability (above right)

Example: Self-propelled plant protection sprayer in a homogeneous area structure
Homogenous surface structure means either uniformly – here ideally – large, rectangular fields, or uniformly small fields with complex borderlines. If the specificity of the machine corresponds to the narrow range of variability, e. g. by aligning the dimensions of machine and field size, the self-propelled plant protection sprayer may achieve maximum performance. In theory, even the level of maximum installed performance is achievable if the machine can work at maximum speed without headland turns, for example.

Low specificity with high variability (lower left)

Example: 'Smart' combine harvester in hilly terrain
Combine harvesters are equipped with numerous assistant systems that allow adaptation of behavior to different environmental conditions. In order to compensate for slope effects in hilly terrain, these machines are equipped with lateral contour-based control of the cutting unit and mechanical stimulation of sieves for equal distribution of harvested material. A harvester equipped with these technologies allows high performance in a wide range of longitudinal and lateral inclination. However, it can be expected that this performance will not be the best performance as in the even terrain, because adaption to new inclination values entails latencies.

Low specificity in low variability (lower right)

Example: 'Smart' combine harvester in even terrain
Even terrain can be considered as an optimal characteristic of the working environment. Because a 'smart' combine harvester can operate in a variety of different environments, it can achieve a high performance in this context. Given an appropriate machine design, it is quite possible that this performance is also in the area of performance of a high-specific machine. In certain situations, the configurability may be insufficient to yield an acceptable performance.

Discussion of these rather extreme examples shows that the ability to influence the two core factors varies widely between variability and specificity. The variability in the environment has been greatly reduced in classical industrial processes by transition to closed workshops and repetitive processes with automated work steps. For these low-variance environments, machines that provided optimal services in this parameter area and yet were comparatively low-cost could be developed.

In agriculture, geoengineering approaches go in a similar direction, but without being able to draw anywhere near as sharp as the industrial environment mentioned above. The single parcel sizes, which require, for example, the automated plant protection injection, can only be implemented in specific areas.

Consequently, the average attainable performance in these cases of barely controllable variability can only be improved by the development of adaptable, intelligent agricultural machinery. Based on these results, the next section looks at ways to improve the average attainable performance.

Optimizing potentials

In principle, the above points show that two directions for reducing the performance gap of complex machines are conceivable:

- Reduction of specificity by simultaneously trying to maintain maximum power
- Reduction of variability

The design of the specificity of machinery is implicit in the development process and is determined by the defined requirements. The determination of specificity happens at several stages:

1. design related specificity
2. configuration related specificity
3. process related specificity.

The first type of specificity is determined primarily by machine design and then further specified by the factory-provided configuration. This specificity is reflected, for example, in the ability of the machine to work with different attachments. It essentially defines the maximum limits in which the machine can change further, and thus applies to all processes in which the machine becomes active. In this stage, the user has no or minimal influence.

Configuration related specificity is given by changes in the machinery before the start of work and should then be considered as fixed for the duration of the process, e.g. the choice of the attachment and the use of additional tools at the cutting plant. It is thus a specificity per process.

The use of assistance systems, such as the rules-based adjustment and optimisation system CEMOS (D.I.E. 2017), allows for a continuous adjustment of the best operating point in the ongoing process and thus a further reduction of specificity.

The design of specificity can now be seen as a multidimensional optimisation problem at each of these three levels in view of the expected operational environment. Aside from maximum performance, costs, and operational capability, specificity - and thus the variability of the environment - explicitly adds to design criteria. This explicit consideration of specificity allows for a systematic, quantitative evaluation of new systems. This view thus makes a novel and essential contribution to the problem of streamlining burdens and obligations. Here, it is evident that an optimisation is liable to technical and business restrictions and – perhaps – even faces organisational and cognitive limits. For example, a low degree of specificity with the associated wide operational capability and at the same time a high maximum performance are not generally incompatible goals, but generally requires substantial and costly machinery-building and, increasingly, software related measures. Modern intelligent technical systems, which are self-optimising and examined for example in the leading edge cluster "it‘s OWL", are a very good example as they are considered adaptive, robust, forward-looking and user-friendly (it's OWL 2018).

However, the optimisation of specificity cannot be achieved by isolated consideration of one of the three above levels alone. Developments of new mechanisation concepts or assistant systems should take into account the three above mentioned levels as a whole. Not all aspects of specificity are located in the development of machinery but can be encouraged or impeded by them. Bad coordinated or tunable individual systems, e.g. in logistic processes, lead to low performance in the total system. Therefore, in particular in the field of procedural specificity, the cooperative behaviour should be considered. In this area, assistance systems provide support for decision-making through transparency and predictions.

While a variety of engineering methods is available in the design of specificity, the situation regarding variability is fundamentally different. The degrees of freedom are clearly restricted. This is due to the limited number of effective or accepted methods and the level of costs involved. In principle, two paths are available. This is on the one hand the creation of standard environmental conditions by eliminating natural exposure. Glasshouses are a well known example. To a lesser degree, this also applies to mews. On the other hand, variability in environmentally exposed areas can be reduced with geo-engineering methods and shifted to favourable areas. Examples include the relocation of drainage units, the cultivation in dams or, in extreme cases, the artificial triggering of precipitation. In individual cases, an influence on variability should be considered in the context of the ability to design specificity. Certainly, however, the given variability of the environment in the development of machinery and optimisation of processes must play an explicit role.

Case Study

In order to clarify the introduced terms, approximately 1.000.000 data sets of 56 combine harvester (CLAAS LEXION 770) have been evaluated hen harvesting of winter wheat. The records were logged every 15 seconds and included the current flow rate in t/h, the humidity in percent, the longitudinal and lateral angles of the machine. The flow rate was used as approximation to power under the model considered here, and moisture or inclination as an environmental dimension. In order to analyse the influence of these sizes, only one size (moisture or inclination) has always been varied, and the other is largely constant. Here we only give the results for an analysis of the influence of the grain moisture on performance. Analogue results resulted in an analysis of machine inclination.

Figure 6 is in analogy to Figures 4 and 5. It turns out that the combine harvesters provide constant performance over the whole range of moisture that occurs. However, in low and high humidity, the number of relevant measured values is low, with variations in the range of more than 20% and less than 7% being considered non-significant. The reference value of the power determination L_{inst} has been approximated by the mean value over all machines of the respective maximum values. On the one hand, Figure 6 shows that this machine has a high degree of flexibility and therefore a low degree of specificity and, on the other hand, the evaluation supports the figures of (Feiffer 2004). So, although machine design seems to fit the application area, significant performance losses are observed. As pointed out above, the overlap of the two curves L (x) and P (x) is only necessary, but not sufficient for the highest possible performance. So this first, gross analysis points to these underlying causes of this output gap, such as the variability of the environment during process execution.

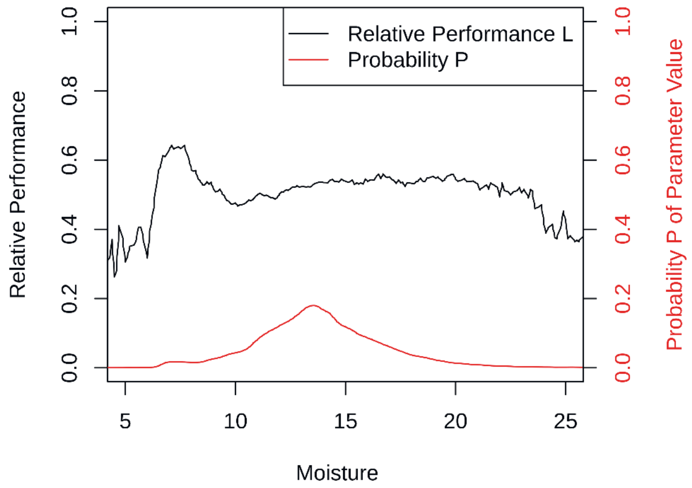

Figure 6: Relative performance depending on the grain moisture and probability of parameter

Conclusions

This contribution addressed the gap between installed and realised performance for mobile working machinery in the agricultural working environment. The much greater difference compared to other sectors of the economy motivates a closer look at the causes responsible for this gap and subsequently, at means to reduce it.

The recognition that the specificity of the environment and variability of the environment are essential determinants of the performance of working machinery is, in principle, already contained in some established approaches, as evidenced by transaction costs (Williamson 1985) and analyses of OEE (Garza-Reyes 2010). An explicit consideration which relates measurable but so far hardly systematically investigated quantities, such as the output gap, was missing.

Of course, requirements have also been taken into account in the past with regard to environmental conditions, but mostly implicitly. The complex interplay between specificity and variability was only partially investigated.

Here, these quantities are for the first time described in a systematic way and are conceptually and formally linked. It shows that two conditions have to be met to achieve the lowest possible performance gap: the specificity of the machinery must be adapted to the variability of the environment and the variability per execution must be reduced. In cases such as agriculture where this is only possible to some limited extent, performance losses are inevitable. Only their size can be reduced by skilful design of machinery and increased operability of the associated adjustment possibilities.

The two concepts of specificity and variability highlighted in this article provide a simple framework for such a categorisation and evaluation of machine concepts and allow initial conclusions on optimisation approaches. For example, an increase in the maximum power of a machine can be counterproductive if the design does not involve the variability of the environment. Indeed, a more accurate mathematical analysis confirms the intuitive picture that higher-performance machines may lose more performance than smaller facing increased variability (Nüßer and Steckel 2018). However, the reversal is not necessarily a way either if choosing the areas of operation accordingly. Rather, the trend towards more intelligent systems with the related narrower specificity is a more promising one. The conceptual framework developed here thus provides a contribution to evaluate traditional and up-to-date mechanisation and production processes, e. g. in the form of robotics or pixel farming.

So the systematic approach presented here already has a great potential for explaining, but it needs to be developed in two directions. First, a more accurate, mathematical analysis of the impact of variation on the output gap is outstanding. Secondly, operational use requires a deeper analysis of specific data. In the context of this article, only a coarse first analysis has been presented to simplify presentation and emphasis on universality. Based on this, however, it is useful and necessary to make application-related observations using real data. Telematic and environmental data are available for this purpose.

The contribution is also limited to looking at individual (sub-) processes, like spraying and harvesting. The success of a process is rarely determined by a single system alone but by the successful interaction of interdependent systems, e. g. in harvesting chains. The approach developed in this contribution should be improved from a cooperative viewpoint and could then consider the specificity and variability of entire processes and thus contribute to optimising them.

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