Adaptive operator systems in tractors - analysis of potentials and methods for specification and evaluation

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Illerbeuren, im Dezember 2023 Timo Thomas Schempp

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ABSTRACT

As a universal machine, the tractor is used in agriculture, construction, forestry, and the municipal sector. For this purpose, it is alternately coupled with various implements to operate them. This results in changing operating scenarios with different requirements for the control of the coupled implements. Today's operator systems in tractors are static and therefore a compromise solution for changing control requirements. Adaptive operator systems, on the other hand, are capable of adapting to changing operating scenarios. From this derives the directional main hypothesis investigated in this work, which could be verified with the results of the investigation:

> If a tractor's operator system adapts itself to an operating scenario, then both cognitive and physical ergonomics improve.

First, the state of the art of operator systems in tractors is described in general and explicitly for three selected tractor operator systems. In addition, the state of the art of adaptive control elements is described.

This work presents four methods: two for specifying an adaptive operator system, and two for evaluating the cognitive and physical ergonomics of an operator system. Both methods can be used within a V-model based development process.

The specification of an adaptive operator system for tractors is accompanied by a theoretical and practical potential analysis. The theoretical potential analysis is based on the fundamentals of ergonomics and how the tractor's functions are used. The practical potential analysis evaluates and analyzes nearly 500 hours of field measurement data from 14 operating scenarios. With the results of this analysis, a sub-thesis of this work was proven:

> Not all control elements of a state-of-the-art tractor are needed in each operating scenario.

In the second part of this work, an adaptive operator system is methodically specified. The fully functional result is described and evaluated methodically. The evaluation results show significant improvements in physical and cognitive ergonomics, proving the directional main hypothesis formulated above.

KURZFASSUNG

Der Ackerschlepper wird in der Landwirtschaft, auf dem Bau, im Forst und im Kommunalbereich als Universalmaschine eingesetzt. Dazu wird er wechselnd mit einer Vielzahl von Maschinen gekoppelt, um diese zu betreiben. Es ergeben sich wechselnde Bedienszenarien mit unterschiedlichen Anforderungen an die Bedienung der gekoppelten Maschinen. Heutige Bediensysteme sind statisch und müssen demzufolge als Kompromisslösung für diese unterschiedlichen Anforderungen an die Bedienung eingeordnet werden. Adaptive Bediensysteme sind hingegen in der Lage sich an wechselnde Bedienszenarien anzupassen. Daraus leitet sich die untersuchte und gerichtete Haupthypothese dieser Arbeit ab, die mit den Ergebnissen der Untersuchung verifiziert werden konnte:

> Wenn sich das Bediensystem eines Ackerschleppers an ein Bedienszenario adaptiert, verbessert sich dessen kognitive und physische Ergonomie.

Diese Arbeit beleuchtet den Stand der Technik der Bediensysteme in Ackerschleppern allgemein und explizit an drei ausgewählten Ackerschlepperbediensystemen. Zudem wird der Stand der Technik adaptiver Bedienelemente dargestellt.

Ferner werden zwei Methoden beschrieben, mit denen ein adaptives Bediensystem spezifiziert werden kann. Für die Bewertung der kognitiven und physischen Ergonomie eines Bediensystems werden zwei weitere Methoden vorgestellt. Alle Methoden können in einem V-Modell basierten Entwicklungsprozess eingesetzt werden.

Die Spezifizierung eines adaptiven Bediensystems für Ackerschlepper im Rahmen dieser Arbeit wird begleitet von einer theoretischen und praktischen Potentialanalyse. Die theoretische Potentialanalyse stützt sich auf die Grundlagen der Ergonomie und auf die Art und Weise wie die Funktionen in einem Ackerschlepper genutzt werden. Die praktische Potentialanalyse stützt sich auf die Auswertung und Analyse von Messdaten aus dem Feld mit fast 500 Arbeitsstunden aus 14 Bedienszenarien. Mit den Ergebnissen dieser Analyse konnte eine Nebenthese dieser Arbeit bewiesen werden:

Nicht alle Bedienelemente eines Stand der Technik Ackerschleppers werden in jedem Bedienszenario benötigt.

Im zweiten Teil der Arbeit wird eine adaptive Ackerschlepperarmlehne methodisch spezifiziert, das voll funktionsfähige Ergebnis beschrieben und mit Hilfe der zwei Methoden bewertet. Es zeigen sich signifikante Verbesserungen der physischen und kognitive Ergonomie als Ergebnis, womit die oben formulierte gerichtete Haupthypothese bewiesen werden konnte.

SYMBOLS

a	%	Actual value of operator inputs for a reach zone spot
A	-	Threshold of the CE for float position of an SCV
b	-	Number of bins
B	-	Threshold of the CE for the B-direction of an SCV
C	-	Threshold of the CE for the C-direction of an SCV
d	-	Effect size t-test
eg	-	Degree of fulfillment
i_{high}	-	Highest number of operator inputs made with one CE
i_{low}	-	Lowest number of operator inputs made with a CE
i	-	Number of operator inputs
i_j	-	Number of operator inputs of a specific CE
j	-	Identification number of a CE
k, m, n	-	Counting parameters
M	-	Mean
M_{Rank}	-	Mean rank Mann-Whitney-U-test
N	-	Neutral value of the CE for an SCV
OF_{cog}	-	Cognitive operability factor
OF_{phy}	-	Physical operability factor
p	-	Probability value of the null hypothesis
r	-	Rank of a reach zone spot
r_{es}	-	Effect size Mann-Whitney-U-test
SD	-	Standard deviation

t	s	Time
t	-	T value t-test
U	-	U value Mann-Whitney-U-test
v	%	Target value of operator inputs for a reach zone spot
w	-	Bin width
x, y, z	m	Coordinates
Z	-	Z value Mann-Whitney-U-test
α	-	Significance level
$\sum_{achv}$	-	Sum of the achieved score
$\sum_{max}$	-	Sum of the maximum score

ABBREVIATIONS

AI	Artificial Intelligence
AOS	Adaptive operator system
CE	Control element
CCW	Counter-clockwise
CW	Clockwise
HMI	Human-machine interface
IEA	International Ergonomics Association
MFA	Multi-functional armrest
OS	Operator system
OF	Operability factor
PPDAC	Problem, plan, data, analysis, and conclusion
PTO	Power take-off
RF	Relative frequency
RCF	Relative cumulative frequency
SCV	Selected control valve
SIP	Seat index point
SOAOS	State-of-the-art operator system
SPM	Self-propelled machinery
SRP	Seat reference point
TOT	Total
TPH	Three-point hitch
UASW	User, display A, control element S, and effective part W

1 INTRODUCTION

More than 50 % of the participating farmers (*n* = 902) say the design of an agricultural tractor cabin is decisive for purchasing a tractor. Regarding the operator system (OS) as part of the cabin, even 67 % of the participating farmers see it as a decisive component when purchasing a tractor. These are the results of a study conducted by the Institute for Agricultural Engineering at the beginning of 2016. Parts of it were published in the magazine profi [1]. The study emphasizes the need for well-designed operator systems in agricultural tractors to be successful in the market. However, what are the requirements for a well-designed operator system in a tractor? All requirements need to pay in one of the keywords comfort, intuitiveness, and impression.

Comfort belongs to physical ergonomics. Less physical effort to operate control elements and a pleasing arrangement of these control elements in easy-to-reach zones result in a high comfort level. An increased sense of comfort also demands control elements that are advantageously designed with anthropomorphic counter forms to be pleasant to grip without pressure points. Intuitiveness belongs to cognitive ergonomics. The corresponding requirements are related to the human brain. Hence, an operator system must be designed in a way that the users can execute their input intention without thinking about it for long. However, as a precondition, the users must be familiar with the functionalities of tractors in general. If the users can operate the expected functionality of a tractor according to their stereotype, it is an intuitive operator system. Operability aligned with the users' stereotype is intuitive operability. In general, a machine's proper functionality for the task and intuitive operability add up to usability [2]. The impression results from the value and aesthetics of the operator system. Whereas comfort and impression have steadily improved in modern tractors in recent years, it is evident that intuitiveness conflicts with the versatile use of a tractor.

The agricultural tractor is a key machine in the agricultural sector and is also used in forestry, municipal applications, and construction sites. In [3] the agricultural tractor is defined as a self-propelled agricultural vehicle having at least two axles and wheels, or endless tracks, particularly designed to pull agricultural trailers and pull, push, carry, and operate implements used for agricultural work (including forestry work), which may be provided with a detachable loading platform. According to this definition, the design of a tractor allows it to be connected to suitable implements to perform a particular task successfully. For this reason, a standard tractor offers the following standardized rear and front interfaces: Trailer hitch, three-point hitch (TPH), power take-off (PTO), and electrohydraulic select control valves (SCV) to couple hydraulic cylinders and motors. Besides the task of driving the tractor, the users must also control these interfaces, with the exception of the trailer hitch. The four main function groups driving, TPH, PTO, and hydraulics, are the key parts for the operation of a tractor to achieve added value. Thus, an implement must be coupled to at least one of these interfaces to operate it with a tractor. An endless variety of implements on the market yield an endless variety of operating scenarios for a tractor. In contrast, self-propelled machinery (SPM) has permanently mounted devices [3]. An SPM is designed for only one work scenario with at least similar operating scenarios if not just one operating scenario exists. Narrowing this down to the operator system, it is understandable that an operator system in an SPM can be static and is still sufficient to operate the SPM in an ergonomically advantageous way.

Coming back to the agricultural tractor and its characteristics of use, it is evident that a static OS in a tractor will never be able to offer advantageous cognitive ergonomics in every operating scenario. The users face a compromise solution all the time. Therefore, the directional main hypothesis of this work is formulated as follows:

> If a tractor's operator system adapts itself to an operating scenario, then both cognitive and physical ergonomics improve.

Based on an academic approach, Chapter 2 describes the state of the art of operator systems in today's tractors. It also includes categorizing and structuring general control elements that one can find on such OSs. Chapter 3 overviews state-of-the-art control elements with adaptive features. Diving deeper into the fundamentals of cognitive ergonomics in Chapter 4 helps to understand the requirements for the specification of an adaptive operator system (AOS). Chapter 5 reveals methods that support the specification and the ergonomic evaluation of AOSs in the development process. To prove the potential of AOSs, Chapter 6 outlines a theoretical potential analysis for AOSs in tractors and a potential analysis based on measurement data from the operation of a tractor in the field. Chapter 7 describes the specification of an AOS based on the methods revealed in Chapter 5. This AOS with all its features is described in Chapter 8. Chapter 9 shows the results of the ergonomic evaluation of this AOS based on the methods revealed in Chapter 5. The discussion in Chapter 10 gives a critical view of AOSs in tractors, particularly of the AOS described in this work. The approach suggested in this work to specify and evaluate AOS is also under discussion. The outlook outlines further steps in the continuation of research and development of AOSs and points out systemic needs beyond this work such as standardized communication protocols in the interplay between tractor, implement, and AOS.

2 STATE OF THE ART OF OPERATOR SYSTEMS IN TRACTORS

To understand a tractor's operator system, one must understand the tractor, its use, and its design. **Figure 1** depicts a standard tractor. With a standard tractor, there is one attachment space for implements in the front and one in the back. For low-class to mid-class standard tractors, there can be a third attachment space right in front of the cabin to attach a lifting frame of a front loader. The attachment space in the back comprises a three-point hitch, a mechanical and rotating power take-off, and electrohydraulic select control valve couplings. The attachment space in the front can also be equipped with all these three interfaces.

Figure 1: A standard tractor with an implement in each attachment space. Attached are a pneumatic seed drill in the back and a furrow press in the front.

Tractors have a trailer hitch in the back to attach and pull agricultural trailers as defined in [3]. In this work, the trailer hitch is not considered as it is not operated from the cabin like the three other interfaces.

Modern tractors like the one depicted in Figure 1 offer additional features in the operator system, particularly automated steering systems and farm management tools. Another important feature when operating these tractors is the so-called ISOBUS, defined in [4] as a serial data network for control and communications on forestry or agricultural tractors and mounted, semi-mounted, towed, or self-propelled implements. Its purpose is to standardize the method and format of data transfer between sensors, actuators, control elements, and information-storage and -display units, whether mounted on the tractor or implemented [4].

2.1 The operator system in the context of the operator station

The cabin is the operator station and must accommodate the users. The OS is part of the operator station. The requirements for the operator station in **Figure 2** form the context to which the design of an OS must be aligned.

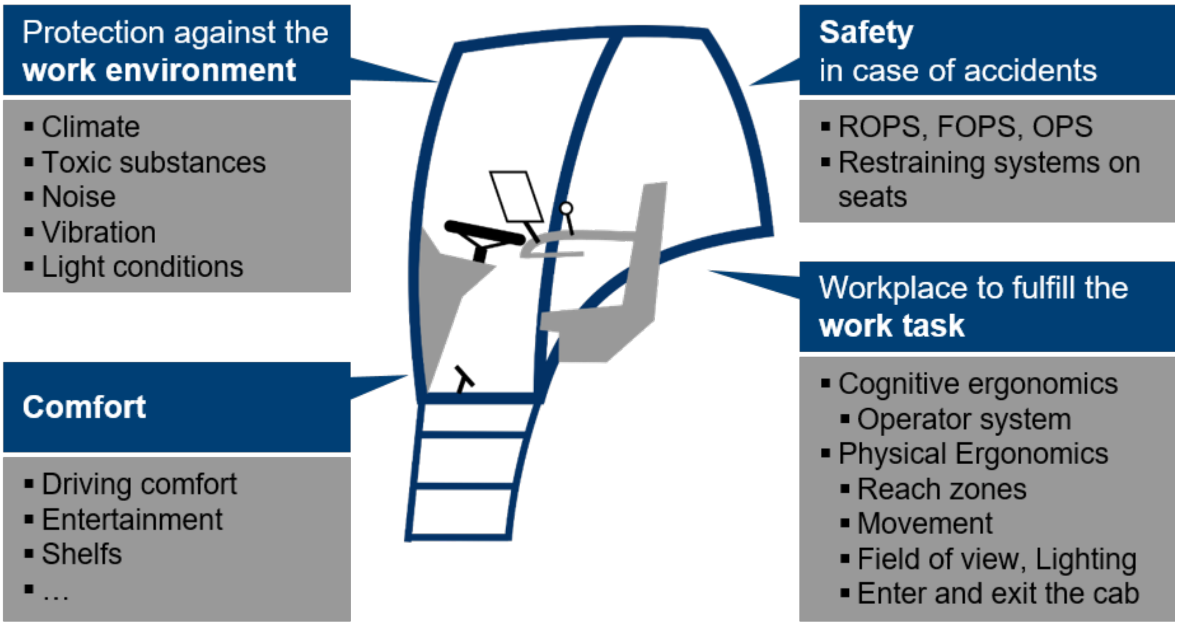


Figure 2: The main requirements that the tractor's operator station must fulfill in order to enable safe, effective, and efficient work. [5]

Even though there are low-class tractors that do not feature a closed cabin as an operator station, the requirements shown in Figure 2 stay the same. Therefore, protection against the work environment in particular must be ensured with personal protective equipment.

2.2 Control areas in tractor cabins

The OS in a tractor cabin is subdivided into several control areas. Illustrated with the example of the tractor cabin in **Figure 3,** the following control areas can be identified as the state of the art:

- Steering column (1)
- Multi-functional armrest (MFA) with a screen on the right (2)
- Side panel (3), A-pillar (4), and B-pillar (5)
- Cabin canopy (6)
- An additional screen on the side window bar (7)
- Left side of the seat, floor level (8)

Figure 3: Control areas inside a cabin of a state-of-the-art tractor. The floor level area (8) on the left side of the seat is not visible. Underlying picture [6].

In particular, for (2) and (7), there is a tradeoff concerning the field of view and reachability. For an ergonomically advantageous design, the arrangement of the areas (1) to (8) must comply with guidelines from the literature. Based on the measures of a low-percentile woman and a high-percentile man, the literature defines reach zones wherein control areas can be placed. Within these reach zones, the comfort in reachability differs. **Figure 4** gives an example of dimension specifications for such a reach zone divided into an optimum and thus preferred zone, and a basically reachable maximum zone.

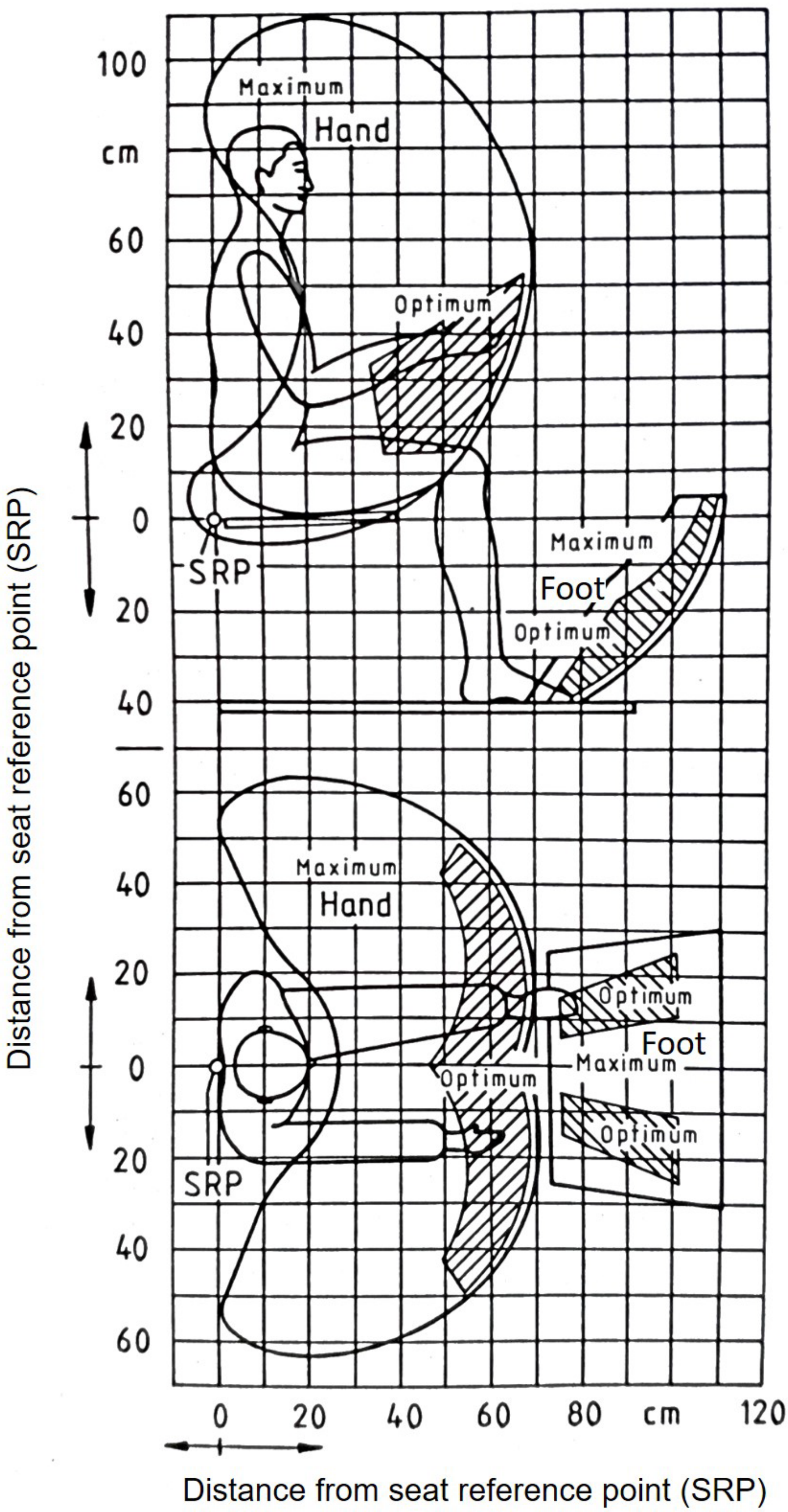


Figure 4: Reach zones based on the seat reference point (SRP). [7; 8]

The literature provides further dimension specifications. For instance, DREYFUSS outlines reach zones for the 1st percentile US woman and the 99th percentile US man for seating in agriculture machines and industry [9]. This work references the reach zone dimensions from DIN EN ISO 6682 [10]. **Figure 5** shows the reach zone from DIN EN ISO 6682 that is sectioned into a reach zone and a comfort zone for foot-operated and hand-operated control elements with reference to the seat index point (SIP) as the zero point.

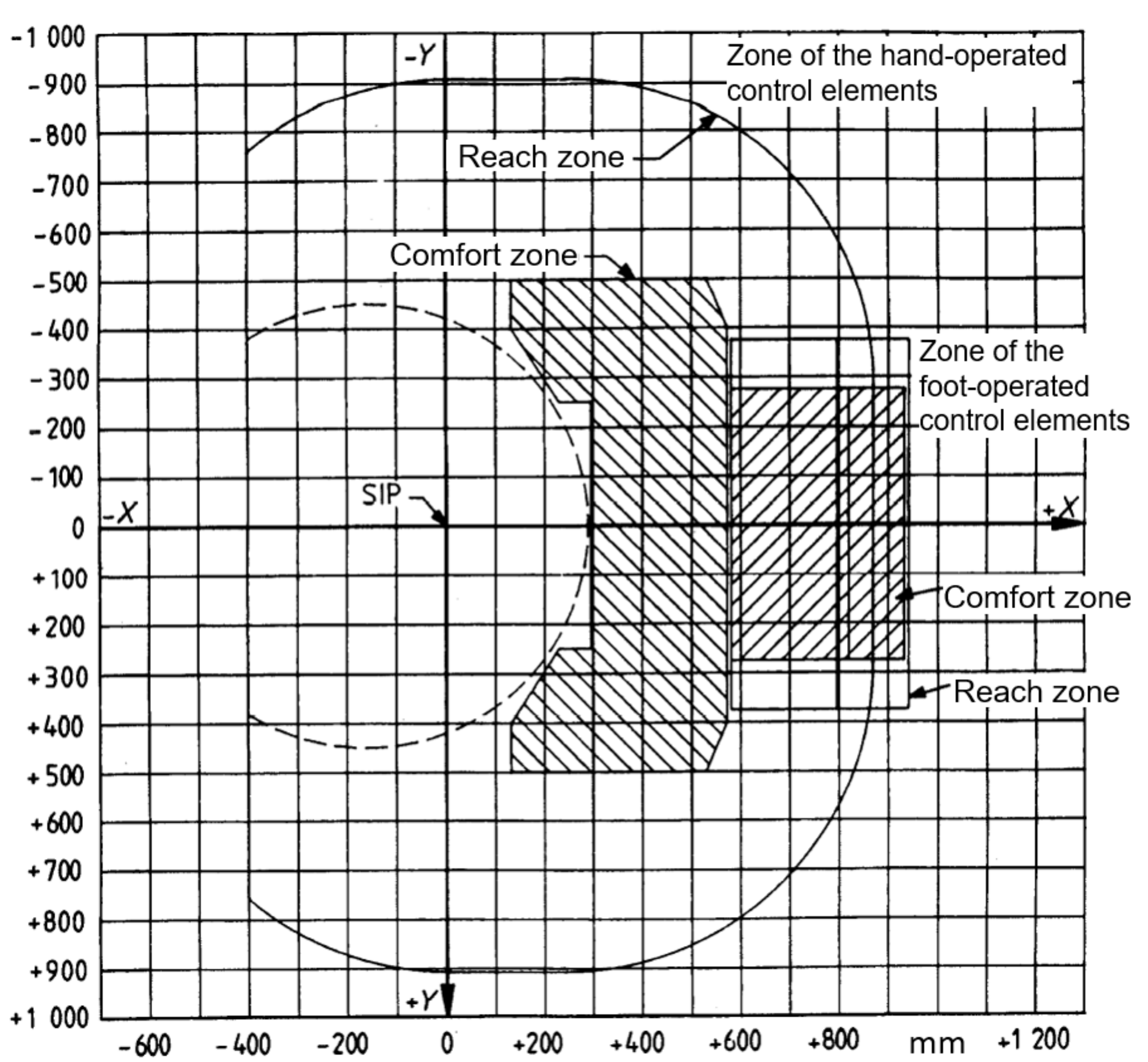


Figure 5: Comfort and reach zones for foot- and hand-operated control elements based on the seat index point (SIP) as zero point. [10]

The reach and comfort zone in DIN EN ISO 6682 is based on anthropometric data from DIN EN ISO 3411 [11] that covers the USA, Europe, and Asia. The anthropometric data comprises the small machine operator at the 5th percentile, the medium-sized machine operator at the 50th percentile, and the large machine operator at the 95th percentile.

According to DIN EN ISO 5353 [12] the SIP can be considered equal to the intersection between the theoretical axes of the human torso and the human thigh on the vertical plane through the seat centerline. **Figure 6** depicts the relation between SIP and SRP. The SRP can therefore be considered as the intersection of the backrest surface and the seat surface. The position of the SIP 90 mm above and 140 mm in front of the SRP is also defined in ISO 5721 [13]. The SIP is a characteristic value for the seat and can therefore be specified directly by the seat manufacturer [12].

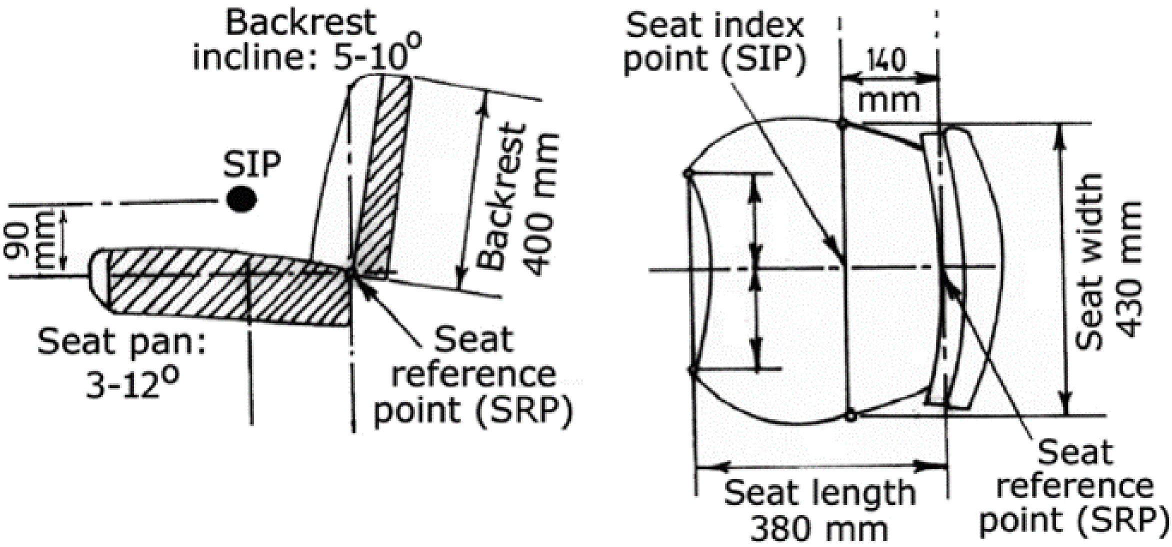


Figure 6: Relation between SIP and SRP. [14]

Using the findings for reach zones in the literature, the afore-listed control areas (1) to (8) in Figure 3 can be ranked. The result is illustrated in **Figure 7**, where the coloring assigns a qualitative ergonomic value to the control areas. From green to orange to red, the physical ergonomic value decreases. Therefore, it is advantageous to link the ranking of the areas to the frequency of use of control elements, so that the primary or preferred areas (green) contain control elements with the highest frequency of use.

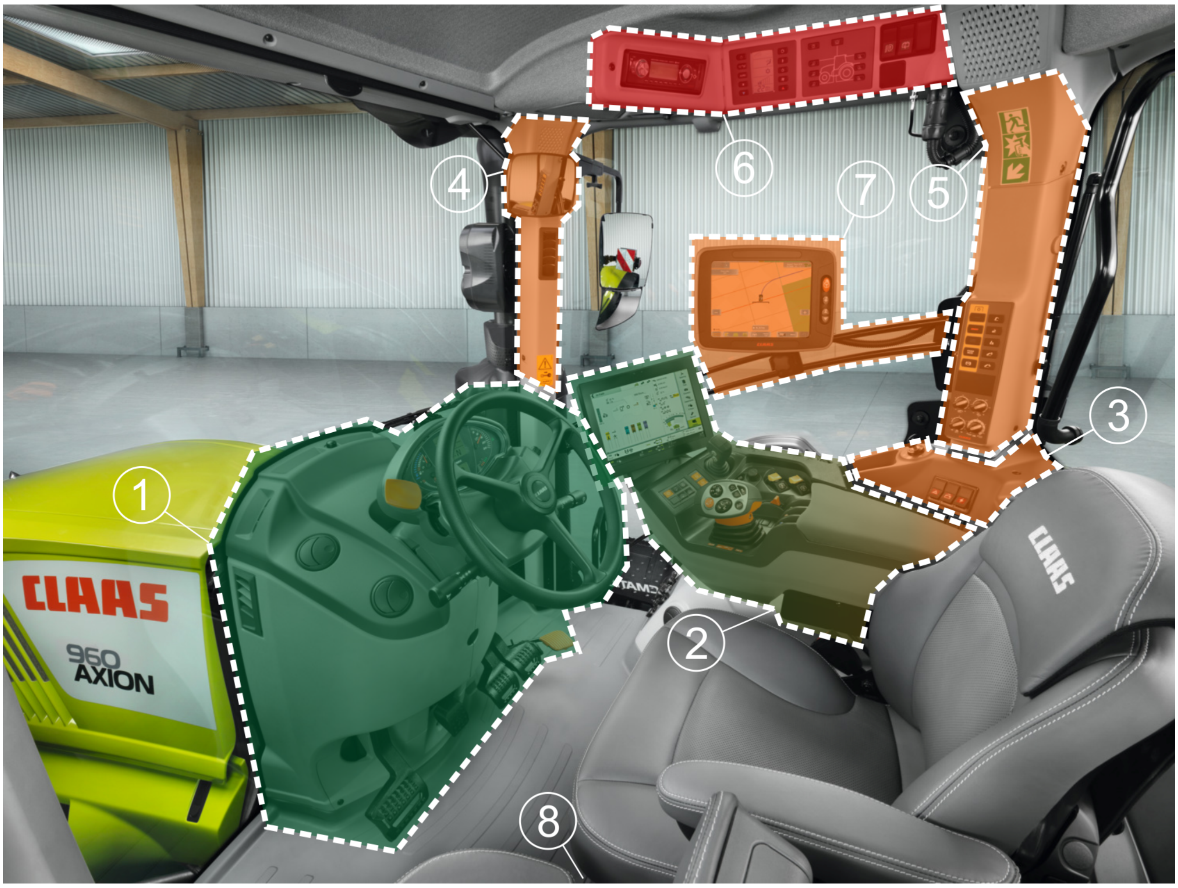


Figure 7: Ranked control areas in a state-of-the-art tractor. From green to orange to red, the physical ergonomic value decreases**.** Underlying picture [6].

2.2.1 The basic structure of state-of-the-art MFAs

As shown in Figure 3 and Figure 7 and marked with 2, the armrest on the right side of the seat contains the operator system's main control elements in particular for the main function groups drivetrain, TPH, PTO, and hydraulics. According to Figure 4 and Figure 5, this placement is ergonomically advantageous for highly used control elements. Since such armrests comprise a multitude of control elements, they are called multi-functional armrests. **Figure 8** illustrates the basic layout of a high-class tractor's MFA. From a physical ergonomics point of view, the hand-arm system has the highest comfort with the hand in the rank 1 spot in the green area. Hence, high-frequency control elements should be placed there. Lower frequency control elements are placed following the radial path, yellow - orange - red, outwards. The dashed arrows illustrate the inner and outer rotation of the shoulder joint as circular paths. A more distal circular path causes stretching of the hand-arm system, whereas a more proximal path causes flexing of the hand-arm system. Too much flexing, stretching, or outer rotation causes discomfort.

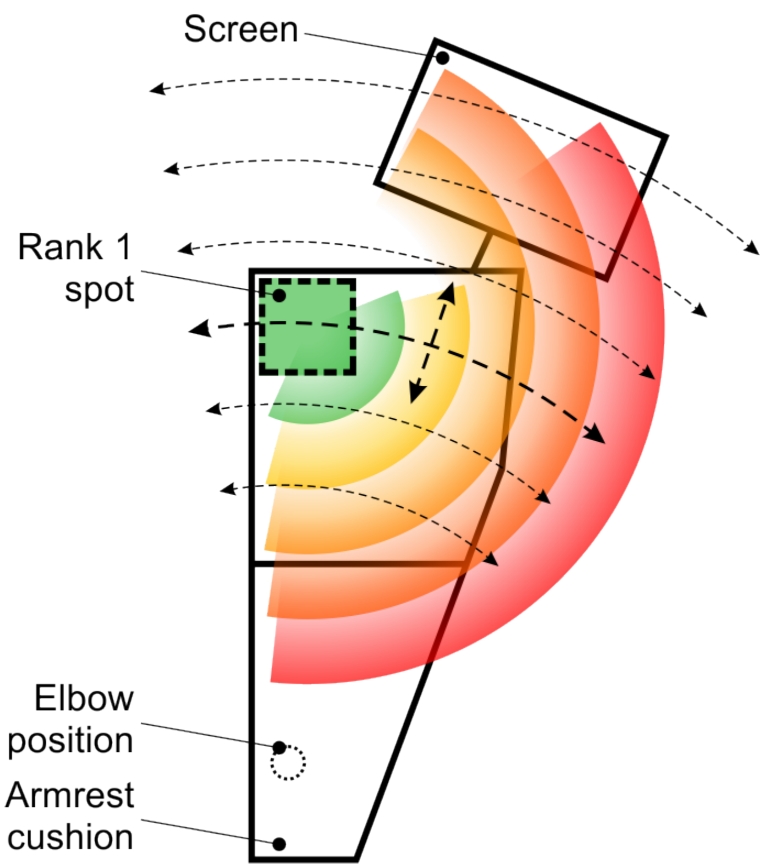


Figure 8: Basic layout of an MFA where the rank 1 spot is the best position from a physical ergonomics point of view.

Since the MFA of a tractor is the most important control area for controlling the four main function groups, this work will focus only on the MFA of an operator system. Hence, in the following the term “operator system” means “multi-functional armrest” and vice versa.

2.3 Operator-controlled functions in a tractor

Besides the main function groups comprising hydraulics, PTO, TPH, and driving, the comfort functions form another function group. Based on the manual of the Agrotron 9-Series from Same-Deutz-Fahr [15], **Table 1** lists and sorts all functions that can be controlled inside the cabin. Even though Table 1 is based on the Agrotron 9-Series from Same-Deutz-Fahr, almost all functions are generally valid for state-of-the-art tractors. The numbers in the “control area” column refer to those introduced for control areas in Chapter 2.2 and Figure 3.

Table 1: General functions for a state-of-the-art tractor.

Function group	Code	Function name	Function characteristic	Control area
Driving (main function group)	D10	Steering	Turn the wheel left and right	1
	D20	Acceleration	Push pedal	1 with the foot
	D30	Braking	Push pedal	1 with the foot
	D40	Clutch	Push pedal	1 with the foot
	D50	Change direction	Backward, neutral, forward shuttle lever switch; forward and backward buttons	1; 2
	D60	Idle running	Button	2
	D70	Indicator, horn, windshield wiper, high beam	Steering column switch with down, neutral, and up for indicator; push for horn; turn for windshield wiper; forward and backward for high beam	1
	D80	Parking brake	Push and pull a lever	1 or 2 or 8
	D90	Parking light and low beam	Push button	5
	D100	Worklights	Push buttons	5
Drivetrain (main function group)	DT10	Hand throttle	Forward and backward lever	2
	DT20	Four-wheel drive	Button	2
	DT30	Differential lock	Button	2
	DT40	Drive train management	Button	2
	DT50	Cruise control	Button	2

Function group	Code	Function name	Function characteristic	Control area
Drivetrain (main function group)	DT60	Engine speed memory	Button	2
	DT70	Transmission modes	Button	2
	DT80	Unlock / lock the front suspension	Button	2
	DT90	Set maximum speed	Joystick forward and backward	2
	DT91	Fine-tuning of speed limit also when in cruise control	Rotary wheel	2
	DT100	Trailer stretch	Button	2
	DT110	Acceleration intensity	Rotary switch	2
	DT120	Engine speed range	Rotary switch	2
Three-point hitch (main function group)	TPH10	Unlock / lock	Button	2
	TPH20	Up / down	Buttons	2
	TPH30	Stop	Button	2
	TPH40	Depth control	Hitch wheel to set a lowering limit	2
	TPH50	Electrohydraulic hitch control with a mix of position and draft control	Rotary switch	2
	TPH60	Lowering speed	Rotary switch	2
	TPH70	Set maximum lifting height	Rotary switch	2
	TPH80	Slip control	Rotary switch	2
PTO (main function group)	PTO10	PTO on and off	Two-stage switch	2
	PTO20	Select rpm	switch	3
	PTO30	Automatic with TPH	button	2

Function group	**Code**	**Function name**	**Function characteristic**	**Control area**
Hydraulics (main function group)	H10	Hydraulic flow or float position for SCVs	Control lever or joystick, the flow rate is proportional to travel of lever / joystick position; latching point for the float position	2
	H20	Adjust the oil flow rate	Screen or button and control lever	2
	H30	Adjust timed oil flow	Screen or button and control lever	2
	H40	Change assignment of control levers and SCV	Screen	2
	H50	Unlock / lock SCVs	Button	2
Assistance (for main function groups)	A10	Trigger headland management	Button	2
	A20	Set up headland management	Screen and Buttons	2
	A30	Activate automatic steering system	Button	2
	A40	Set up automatic steering system	Screen	2
	A50	Activate Easy Steer	Button	2
Comfort	C10	Air conditioning, heating	Several buttons and rotary switches	6
	C20	Infotainment	Several buttons and rotary switches	6
Miscellaneous	M10	Control of the dashboard	Button and rotary switch	2
	M20	Safety button	Button	2

2.4 Examples of operator systems on the market

To get an idea of what operator systems in current tractors look like, the market share of tractor brands in Germany is taken to identify the three most popular ones based on the registration numbers. Based on **Figure 9**, the tractor brands John Deere and Fendt are by far the most popular in the years presented. Hence, their latest operator system on the market is described. The third most popular brand is Deutz-Fahr. Since an Agrotron 9340 TTV from Deutz-Fahr was used as a test tractor in the research project, on which this work is based, a more detailed description of its OS is given.

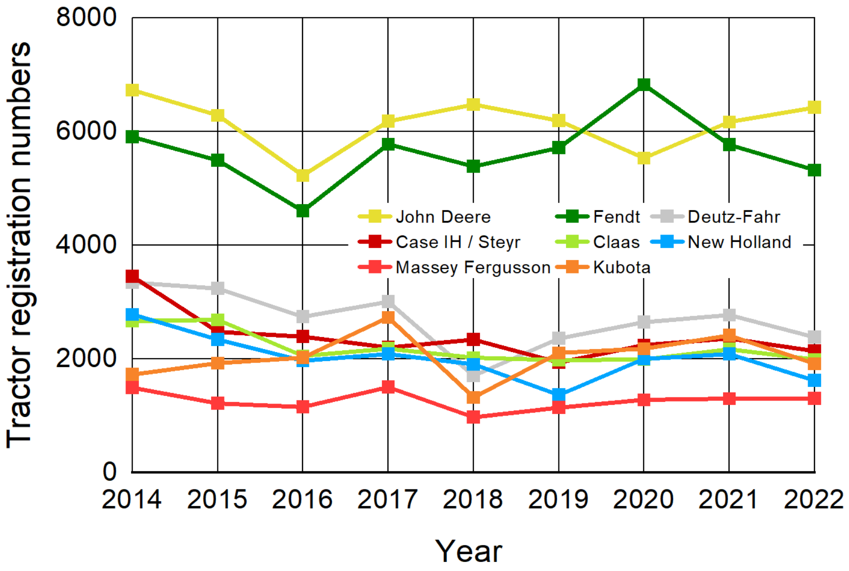


Figure 9: Tractor registration numbers in Germany from 2014 to 2022 based on [16].

2.4.1 CommandPro from John Deere

Figure 10: The CommandPro MFA from John Deere. [17]

Again, the basic structure from Figure 8 is recognizable even if the circular paths are not that obvious. The color coding is reduced to orange for the drivetrain, yellow for the PTO, and black for the rest. Besides the four main function groups, the MFA comprises air conditioning and infotainment control elements. Assignable control elements can be found on the joystick on the rank 1 spot. As shown on the screen in **Figure 10**, the buttons on that joystick can be freely assigned to functions. The visualization on the screen is the only indication of the assigned functions. The assignable rocker switches A and B on the front and C and D on the back of the joystick, detailed view in **Figure 11,** can neither change an icon nor an illumination. The same applies to the assignable buttons 12 (front) and 10,11 (back). The buttons of the small joystick on the right side of the MFA can also be assigned different functions. However, the only visualization of the assigned functions is on the screen again. The SCV control levers can be assigned to all available SCVs via the screen. Concerning the indication of the assigned SCV, the assignment is again only visible on the screen. The four buttons 1 to 4 to the right of the hand throttle are also assignable. These can be used to assign headland management sequences. Again, the indication of which sequence is assigned to which button is indicated on the screen only.

Figure 11: Close-up of the CommandPro Joystick from John Deere. [18]

2.4.2 Fendt One from Fendt

Figure 12: The MFA of the operator system Fendt One from Fendt. [19]

Looking at the operator system Fendt One in **Figure 12**, the basic structure and layout based on circular paths described in Figure 8 are easily recognizable. As depicted in **Figure 13**, the MFA comprises control modules and elements for the main function groups but also a module that is right front to control the air conditioning, the infotainment, and the menu on the screen. The color code is orange for the drive train, yellow for PTO, turquoise for headland management, blue for TPH and hydraulics, and black for comfort functions. Besides the static control elements, this MFA features manually assignable white buttons (**Figure 14**). Via the screen, the users can change the default assignment of the white buttons according to their wish by choosing from a list of available functions. In the bottom line, the white buttons are illuminated with the color of the main function group from which the assigned function was chosen. A white button with no default function shows a generic icon when assigned to a function. If the default function assignment of a white button with a specific icon is overwritten by a free assigned function, it shows no more icon. The header line of a white button is illuminated when the function is active. For the SCVs, the control elements can be assigned to each available SCV via the screen. The indication of the current SCV assignment is realized by a color illumination next to the control elements. Next to the SCV and TPH control elements, little displays show the current state of the controlled function like plus, minus, float position, et cetera for the SCVs or up, down, float position, et cetera for the TPHs.

Figure 13: Control elements, control modules, and their purpose on the Fendt One MFA. [20]

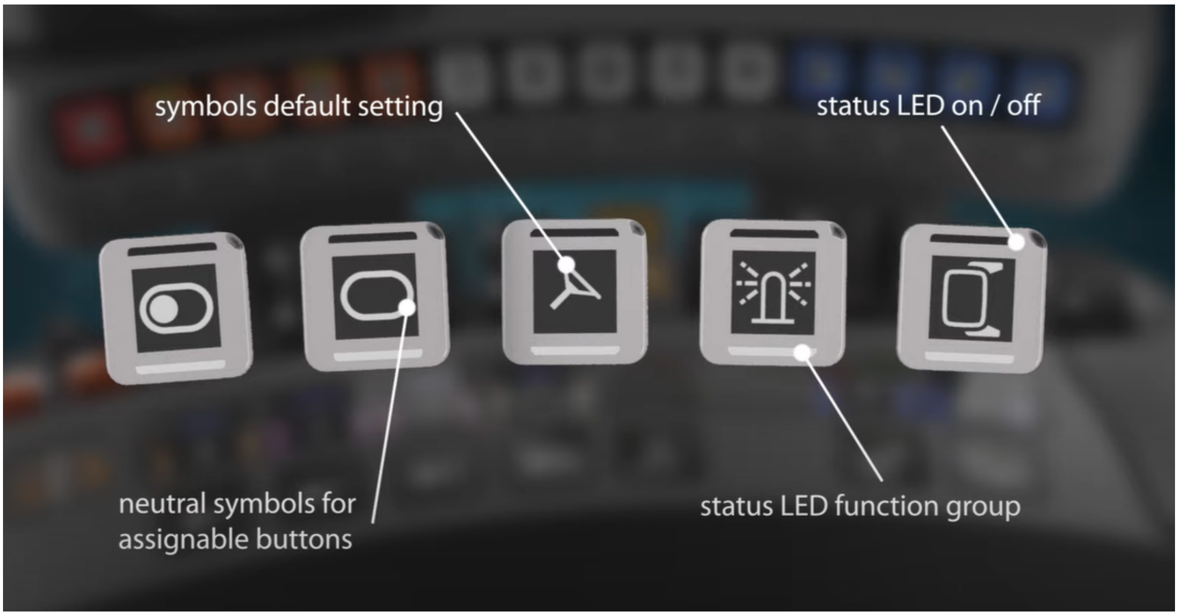


Figure 14: Assignable buttons on the Fendt One MFA. [20]

2.4.3 Agrotron 9340 TTV from Deutz-Fahr

The basic structure depicted in Figure 8 is recognizable when looking at the MFA from Deutz-Fahr in **Figure 15**. The MFA has a color code based on the four main function groups described in Chapter 2.2.1. Orange for driving and drivetrain, green for the three-point hitches, yellow for the PTO, and blue for hydraulics. The cushion is designed as a flap comprising less frequently used control elements. From the basic principles of arranging control elements described in [21], the primarily used principle is an arrangement by frequency followed by an arrangement by functionality. For instance, on the joystick in the rank 1 spot, there are just the frequently used control elements of TPH, drivetrain, hydraulics, and assistance. On that joystick, they are grouped by functionality.

To get a more detailed understanding of the operator system of the test tractor, **Figure 16** describes the control elements in particular by referring to Table 1. For all control elements, the linked functions are static. Only control elements marked with H10 can be freely assigned to each SCV via the screen. The indication of the current SCV assignment can be pulled up in a screen menu.

Figure 15: MFA of the test tractor Agrotron 9340 TTV from Deutz-Fahr.

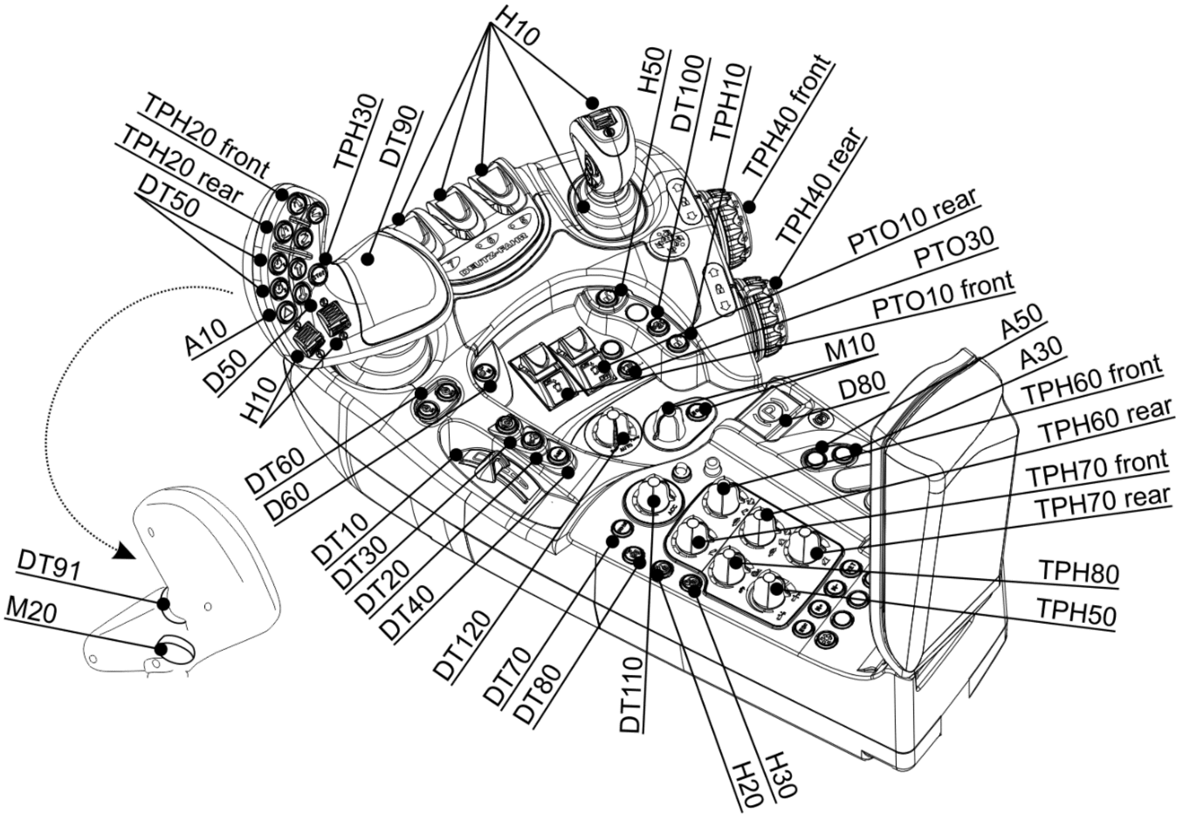


Figure 16: MFA of the test tractor referring to the control elements in Table 1. Underlying figure [15].

3 STATE OF THE ART OF ADAPTIVE CONTROL ELEMENTS

SCHMID describes the research field of adaptive control elements as very young. He names them adaptive variable control elements and defines them as input devices that adapt to an operating situation. They alternate their partial designs, structure, shape, and surface based on this operating situation. Moreover, SCHMID also lists a change in the force or torque of a control element as an adaptivity feature. [22]

This work focuses only on the context-based adaptivity of control elements to improve usability in each context. Adaptivity that serves other purposes, such as demographic factors, is not considered. For the sake of simplicity in this work, only the term adaptive control elements is used, as the variability is seen as indispensable included when speaking of adaptivity.

The “adaptivity” of haptic CEs in tractors on the market is limited to the manual change of the assigned function. However, this is only feasible with a few control elements of the operator system. As described in Chapters 2.4.1 and 2.4.2, only an indication on the screen or generic icons display the function assignment. The adaptivity feature color can be found in control elements for SCVs with a changing color illumination based on the assigned SCV. For instance, the Fendt One operator system, described in Chapter 2.4.2, has such control elements for the SCVs. Other adaptivity features in tractor control elements are unknown to the author.

The general state of the art for ACEs is described with ACEs available on the market, with concepts and prototypes from science, and with concepts for agriculture purposes disclosed in patents.

3.1 Available on the market

As depicted in **Figure 17**, the touch bar from apple on its 13” MacBook Pro is an adaptive control module using the adaptivity feature graphic. Based on the application that is currently active on the screen, it changes the icons. Instead of generic icons on the keyboard, users encounter self-explaining icons. Moreover, the touch bar can provide both push buttons and sliders. [23]

Figure 17: Context-sensitive touch bar of a 13“ MacBook Pro from Apple. [23]

In 2015, Jaguar introduced their model XF with a gear selector using the adaptivity feature availability. When starting the car, the gear selector comes up and is controllable, whereas it goes down again when the car is turned off and is not controllable anymore. [24]

Figure 18: Retracting and extending gear selector in the Jaguar XF 2015. [24]

In 2022, Genesis introduced their model GV60 with a gear selector also using the adaptivity feature availability. The gear selector is a sphere that rotates 180° when the car is turned on to be controllable. When the car is turned off, it rotates another 180°, and the illuminated backside of the sphere is shown. Since the GV60 is an electric car and thus very quiet, this feature also helps the driver to recognize when the car is ready to drive. [25]

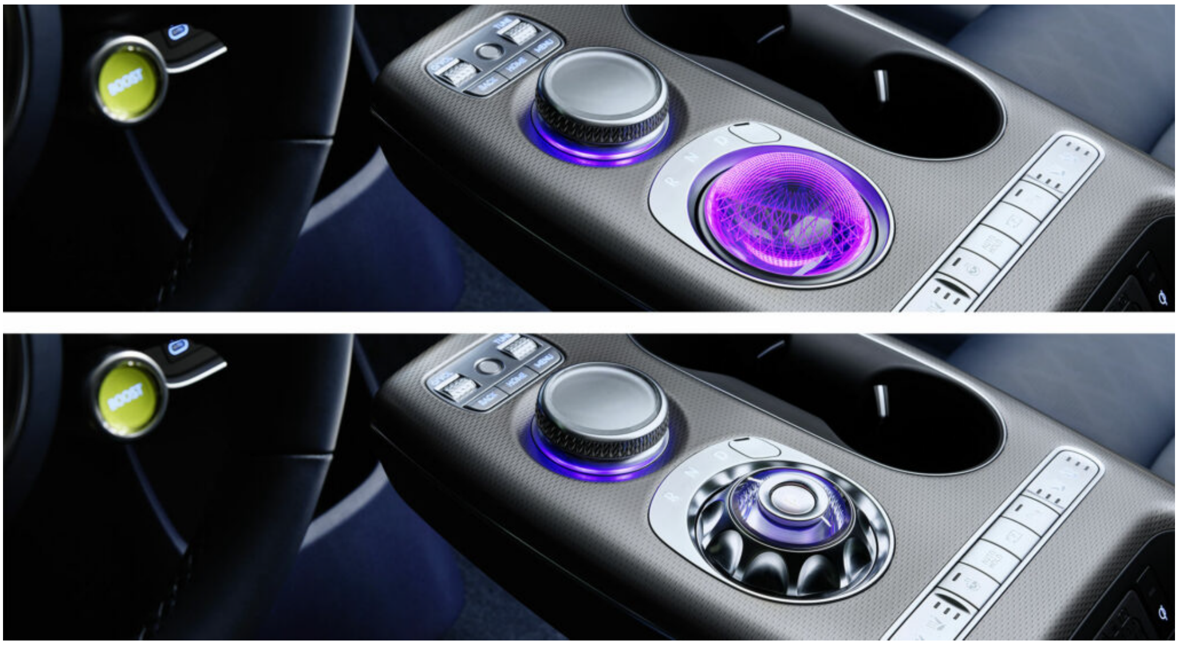


Figure 19: Gear selector in the Genesis GV60 as a sphere that rotates 180° when the car is turned on or off. [25]

In 2022, Razor introduced the gaming mouse Naga V2 Pro. The mouse wheel can change its torque based on the degrees of rotation. This change can be triggered by applications the mouse is used with or by the users. For instance, the mouse wheel can provide very low constant torque or clicks or can be blocked. [26]

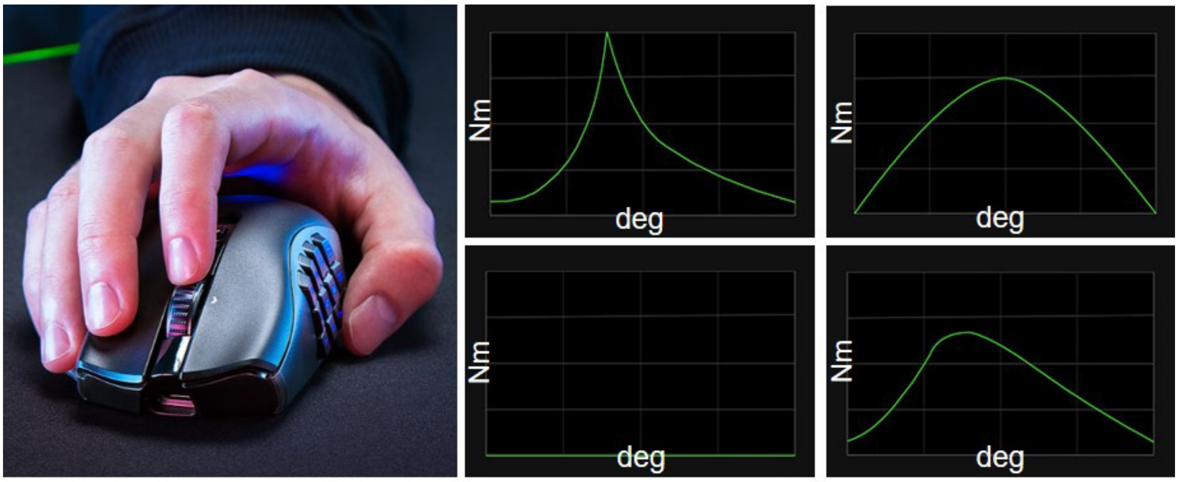


Figure 20: The Razor Naga V2 Pro can adapt to different torque curves. [26]

The XeelTech GmbH offers the product Hapticore, a rotary haptic actuator that can change its torque curve. The torque variation can be related to the rotary actuator's speed and position. The technology is based on magnetorheological fluid and powder. When exposed to a magnetic field, the mixture changes its rheological state quickly. The thereby built and released particle bridges can cause ticks, barriers, increasing torque, et cetera. [27] **Figure 21** illustrates different haptic modes based on torque variation.

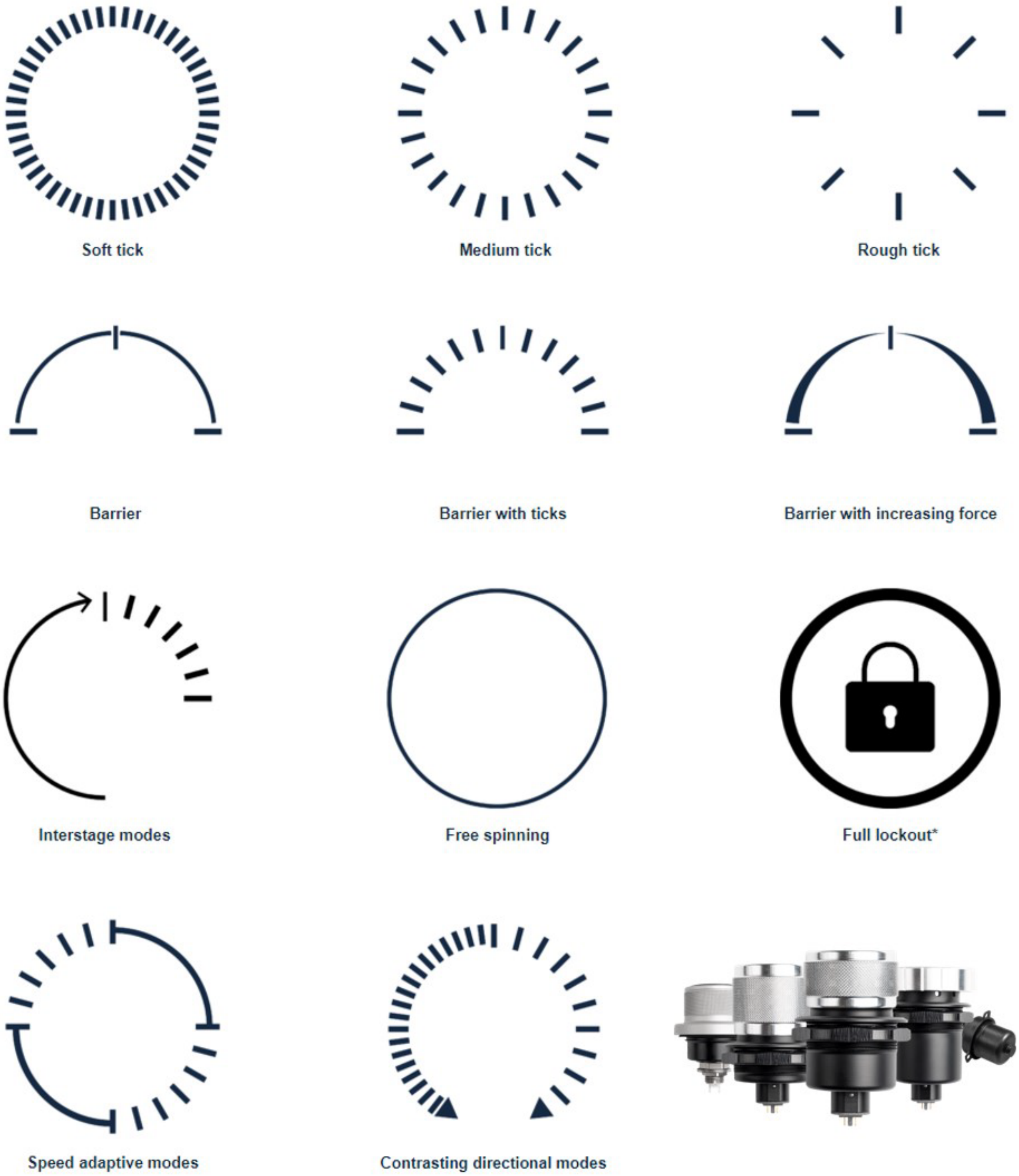


Figure 21: The Hapticore rotary actuator from Xeeltech GmbH with some exemplary haptic modes it can adapt to. [27]

3.2 Disclosed in science

In [28], MICHELITSCH discloses a prototype as part of the project Haptic Chameleon, depicted in **Figure 22**. It is a dial that users can change to a circular, semicircular, or rectangular shape. Each shape is assigned a different function and has a different force feedback effect. The idea is that the users can physically grasp the dial's meaning in each mode, particularly which function is currently assigned. [28]

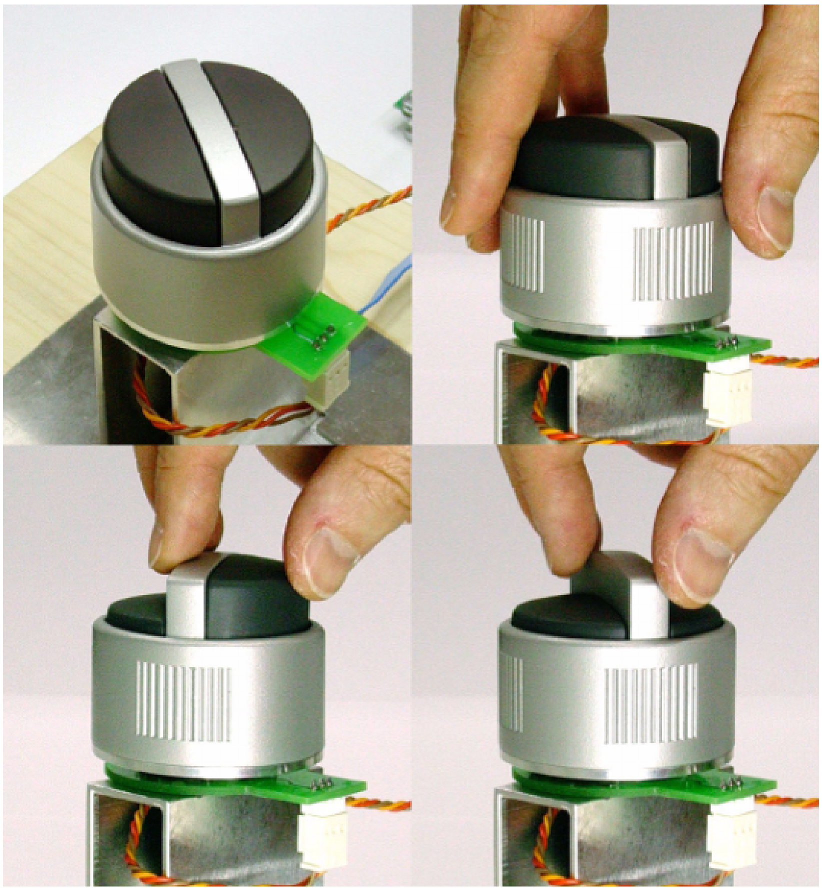


Figure 22: The dial prototype of the project Haptic Chameleon. It provides three modes into which users can change it. Each mode is assigned to a matching function and force-feedback effect. [28]

In [29], PETROV describes the shape-changing dial from his unpublished diploma thesis [30], depicted in **Figure 23**. The dial, as the central control element for a car's middle console, can change between two shape states: circular and square. The change is based on a radial translation of the lamella packages using scissor kinematics. State 1 allows a rotation around the vertical axes, whereas it can be swiveled around the longitudinal and transverse axis in state 2. The control element needs to be in an aligned position to change the states.

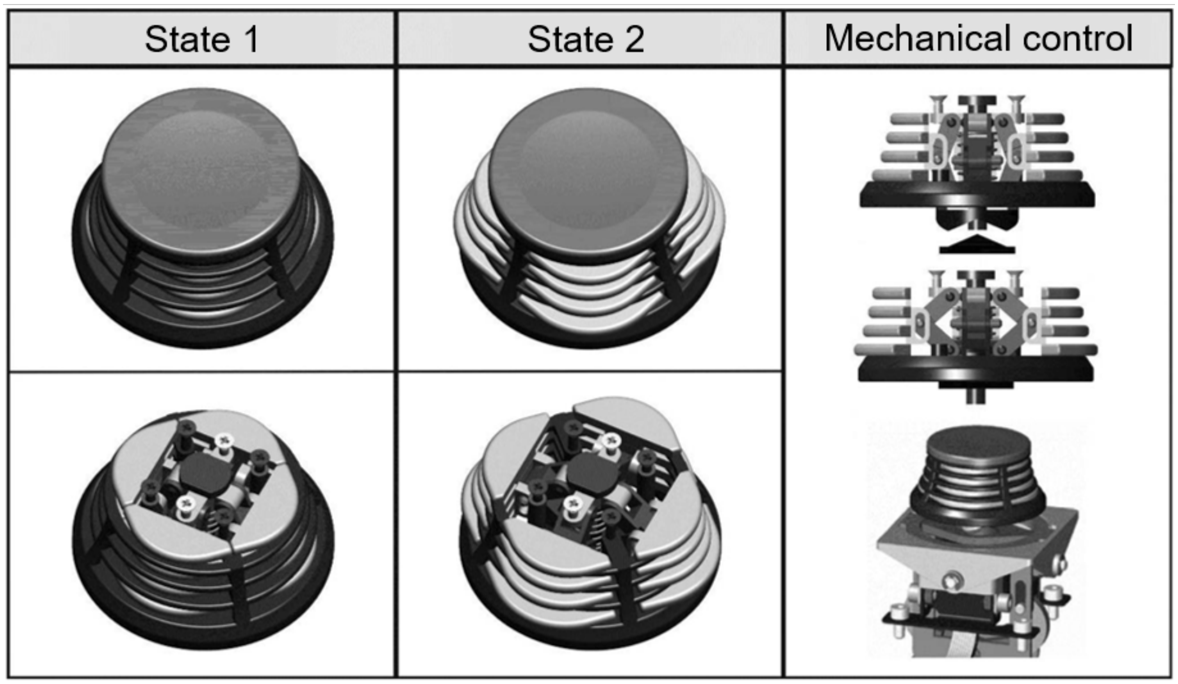


Figure 23: States and mechanical kinematics of the adaptive dial. [30]

In [31], SENDLER gives design recommendations for variable labeling of buttons and central control elements in the middle console of a car. The latter is depicted in **Figure 24**. Basically, it has the same concept PETROV developed in [30]: changing the shape of a control element from square to circular et vice versa by retracting or extending lamella packages. The difference to PETROV's concept in [30], SENDLER [31] retracts the lamellas for the square shape and extends them for the circular shape. With PETROV [30], it is vice versa. The mechanical kinematic of SENDLER is a symmetrical cross that pushes the lamellas outward against a spring when the cross is turned by 45°. The spring pulls it inwards again when turning the cross another 45°.

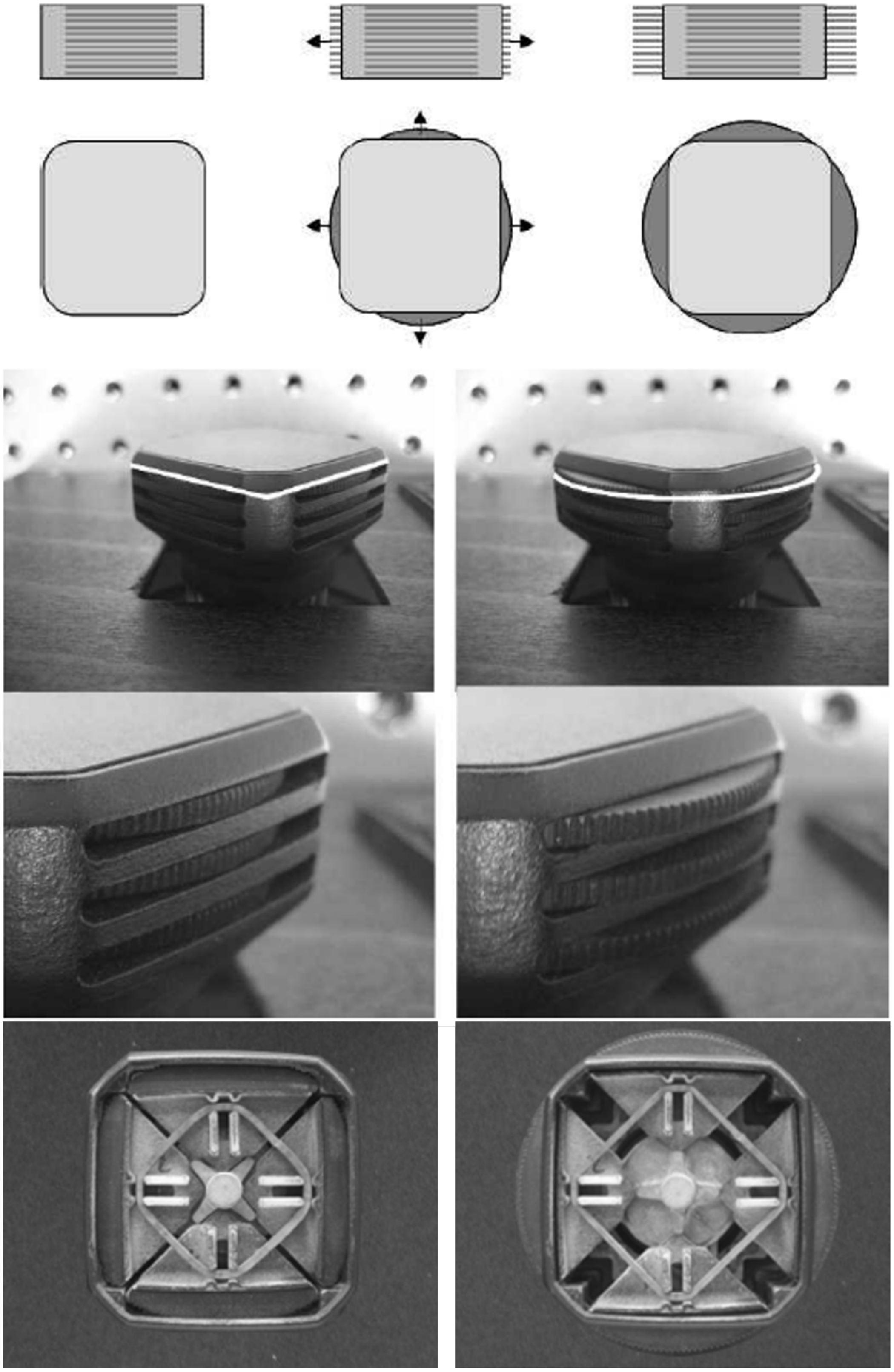


Figure 24: Top: Basic shapes of the variable central control element, square with retracted lamellas (left) and round with extended lamellas (right). Middle: The adaptive central control element for “swiveling” (square, left) or “rotating” (round, right). Bottom: Mechanical kinematic with a rotatable cross. [31]

In [32], PETROV introduces more adaptive control elements that are characterized by the following features:

- Variation of the location and position,
- Relation of operating task and actuation type,
- Variation of the shape and surface elements,

with what he is referring to [33 - 35]. He describes the systematics of adaptive control elements based on their shape and presents concepts for adaptive control elements that can change their shape, depicted in **Figure 25**. In addition to [30] and [31], PETROV reveals another concept of an adaptive rotary switch for a car's middle console in [32]. This rotary switch can be hidden entirely, can be a classical rotary switch with a cylindrical shape, or in a third state, a rotary switch with four extendable circular segments on its lower level that can be used as buttons.

In [29], PETROV describes design recommendations for adaptive control elements based on their shape variation. In a study with subjects, the finding was that the basic shape of a control element, geometrical aspect, or measure needs to change by a factor of at least 1.189 to receive a perceptible difference. For a shape morphosis of a basic shape in direct comparison, the factor of 1.189 also applies to the length of a non-tangent edge rounding or the radius of a tangent edge rounding. The radius and the length must have a minimum measure of 1.7 mm. For a shape morphosis of a basic shape with a waiting time of ten seconds between exploring two different shapes for another ten seconds, the factor of 1.189 also applies to the length of a non-tangent edge rounding or the radius of a tangent edge rounding. The radius and the length must have a minimum measure of 2 mm. Basically, non-tangent edge roundings yield a better differentiation of shape morphoses of basic shapes. [29]

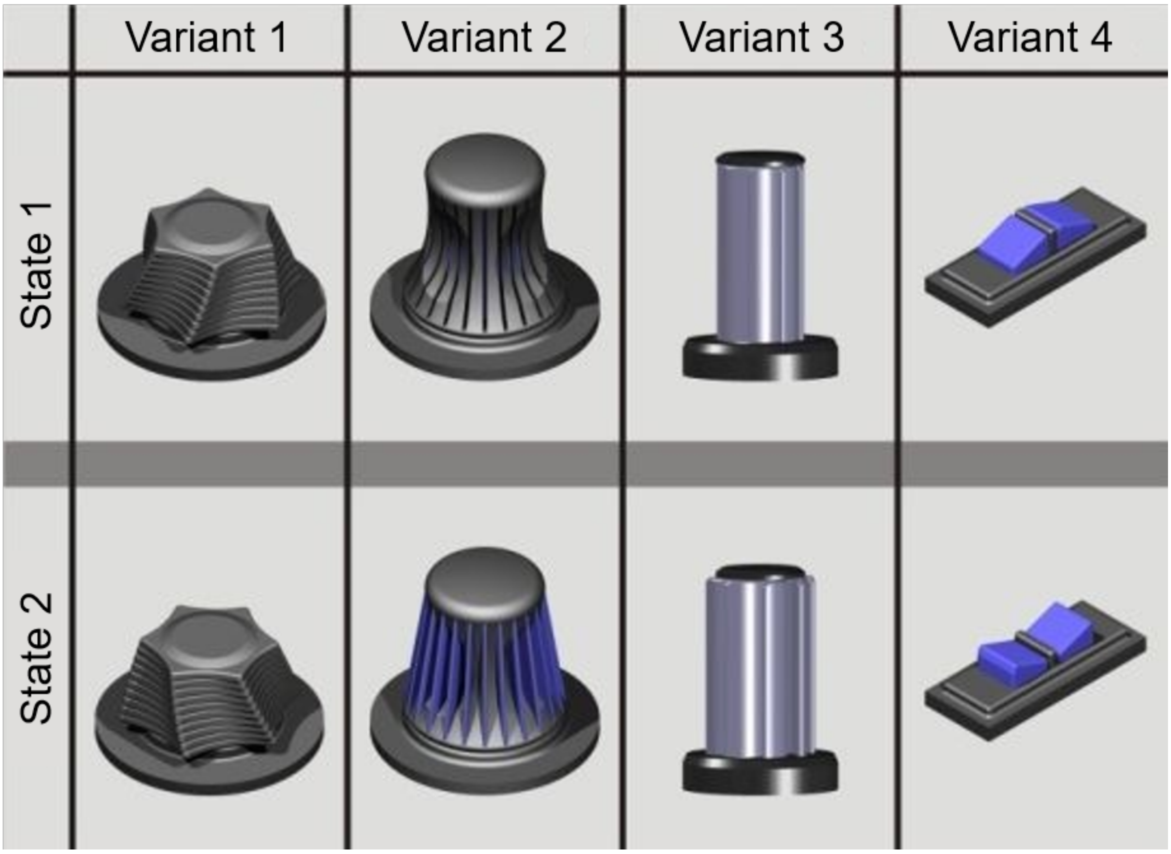


Figure 25: Concept variants of shape-changing adaptive control elements. [34]

3.3 Disclosed in patents

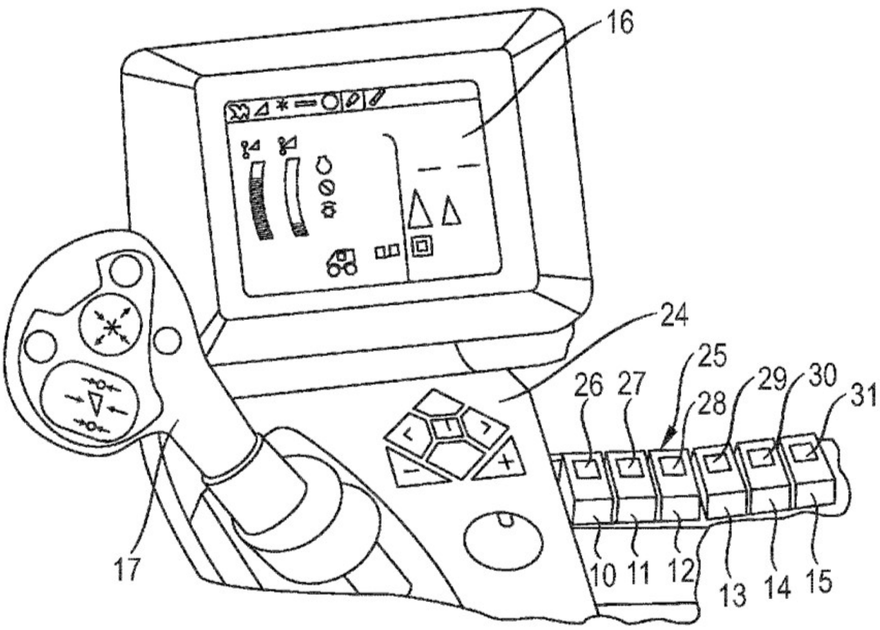


Figure 26: Operating and display device of a tractor, in which the assignment of buttons 10 to 15 provided for SCV operation is indicated by colored LEDs 26 to 31. [36]

As depicted in **Figure 26**, the patent [36] discloses input devices that can be used to visualize the assignment of a control element to a hydraulic coupling on the tractor. The driver does the assignment on a separate switching device. Colors, numbers, and letters are named as possible graphic icons to do so. Each of the individual button-shaped control elements 10 to 15 have a color LED 26 to 31 that shows a specific color. The color is changed automatically if the assignment of the control elements 10 to 15 is changed concerning the controllable coupling elements via the switching device. An automated setting of the operator system is not disclosed. The indication of the assigned function of an implement via icons on the control elements is not disclosed either.

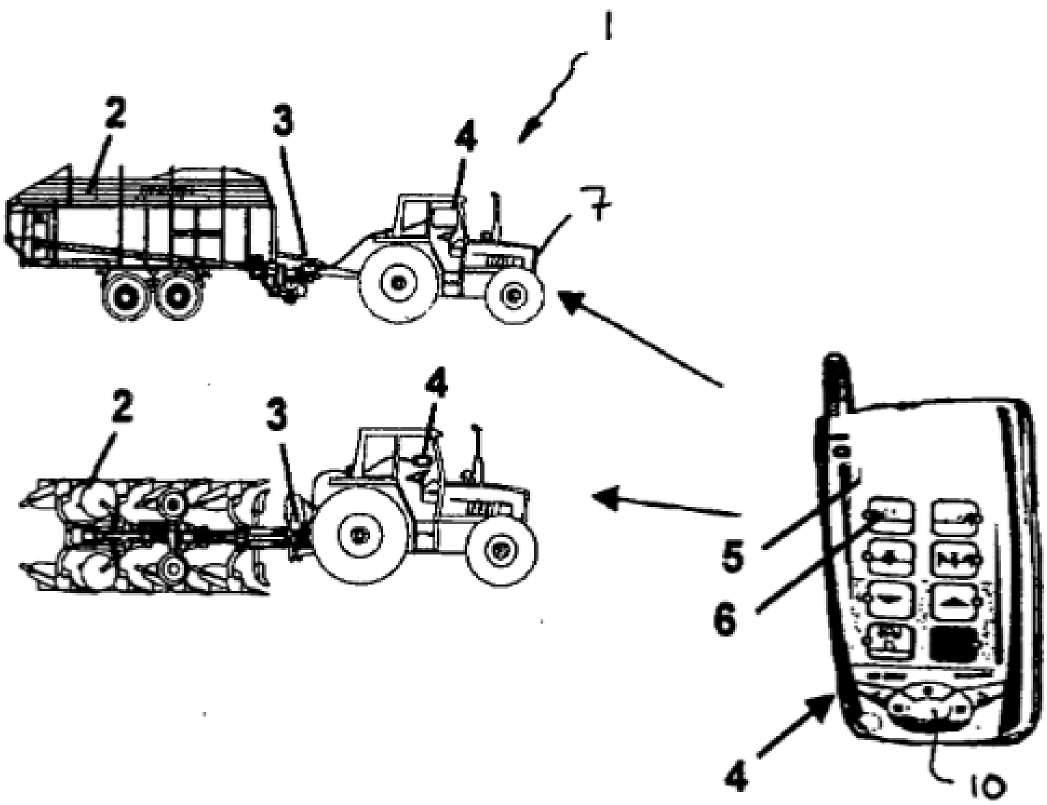


Figure 27: A terminal 4 with control buttons 6 showing the functions assigned to the buttons by users or automatic implement detection. [37]

As depicted in **Figure 27**, the patent [37] discloses a terminal 4 with control buttons 6 with screens behind them. The users can change the button assignment. It can also happen automatically, depending on the agricultural machine identification.

According to the change of the assigned function, the indicated icon on the button's screen will change. Further adaptive features are not disclosed.

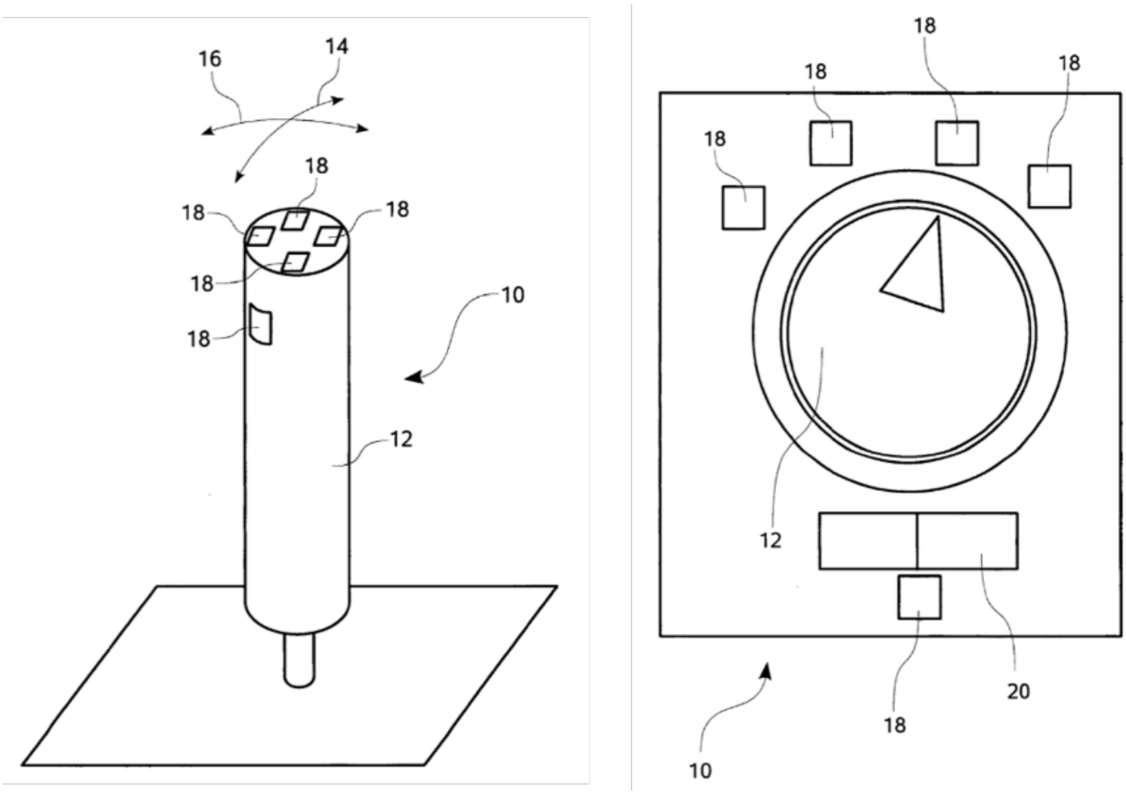


Figure 28: Two variants of an operator system 10 comprising at least one control element 12 and screen element 18. [38]

As depicted in **Figure 28**, the patent [38] discloses a control element 12 with screens 18 that show icons associated with currently controlled functions. As the assignment of a function changes, the icon changes accordingly. Either the users or the system itself changes the assignment. The screens can also comprise a pushbutton or switch element.

As depicted in **Figure 29**, the patent [39] describes an invention that allows the users to create labels on a large screen in the status bar of the hydraulic valves in text or icon form, which makes it easier for the users to remember which function of the implement is assigned to which hydraulic valve.

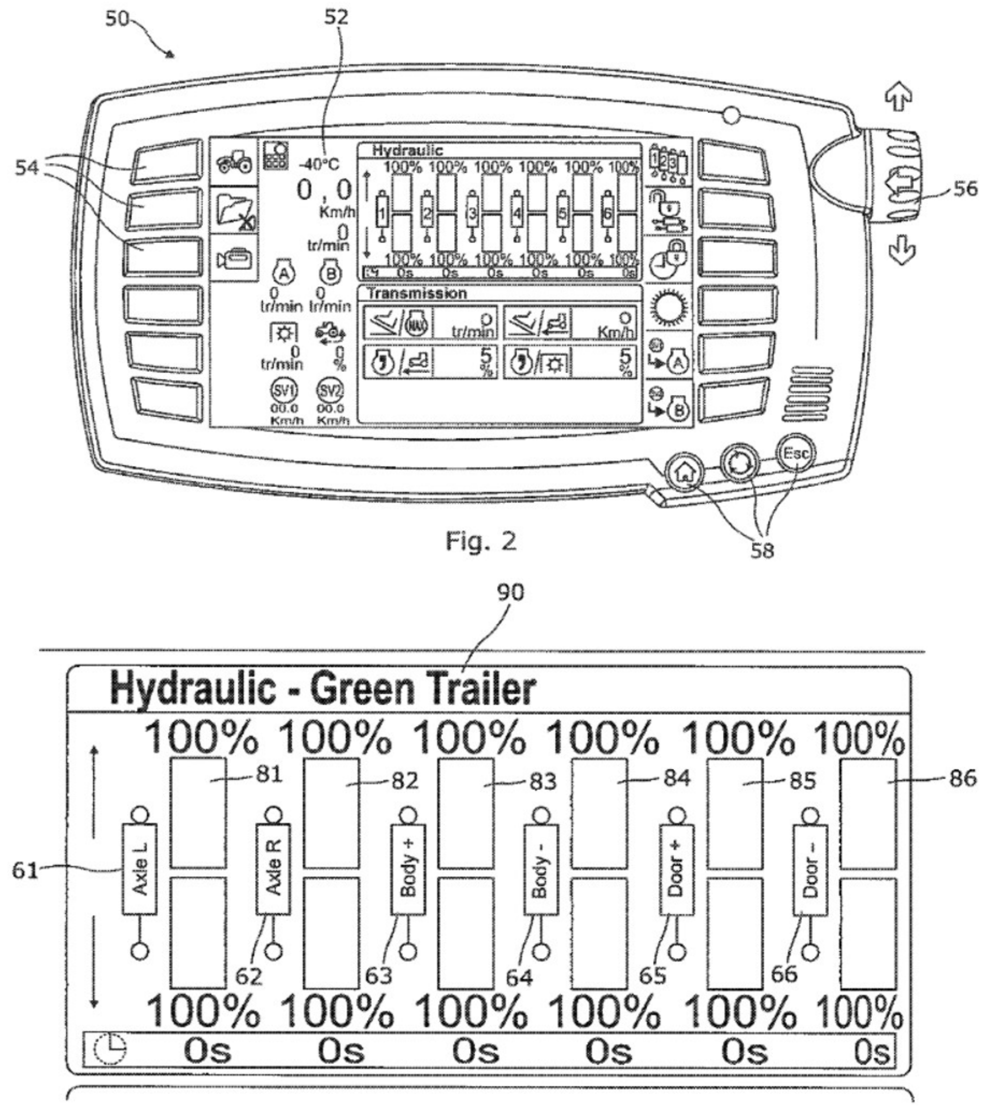


Figure 29: Tractor terminal 50 and an enlarged view of the hydraulic section that shows information about the SCVs 81 to 86 and user-defined labels 61 to 66. [39]

As depicted in **Figure 30**, in the expired patent [40], a control system is disclosed for a work machine having a plurality of attachable work tools. The control system has at least one operator input device configured to control the work machine's movement speed or a work tool. The control system also has a tool recognition device. In response to the recognized work tool, a controller is configured to change the ratio of the actuation position of the input device to the work machine's or work tool's movement speed. [40]

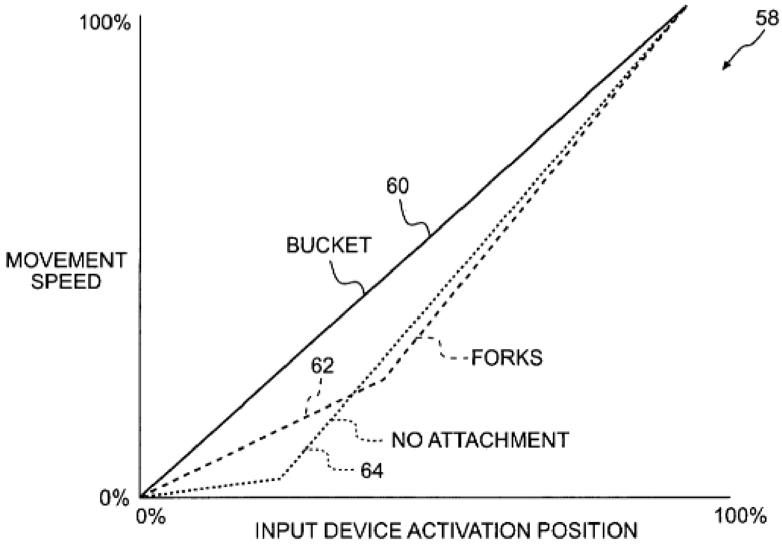


Figure 30: Adaptive ratio of the input device signal and caused movement speed based on the attached work tool. [40]

As depicted in **Figure 31**, in the expired patent [41], an operator control assembly is disclosed comprising an electronic control module 17. The electronic control module 17 allows the operator to program limits, calibration values, modulation characteristics, and the functionality of the control elements. Further, comprising an implement range limiting device 30 with a slide mechanism 36 for setting an upper limit, a wheel mechanism 34 for setting a lower limit, and a block switch 32 to limit the linear translation of the at least one tool.

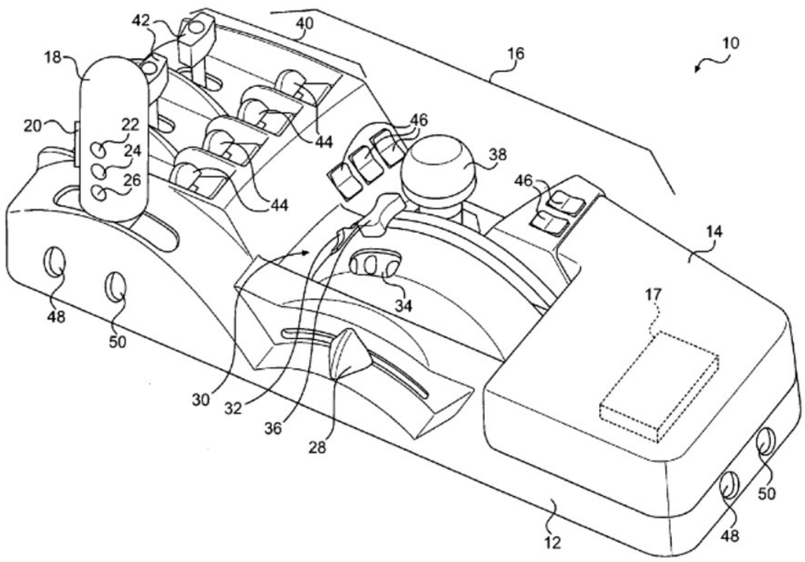


Figure 31: Exemplary embodiment of an operator control assembly with an integrated armrest and machine control. [41]

3.4 Summary and gap assessment

There are mainly single adaptive control elements that are available on the market or disclosed in science. Both focus on the use in consumer electronics or automotive applications. The used adaptivity features are graphic, torque, availability, and shape.

The state of the art disclosed in patents related to mobile machinery is mainly about allowing the users to adjust a limit or range of a control element to a function or letting the users mark their assignment of a function to a control element. Other disclosed features include the automatic color indication of control elements based on the users' assignment of SCVs. The display of a function graphic on a screen of the control element, that is either triggered by the users' assignment or by implement detection, is also disclosed. Another feature is the adaptation of the ratio of the actuation position of an input device to the work machine's or work tool's movement speed based on the trigger of a tool recognition device. The adaptivity features used are graphics and torque.

This work aims to close the gap between known concepts and designs for adaptive operator systems in general and a holistic approach for adaptive operator systems in tractors as universal working machines considering different tractor-implement combinations. This holistic approach includes methods for the specification and evaluation of adaptive operator systems with different adaptivity features.

4 THEORETICAL FUNDAMENTALS OF THE HUMAN-MACHINE INTERFACE

When discussing theoretical fundamentals of the human-machine interface (HMI) that motivate the use of adaptive control elements, they need to be understood in the bigger context of ergonomics. For a clear definition of ergonomics in this work, the definition from the International Ergonomics Association (IEA) is used:

> *Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance [42].*

According to [42], the terms ergonomics and human factors are often used interchangeably or as a unit. As depicted in **Figure 32**, the IEA defines three subfields of human factors and ergonomics, whereas this work focuses on cognitive and physical factors.

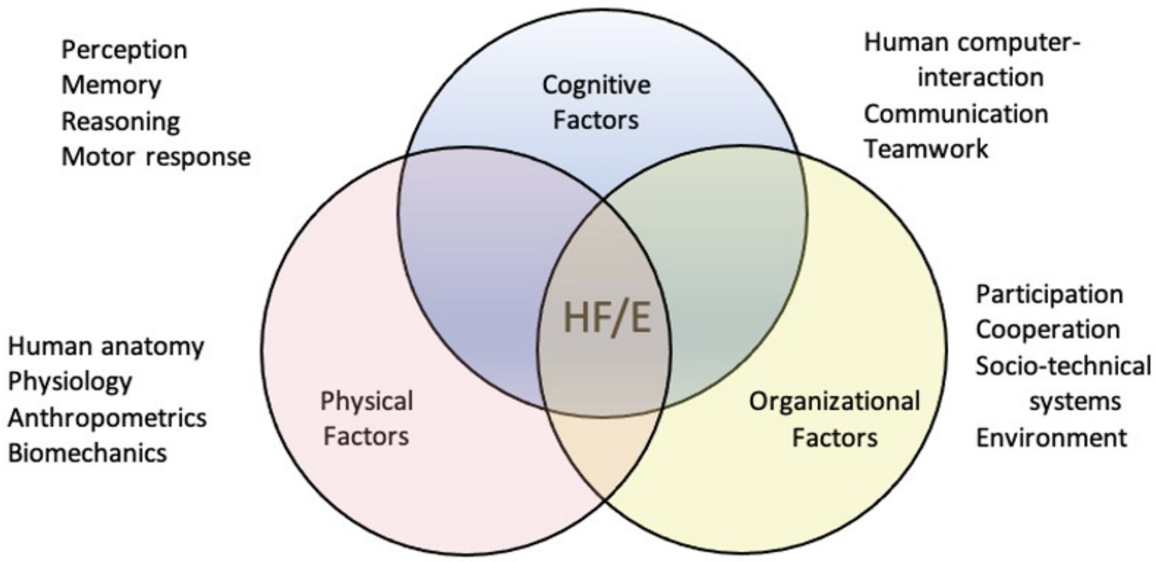


Figure 32: Subfields of human factors and ergonomics defined by the IEA. [42]

In the following chapters, the general ergonomic knowledge is adapted to the specific context of a tractor.

4.1 Ergonomic context of operating a tractor

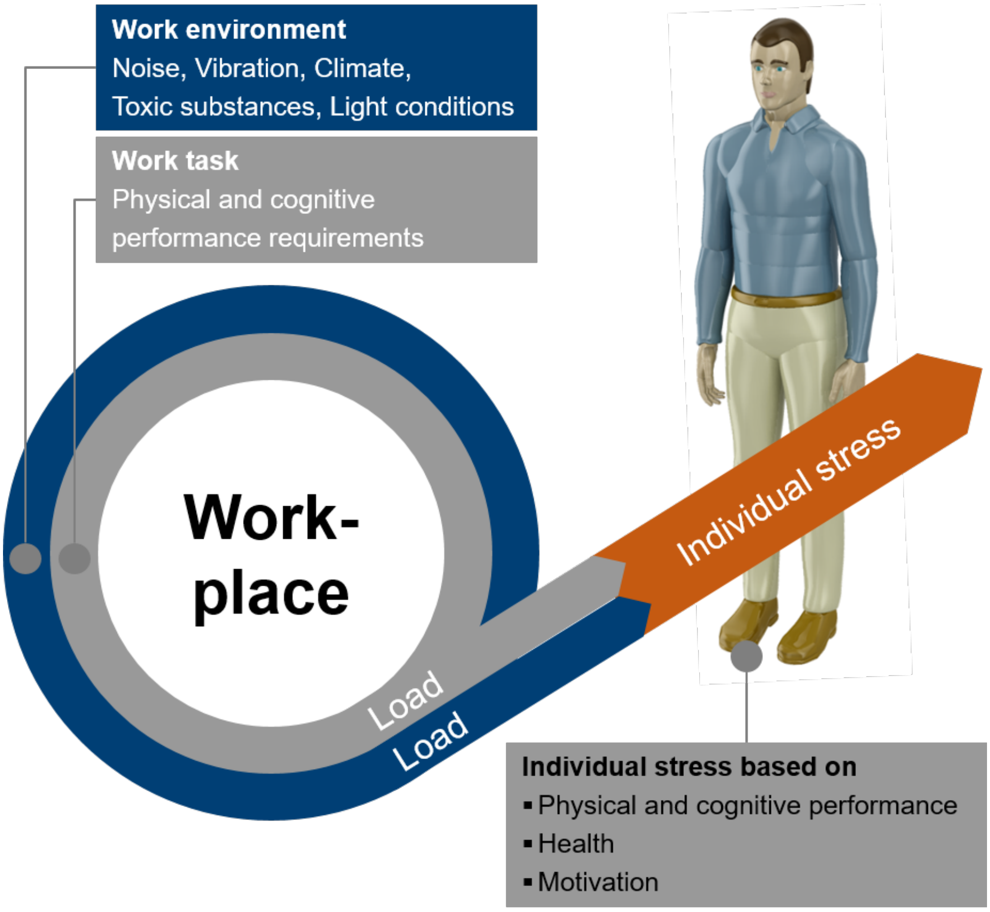


Figure 33: The work task and the work environment in a particular workplace cause load that results in individual stress for a person, such as a tractor operator. [5]

Regarding ergonomics in a tractor, the human, the work task, the workplace, and the work environment with all their specific characteristics form the context. Hence, the scheme in **Figure 33** must be considered for a good design of an operator system. In the workplace, humans perform their work in a work environment. This work causes physical and cognitive load. The work environment involves noise, vibrations, climate, toxic substances, and lighting conditions as loads [43]. Each human experiences the same load in a given workplace with a given work environment and work task. However, the stress on a human is individual. It depends on the human's physical and cognitive performance, health, and motivation. Load and stress are positively correlated, which is why a reduction in load also leads to a reduction in personal stress. Through training, health-promoting measures, and employee motivation, it is possible to reduce the stress on a person with a given load. The task of the engineer, however, is to optimally adapt the loads to the human. Published as the Yerkes and Dodson law [44] and depicted in **Figure 34**, an absolute minimization of the two parameters is not pursued. A stress optimum is the best for optimal performance so that the human is neither over nor under-challenged.

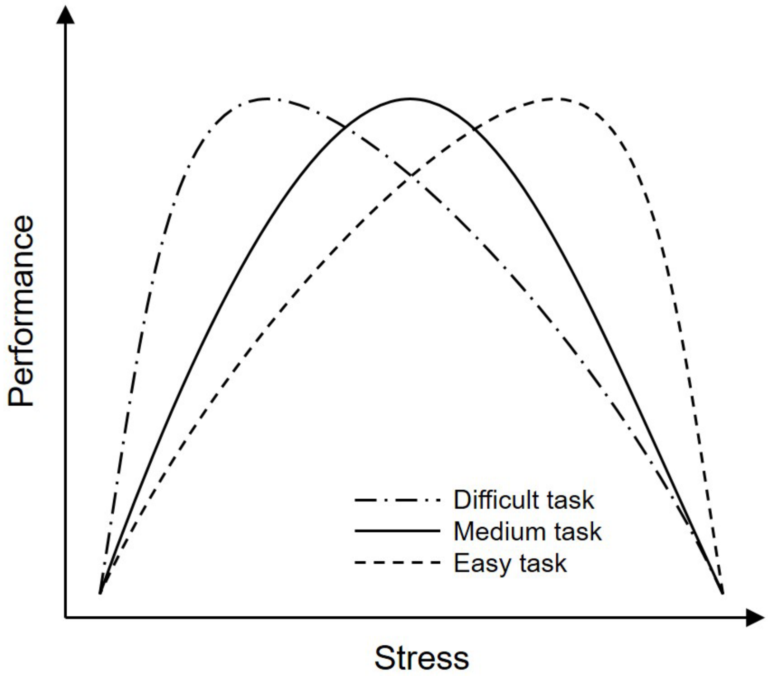


Figure 34: The Yerkes-Dodson law shows the optimal performance level based on stress for different task difficulties. Adapted from [44].

4.2 Human-machine interface in a tractor

The general model of the human-machine interface, as described in [45], [7], [22], and several other references, illustrates the systematics and the connections of its elements that act like parts of a closed-loop control system. **Figure 35** depicts a model of the HMI. The system border separates it from the environment. The target value is created from the task as input and the result as output is the actual value. Interferences from the environment on machine and human cause deviations in the actual value from the target value. Hence, as the controller of this closed-loop control system, the human does the following to align the actual value as close as possible to the target value: With its senses, the human intakes information about the environment, the result, and the machine directly but also via displays, speakers, or tactile feedback which provide sensor-captured information about the environment, the result, and the machine. The intaken information is first perceived and interpreted, then processed via cognition, and finally an action plan is created and executed with motor skills as action [21]. Losses in the perception and cognitive process of the human can delay the alignment of the actual value to the target value.

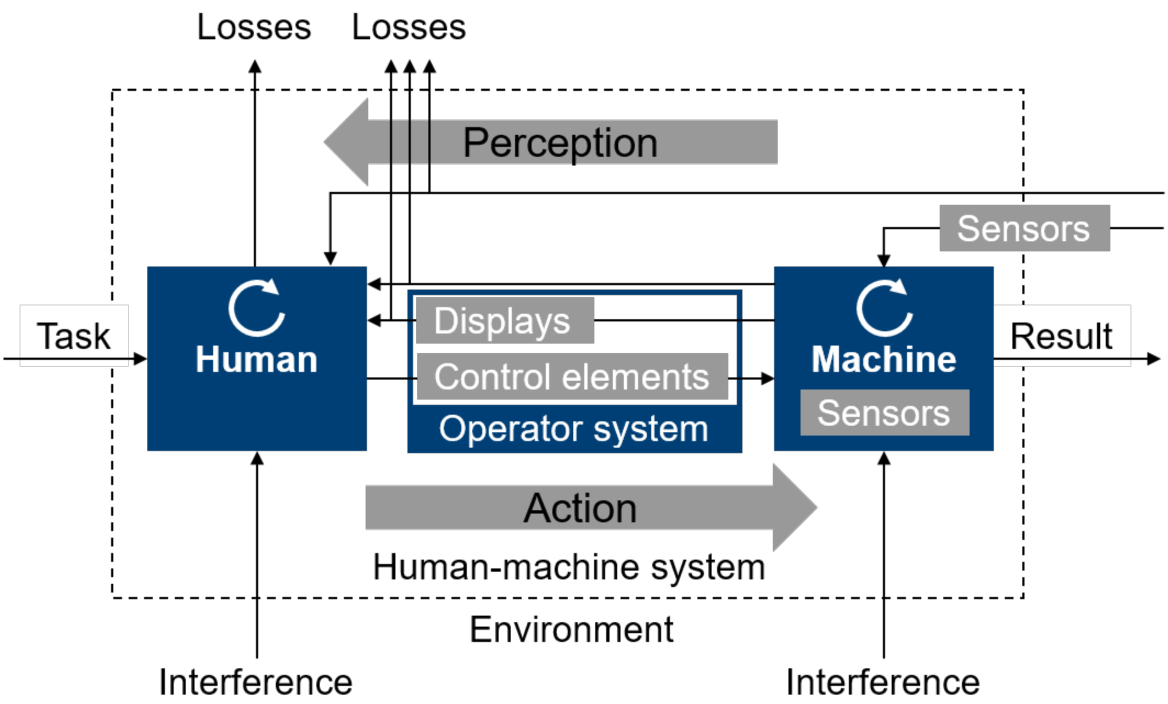


Figure 35: Model of the human-machine interface that can also be applied to a tractor.

For an ergonomic design of an HMI, a deeper understanding of the ergonomic connections and requirements for “perception” and “action” is given in **Figure 36**. The UASW model from SCHMID [46] serves as the basis. Referring to the human-machine interface in Figure 35, the “perception” is from display A to user U. The “action” is from user U to control element S.

U is the user, A is the first letter of the German word for display, S is the first letter of the German word for control element, and W is the first letter of the German word for effect, whereas the effect can be an effective part or an effect itself. For instance, the pick-up of a loading wagon is an effective part, whereas turning on / off the Auto-PTO function causes an effect. Besides other means of displaying the state of an effect or an effective part, the effect or effective part itself can be the display if the user can perceive it sufficiently and the pure visual perception is accurate enough. The current position of a control element can also be a display for the effect or effective part. From a formal perspective, the elements A, S, and W need to exist. However, they can be merged from a physical perspective. The decisive factor for an ergonomic HMI design is the relationship between the elements U, A, S, and W. With the arrows in Figure 36, two types of relationship requirements are illustrated: gray arrows for expectation conformity and blue arrows for movement compatibility.

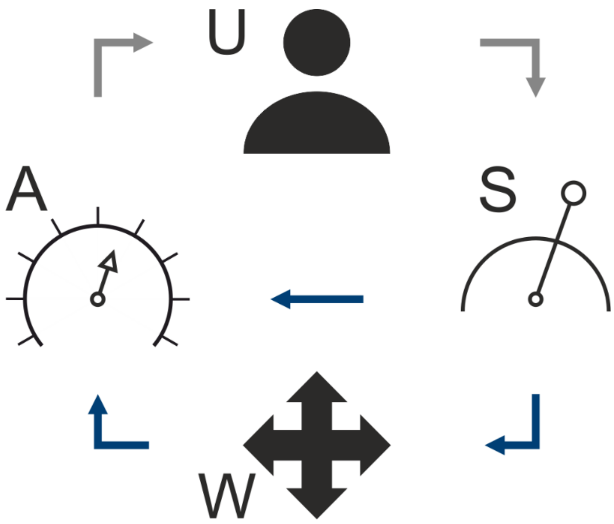


Figure 36: HMI detail level perspective based on the UASW model from SCHMID [46].

Figure 37 from DIN EN 894-2 [47] depicts the requirements for the design of display A to meet the expectations of user U based on her or his stereotype.

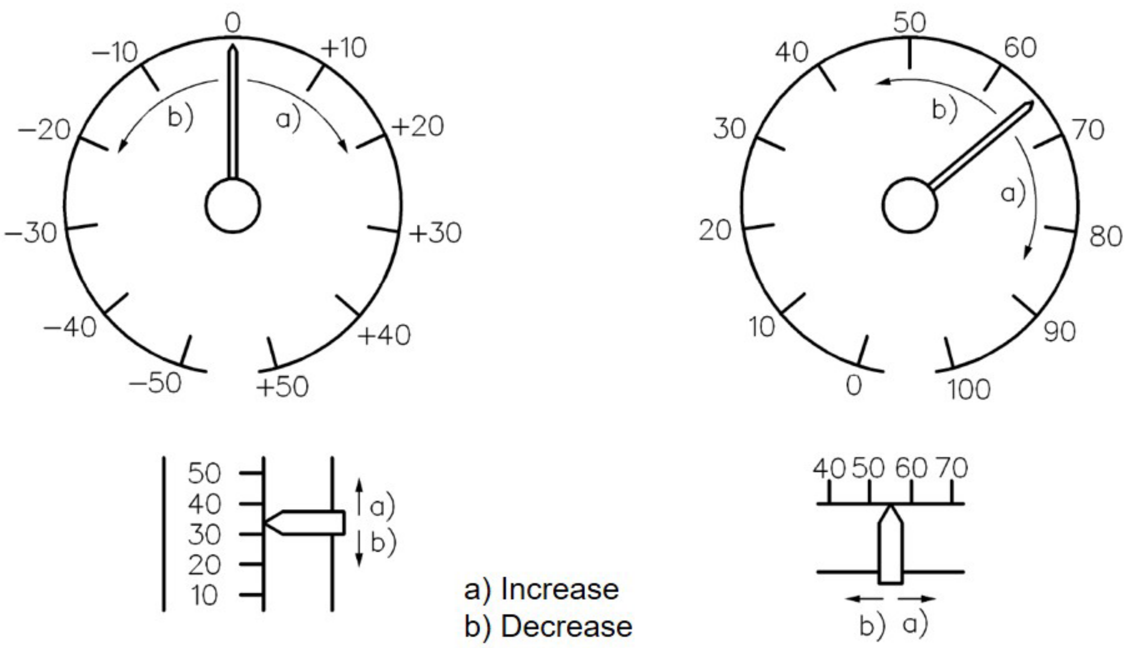


Figure 37: Appropriate directions for the movement of pointers. [47]

Figure 38 from DIN EN 894-4 [48] depicts the requirements for control elements referring to the meaning of the direction of movement to meet the expectations of the users based on their stereotype. There is one exception for rotary valves: the decrease direction is clockwise (CW) [48]. The afore-described and stereotype-based requirements from the display to the user and from the user to the control element can be summed up to expectation conformity (gray arrows in Figure 36).

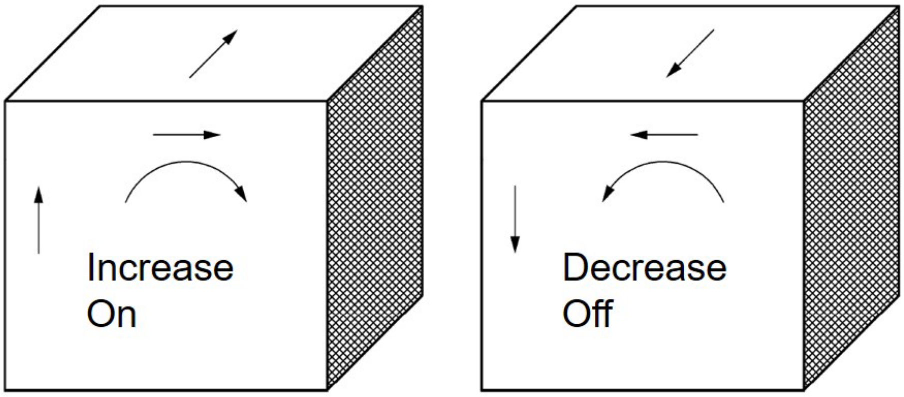


Figure 38: Meaning of the direction of movement of the control elements matching the users' stereotype. [48]

Figure 39 depicts the movement compatibility (blue arrows in Figure 36) between control element S and assigned display A.

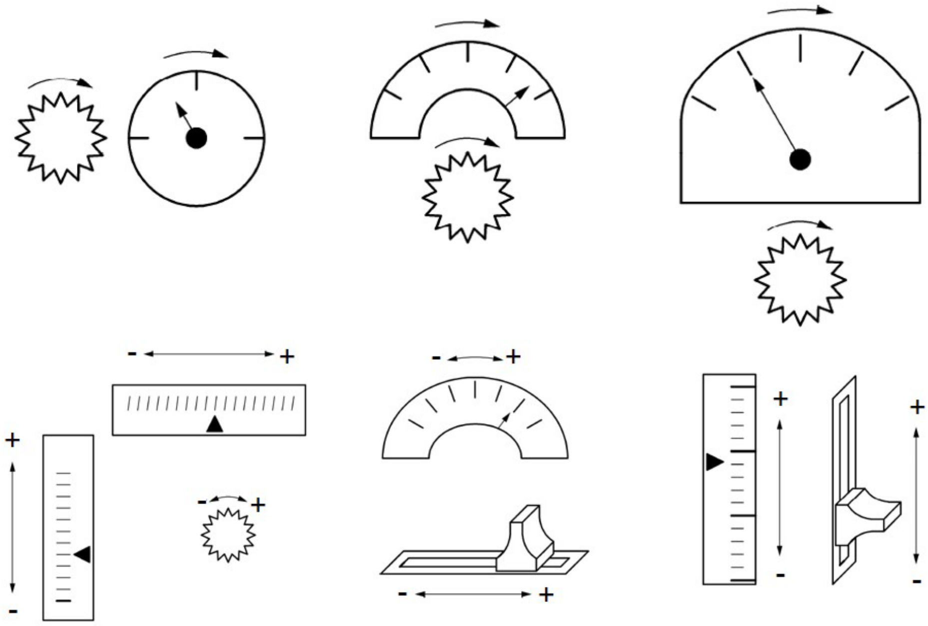


Figure 39: Movement compatibility between control element S and the assigned display A. [48]

The previously described compatibility of movement of A and S implies the compatibility of movement also for A and W, and S and W (blue arrows in Figure 36). Furthermore, the elements A, S, and W of an UASW group should have spatial compatibility to ensure an easy recognition of the group. If the design of an HMI complies with all these requirements, it is a compatible design [45]. BULLINGER [45] names the following positive effects of a compatible design:

- The human learning and practicing phase is shortened,
- the qualitative and quantitative work performance is increased, and
- the risk of operating errors is reduced.

4.3 The conceptual model for operating a tractor-implement combination

As a designer of operator systems, it is essential to understand the psychology of how users approach the cognitive interaction with an operating system since this is decisive for intuitive and easy use. NORMAN devised and introduced a model to describe the connection between the designer, product/system interface, and user [49].

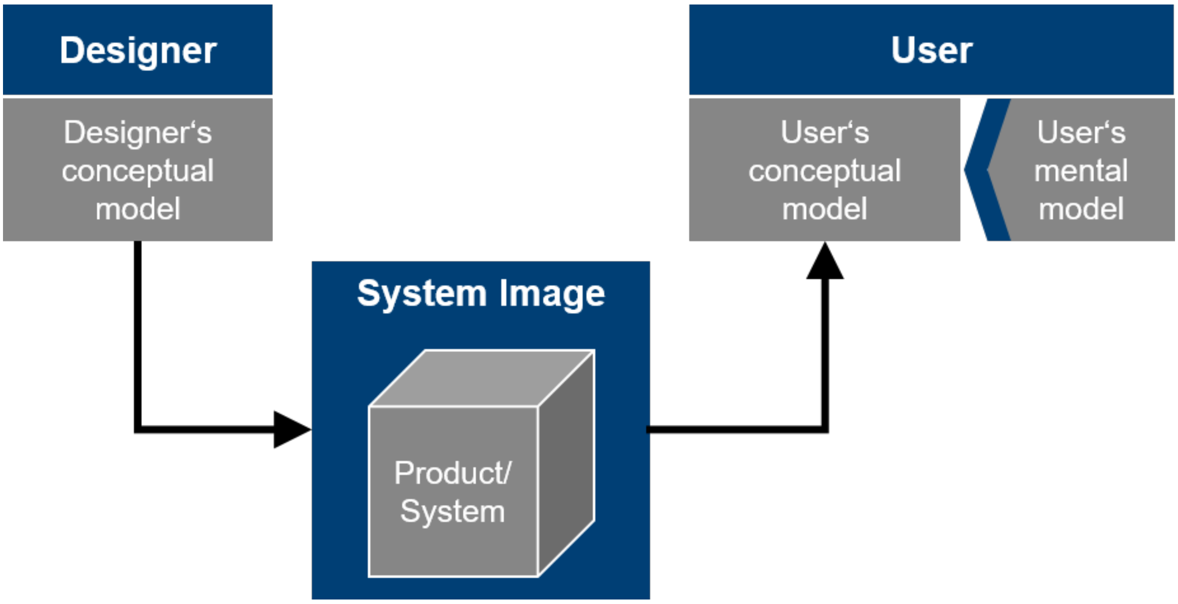


Figure 40: The generic model from NORMAN. Modified from [49].

As depicted in **Figure 40**, NORMAN's model also comprises the terms conceptual model, system image, and mental model. A conceptual model is highly simplified and often incompletely explains how something works. The designer has a conceptual model of a product's look, feel, and operation. WEINSCHENK puts this in a nutshell: A conceptual model is a model that is given to users through the design and interface of the product [50]. Since designers cannot talk to users directly, it is the system image with which they bring their conceptual model to the users. The system image combines all the information available to the users: the perception of the physical structure, documentation, instructions, signifiers, information from websites and salespeople, et cetera. Users have mental models of themselves, others, the environment, and the things they interact with. These mental models are shaped by experiences in the past and intuitive perceptions. They will also be further shaped and updated by new experiences in the future. Based on mental models, users create their conceptual model of a product through the perceived system image, the interaction with the product, experience, training, and instruction. Thus, the burden of communication is with the system image. Hence, the designer must provide appropriate information in the system image to offer an understandable and useable product. To avoid a mismatch between the designer's conceptual model and the user's conceptual model, the designer's conceptual model must be both appropriate and understandable, with clear communication via the system image to help the users understand and use the product. With a mismatch and no training, users would struggle and could not use the product in its intended way or even not at all, which causes frustration on the users' side. [49]

The afore-explained model can easily be applied to a user who only operates a tractor: The tractor designer is aware of the conceptual model of the tractor that is then communicated in the system image T of the tractor. Hence, for the operation of the tractor itself, the user has the appropriate system image T from the tractor designer. So far, this is the afore-explained model. When applying the afore-explained model to a tractor-implement combination, the model becomes more complex. **Figure 41** shows the issues and challenges that occur with state-of-the-art operator systems in tractors when operating one or more implements. The almost static operator system of the tractor's system image T is used to operate changing implements. However, the tractor designer did not consider specific conceptual models of implements when designing the tractor's operator system. In addition, because the tractor's system image T is static, the implement designer cannot transfer the implement's system image I comprising a specific operator system to the user to communicate the conceptual model for the operation of the implement. The ergonomically unfavorable result becomes comprehensive with the extended model in Figure 41: The pain is the users' burden to transform the tractor's system image T to the implement's system image I and vice versa in order to preferentially use the haptic controls of the tractor's MFA. This continuous transformation causes unnecessary cognitive load and is prone to error.

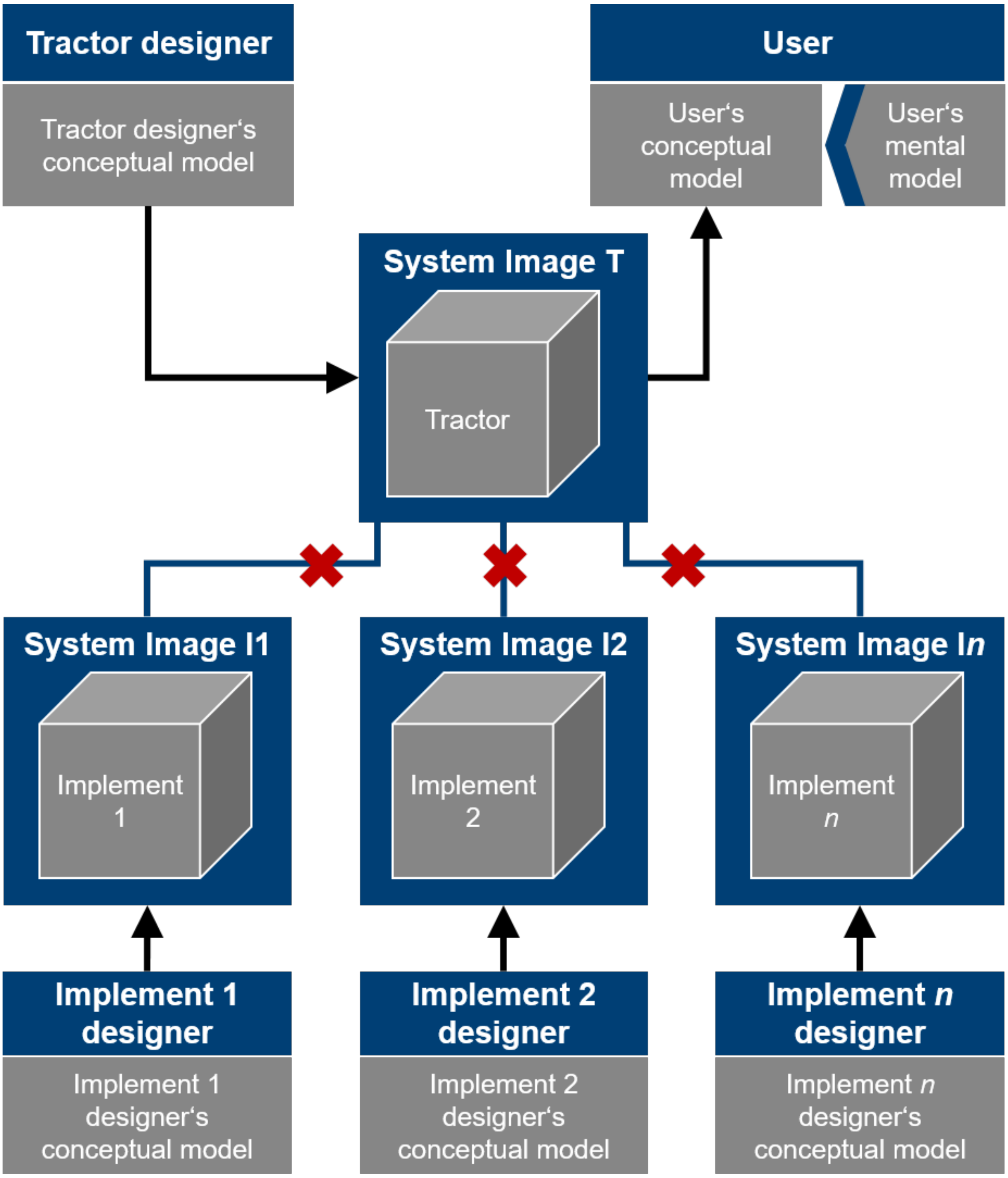


Figure 41: The model from NORMAN [49] adapted to state-of-the-art tractor-implement combination scenarios.

One solution is the ISOBUS [4], with which a virtual software-based control surface of ISOBUS-capable implements can be transmitted to a screen in the cabin. Hence the users can directly control the implement on an operator system belonging to the implement's specific system image. However, additional ISOBUS screens or even tractor screen integrated ISOBUS terminals are more difficult to reach compared to control elements on the MFA. Some MFAs support the mapping of ISOBUS functions to their haptic control elements. However, since the function icon is not mapped an indication is missing and the control element's characteristics remain the same all the time. Another state-of-the-art exception is a little implement-specific control box that the users can mount inside the cabin to get the entire system image of the implement. However, neither mounting and dismounting these control boxes all the time nor having them all inside the cabin simultaneously can be a target-oriented and ergonomically advantageous solution as **Figure 42** impressively shows.

Figure 42: This is what having system images of multiple implements in the cabin looks like with state-of-the-art operator systems. [51]

5 METHODS FOR THE DEVELOPMENT OF ADAPTIVE OPERATOR SYSTEMS

The users' needs must be transferred into a product that satisfies the users' needs. This chapter introduces four methods that support the development of AOSs in particular in the specification and the evaluation phase. The V-model in **Figure 43** puts these methods in the overall context of product development. Methods for conception, realization, and integration are state-of-the-art and thus similar to other product developments.

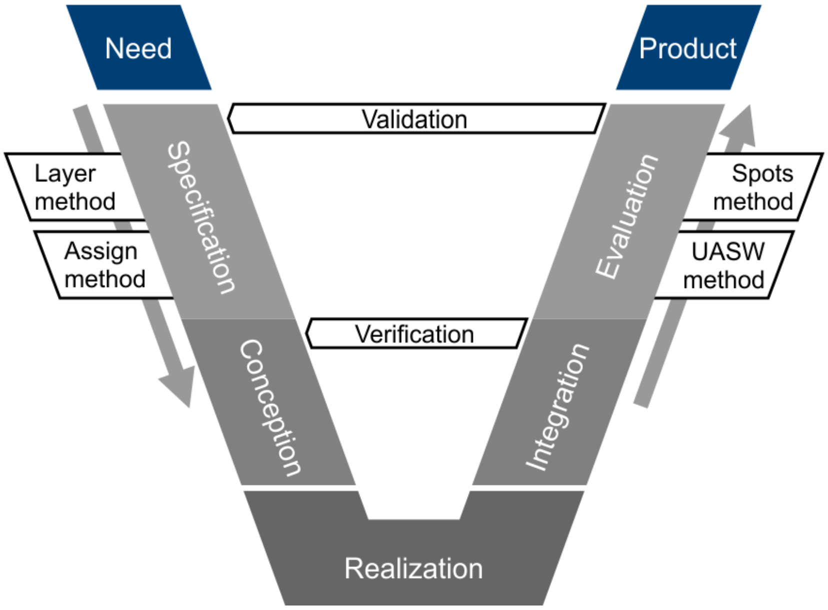


Figure 43: The four methods in the corresponding phases of the V-model, which is the guide for transferring the users' needs into a product. Based on [52].

5.1 Specification of adaptive control elements

SCHEMPP et al. proposed a layer method to specify adaptive control elements on MFAs for tractors [53]. The method yields a specification of basic input characteristics that a control element needs to adaptively provide on a specific position of the MFA layout based on the operating scenarios considered. This method is focused on implement specific functions on the MFA.

The basic input characteristics are ways of interacting with a control element to which every concrete function can be abstracted. **Figure 44** shows six basic input characteristics. They cover all movements along and around the three spatial axes, increasing and decreasing something, turning something on or off, and opening or closing something. On / off can only be a digital input with a discreet on or off, but all other inputs can be either discreet or continuous in their characteristics. For instance, there can be a discreet up and down with two states on the assigned control element. However, there can also be a continuous up and down with a proportional input on the assigned control element.

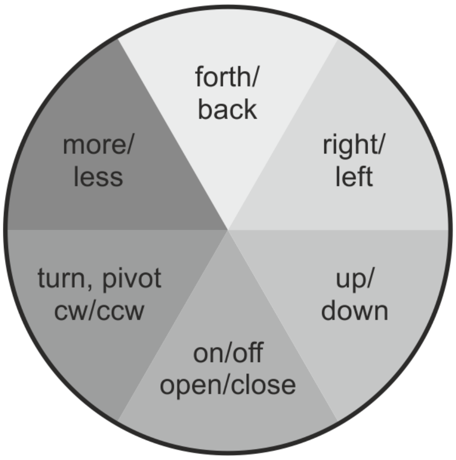


Figure 44: Basic input characteristics to which concrete functions can be abstracted. [53]

First - Define operating scenarios

The method yields the specification based on the operating scenarios that were considered. Hence, the first step is to define these operating scenarios that the target layout of the MFA needs to cover. Then, in each operating scenario, all functions need to be listed based on their frequency of use.

Second – Define MFA base layout

With the alignment to reach zones and the influence of esthetic requirements, a base layout of an MFA can be defined. The fields where the control elements will be placed are defined within that base layout.

Third – Stack operating scenarios

For each operating scenario, all functions are placed in predefined places based on their frequency of use. Hence, high-frequency functions are assigned to better-reachable positions on the MFA. These assignments in each operating scenario are stacked as layers above the base layout. In all layers, a basic input characteristic from Figure 44 is chosen to which the concrete function can be abstracted.

Figure 45 shows a stack of chosen basic input characteristics in the operating scenarios 1 to *n.* The top disc sums up all input characteristics that the control element at that position needs to provide adaptively. On each predefined position for an adaptive control element will be a stack on the base layout of the MFA that specifies all required basic input characteristics for the adaptive control elements.

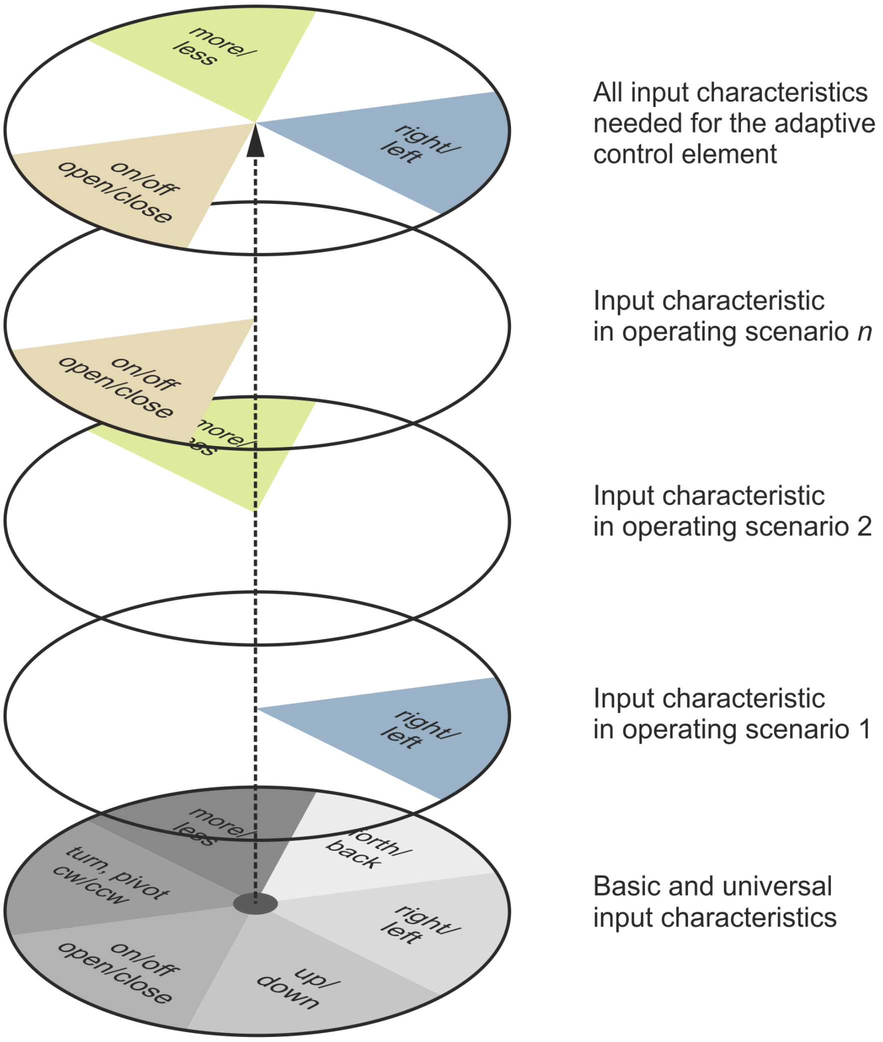


Figure 45: Stacking basic input characteristics with the layer method to specify an adaptive control element at the considered position. [53]

5.2 Assignment of functions to haptic control elements or screens

As depicted in Figure 15, Figure 12, and Figure 10, today's operator systems for tractors comprise haptic control elements on an MFA and a touch-based control area on a screen mounted on the MFA. Even though a screen is advantageous and thus indispensable for information display in today's tractors, it is disadvantageous for operator inputs during operation due to vibration and the need for blind control.

For this, haptic control elements are indispensable [54]. However, the space on MFAs is limited. Thus, functions assigned to haptic control elements must be selected meaningfully according to their frequency of use. The frequency of use of a function depends on the operating phase in which the function is needed. **Figure 46** describes these different operating phases in which a tractor-implement combination is operated and controlled.

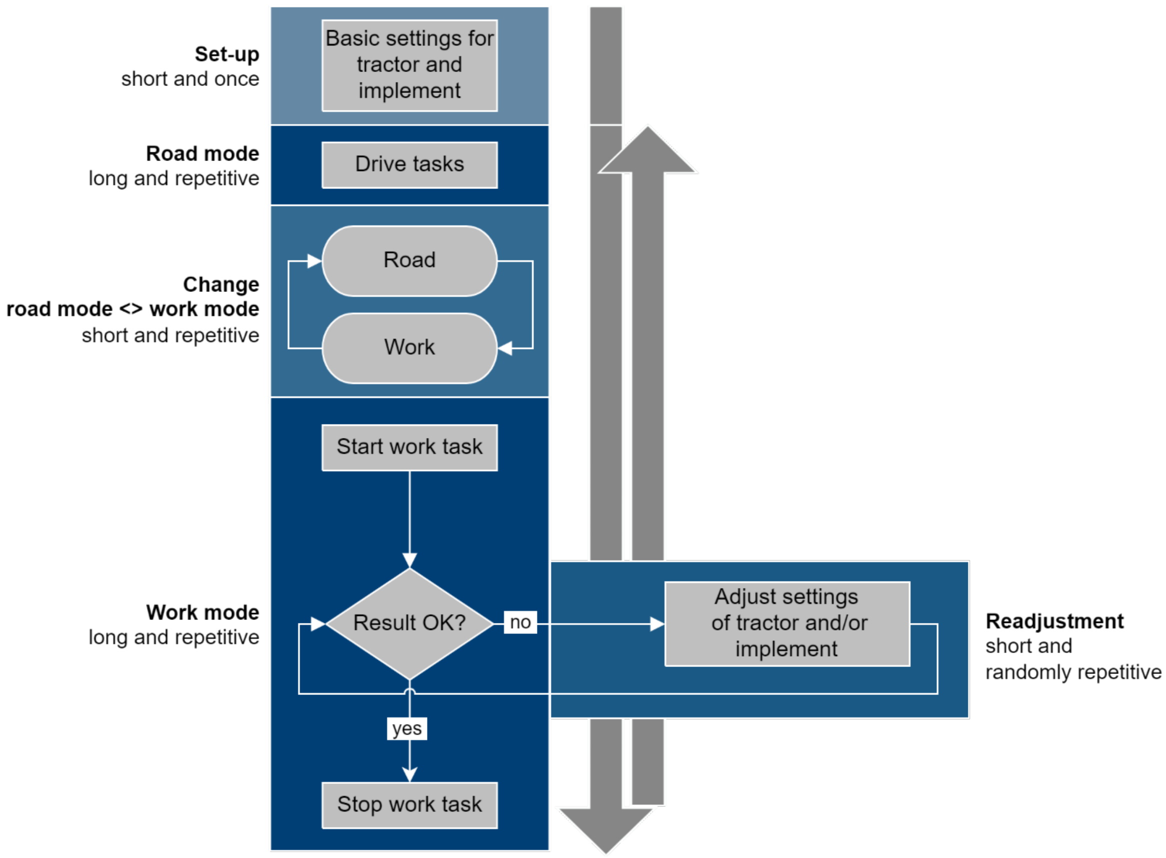


Figure 46: Operating phases for a tractor-implement combination and their qualitative classification considering the relative duration and the frequency of occurrence.

These different phases set the basis for assigning functions to haptic control elements or screens. Each phase has its own relative duration (short or long) and frequency of occurrence (once, randomly repetitive, or repetitive). By means of this qualitative classification, the frequency of use of specific functions in each phase can be estimated:

- Functions of the phases road mode and work mode have the highest frequency of use because they are used frequently during these long and repetitive phases. For instance: change of direction.

- Functions of the readjustment phase have a less high frequency since the phase is short. However, this phase can occur randomly repetitive. For instance: position and draft control of the TPH.
- Functions of the mode change phase have a low frequency. The functions are only used once during the phase. For instance: Lock / unlock TPH.
- Functions of the set-up phase have the lowest frequency since this phase only occurs once when the implement is coupled to the tractor. For instance: Limit the lifting height of the TPH.

Based on the estimates made above, the assignment method uses a simple and fast approach, as shown in **Figure 47**:

- 1. All road mode and work mode-related functions are assigned to haptic control elements (highest frequency).
- 2. Functions of the readjustment phase with a less high frequency should also be assigned to haptic control elements. The backup is the screen.
- 3. The low-frequency functions of the mode change phase are assigned to the screen. In addition, mode changes are often made with a non-moving tractor, which makes it easier to control a screen. However, if there is enough space on an MFA, these functions should also be assigned to haptic control elements.
- 4. All set-up-related functions are assigned to the screen (lowest frequency).

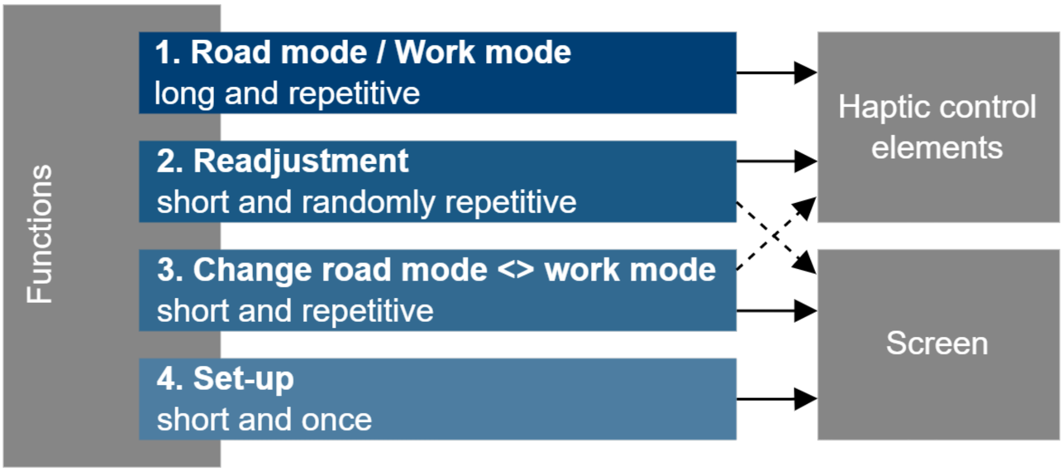


Figure 47: Procedure of the assignment method.

5.3 Evaluation of operator systems in tractors

As shown in Figure 31, cognitive and physical factors are relevant to evaluate HMIs like a tractor's operator system. The methods described and introduced in this chapter cover the evaluation of both factors. All methods are oriented to the definition of usability in DIN EN ISO 9241-11: the usability of a product is the extent to which a product can be used by specific users to achieve specified goals effectively and efficiently and to their satisfaction in a specified context of use [55]. Usability can be further distinguished by functionality and operability [2]. This work focuses on improving the operability of a tractor with given state-of-the-art functionality.

5.3.1 Cognitive factors

Based on the theoretical fundamentals in Chapter 4.2, SCHMID introduced the UASW model and a method to evaluate an operator system by applying the UASW model [22; 46; 56]. The application of his model and method in the field of agricultural machines is described in [5; 57; 58]. It was executed for combine harvesters in [59] and tractors in [57; 58].

As described in Chapter 4.2 and depicted in Figure 36, the elements in the UASW model are related to each other. Based on the evaluation system from VDI 2225-3 [60], the method evaluates the design of the relation between these elements based on the ergonomic principles also described in Chapter 4.2. The result is a cognitive operability factor OF_{cog} that reveals whether the design of the analyzed UASW group is very good ($OF_{cog} \geq 0.8$), good ($OF_{cog} = 0.7$), or insufficient ($OF_{cog} \leq 0.6$).

Figure 48 shows the execution of the method. The method allows the evaluation of the operator system in one or *n* operating scenarios. Within that one or *n* operating scenarios

- a single UASW group ($m = 1$),
- up to all UASW groups for a holistic assessment ($m \geq 2$), or
- the two UASW groups that represent the most difficult case and most frequent case can be evaluated.

Each UASW group *j* is analyzed and evaluated with the scheme in **Table 2**. The criteria expectation conformity and movement compatibility are described in

Chapter 4.2 based on [45]. For each UASW group *j*, this results in a cognitive operability factor $OF_{cog,j}$ showing the group's ergonomic quality. The average of all $OF_{cog,j}$, which can be weighted, then reveals the OF_{cog} for the whole OS based on the analyzed and evaluated UASW groups in the considered operating scenarios.

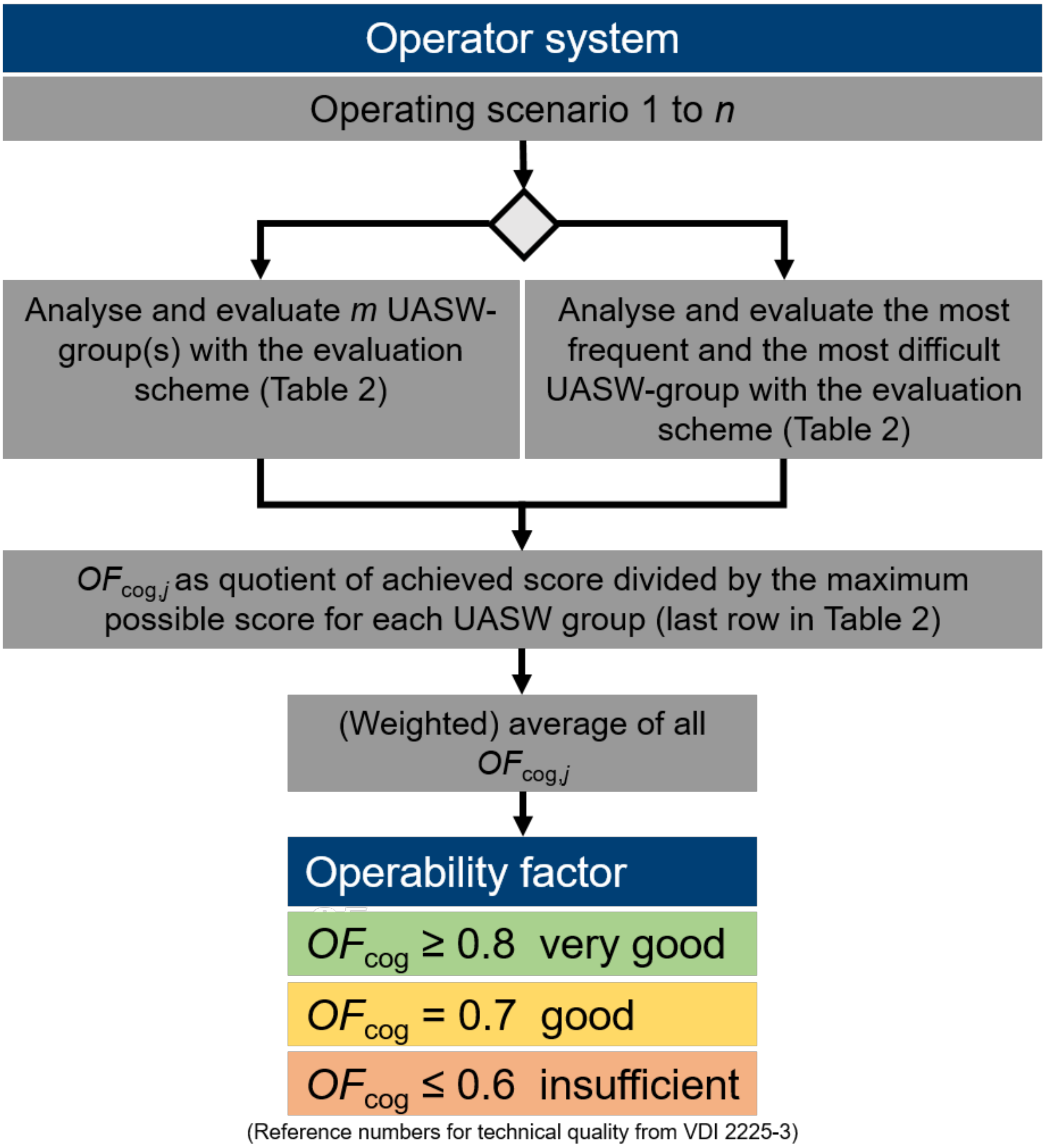
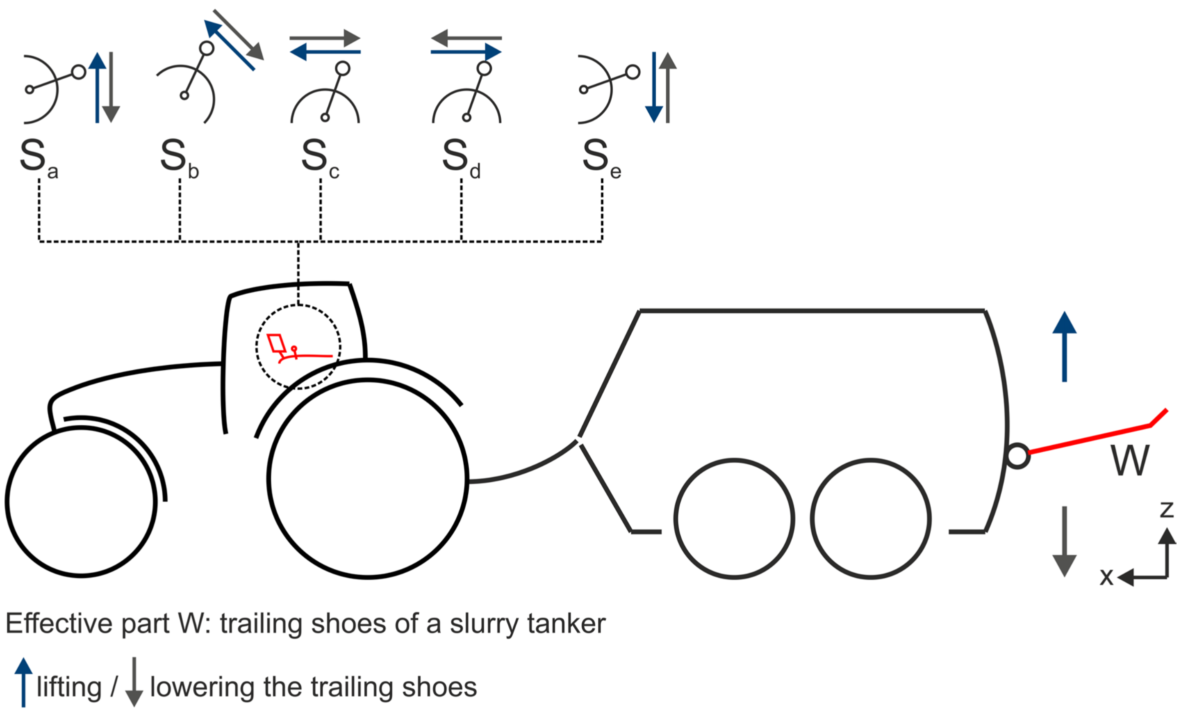


Figure 48: Procedure of the UASW method based on the UASW model and referring to the evaluation scheme in Table 2.

Table 2: Evaluation scheme for the UASW method. [5]

Name of the function		$\sum_{max}$ = 5 x 4 = 20	
Criterion	**Relation**	**Degree of fulfillment *eg***	**Comment**
Expectation conformity	U - A	… out of 4	
	U - S	… out of 4	
Movement compatibility	S - A	… out of 4	
	A - W	… out of 4	
	W - S	… out of 4	
	$\sum_{achv}$		
	Operability factor *OF*$_{cog}$	$\sum_{achv}$ **/** $\sum_{max}$	

As an example, in **Figure 49** the degree of fulfillment *eg* is defined for the W - S relationship (compatibility of movement) based on different control element variants. The lifting and lowering of the trailing shoes of a slurry tanker in the z-direction can be reduced to the x-z plane. The control element variants S lie likewise in the x-z plane. The more the movement of the control element S corresponds to the effective part W, the better the degree of fulfillment concerning the compatibility of movement.



Control element variant	S_a	S_b	S_c	S_d	S_e
Degree of fullfillment *eg*	$eg_a = 4$	$eg_b = 3$	$eg_c = 2$	$eg_d = 0$	$eg_e = 0$
Comment	very good	good	acceptable	insufficient	insufficient

Figure 49: Exemplary evaluation of the movement compatibility: The degree of fulfillment *eg* for the W - S relationship based on different control element variants.

5.3.2 Physical factors

The evaluation of physical factors in ergonomics is based on the load on the cardiovascular and locomotor systems [45]. For state-of-the-art MFAs in tractors, actuating forces are negligible as loads because electro-mechanic control elements allow tuning the actuating forces to an optimum for drivers. However, the locomotor system needs to be considered for the layout of an MFA. In particular, this method evaluates if the high-frequency control elements are placed to ensure the best comfort for the locomotor system. Hence, applying reach zones to check the overall MFA layout is the first step in the method. Second, a ranking order of reach zone spots on the MFA is identified, whereas the rank 1 spot (Figure 8) is the most advantageous one. Third, a frequency analysis of operator inputs is mapped to the MFA layout that is under assessment. Finally, the deviation from a previously determined target share of operator inputs per ranked reach zone spot is calculated, yielding the evaluation result.

First – Reach zones

In particular, the joint angles between limbs of a human body are the origin of reach zones. The literature provides data about comfort angles. However, the data slightly differ from reference to reference. **Figure 50** shows an example from the Institute for Occupational Safety of the German Social Accident Insurance.

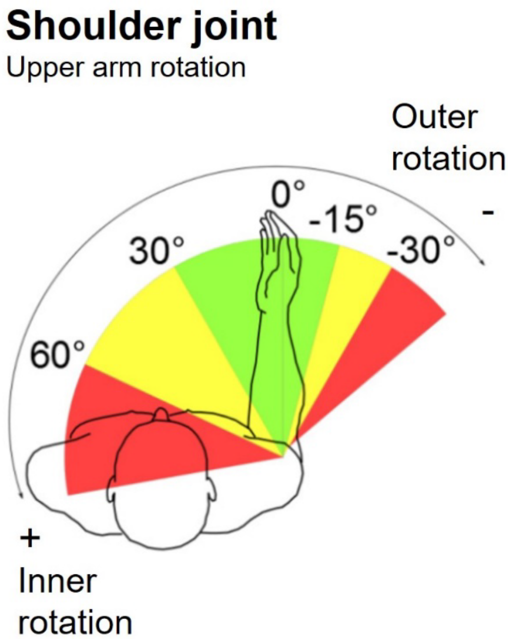


Figure 50: Comfort angle ranges for the upper arm rotation of the shoulder joint. [61]

Based on these comfort angles, reach zones can be defined. Sections within a reach zone that cause only green angles in the joints can be seen as particularly advantageous. The whole chain of joint angles needs to be considered in the assessment: from the hand to the hip point, with the latter as the anchor point for a seated workplace. Literature and standards provide reference reach zones that are sectioned according to ergonomic evaluation, as shown in Figure 4, or the reach zone from DIN EN ISO 6682 [10] depicted in Figure 5. The latter from 2009 is applied as the reference in this work. With the dimensional data provided in this standard, a 3D reach zone was modeled as depicted in **Figure 51**. It is taken to check if the overall MFA layout respectively all control elements on it fit into the comfort zone with reference to the seat index point (SIP). Moreover, the 3D model of the reach zone provides a frame for the overall layout of an MFA in the early stages of the design process.

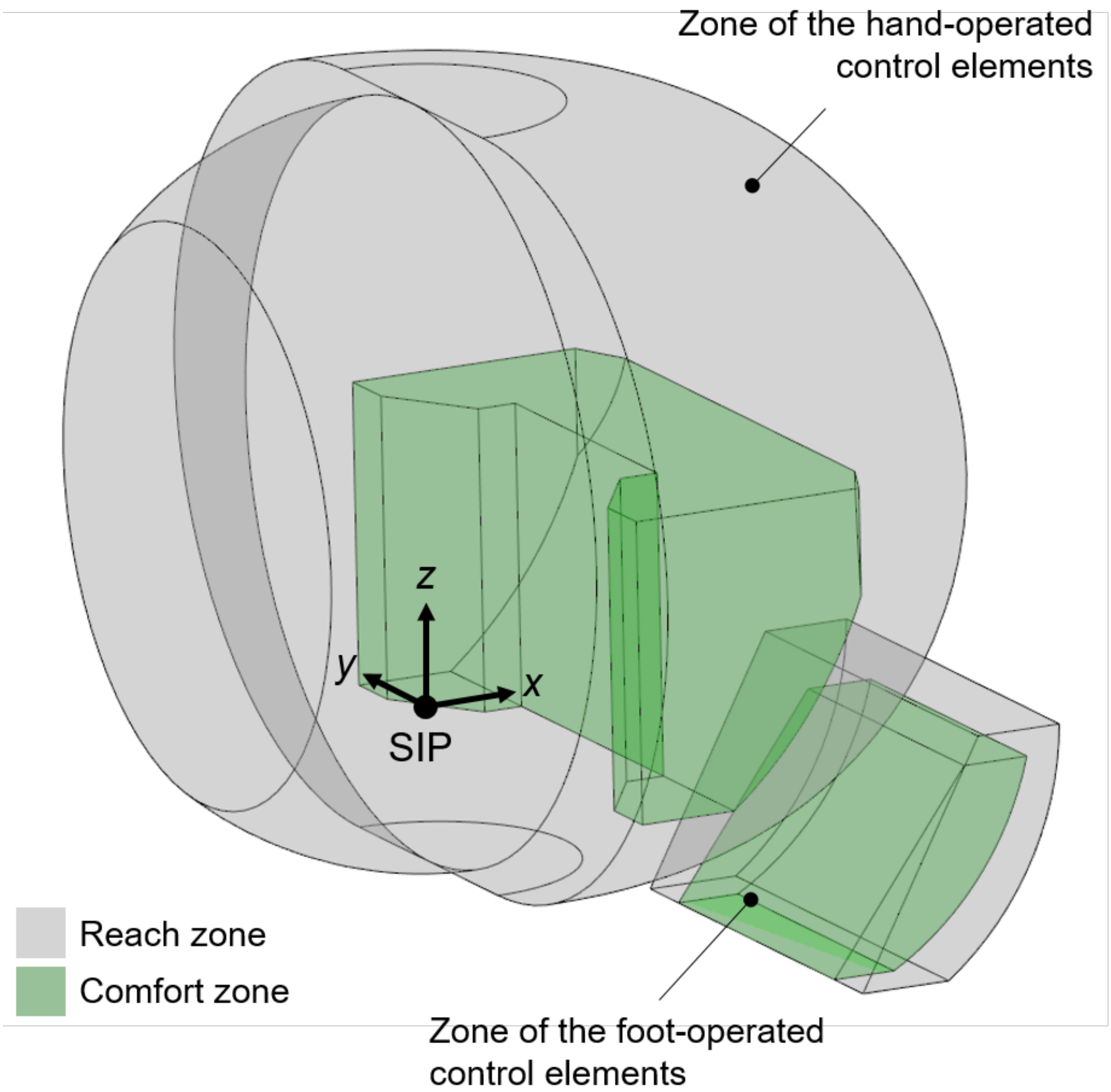


Figure 51: 3D-modeled reach zone from DIN EN ISO 6682 for the reach zone assessment in tractor cabins. The top-view dimensional data are shown in Figure 5, for further dimensional data it is referred to DIN EN ISO 6682.

Second – Reach zone spots

On MFAs, there are several spots for hand positions meaning positions where more than one control element can be operated without moving the hand. In this work, these spots are named reach zone spots. Regarding Figure 8, the rank 1 spot is the best. Beginning from this rank 1 spot, the rank number of the spots increases, whereas the ergonomic value of the spots decreases in the radial direction, as depicted in **Figure 52**.

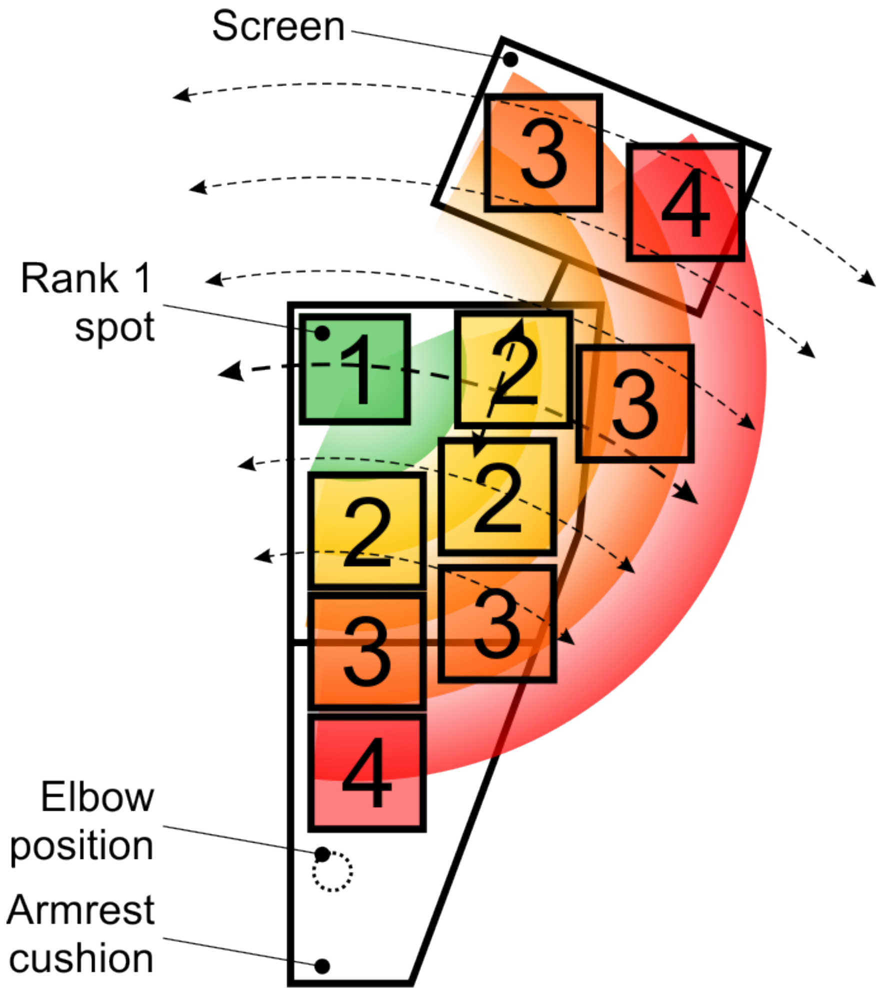


Figure 52: Abstracted MFA with ranked reach zone spots.

Third - Deviation from the target distribution

Target values v_r with $v_r > v_{r+1}$ are defined. The target value v_r specifies the percentage of operator inputs on a specific reach zone spot with rank r. A possible way to define the target values v_r is proposed in **Table 3**. The systematic is an 80 % to 20 % split ratio formed by the looked-at spot and the sum of all higher indexed spots. **Figure 53** qualitatively shows the principle of an ideal distribution of operator inputs. The better, the more operator inputs in the best position with spot rank 1. Hence, the fewer operator inputs in the less advantageous spot ranks with $r \geq 2$, the better.

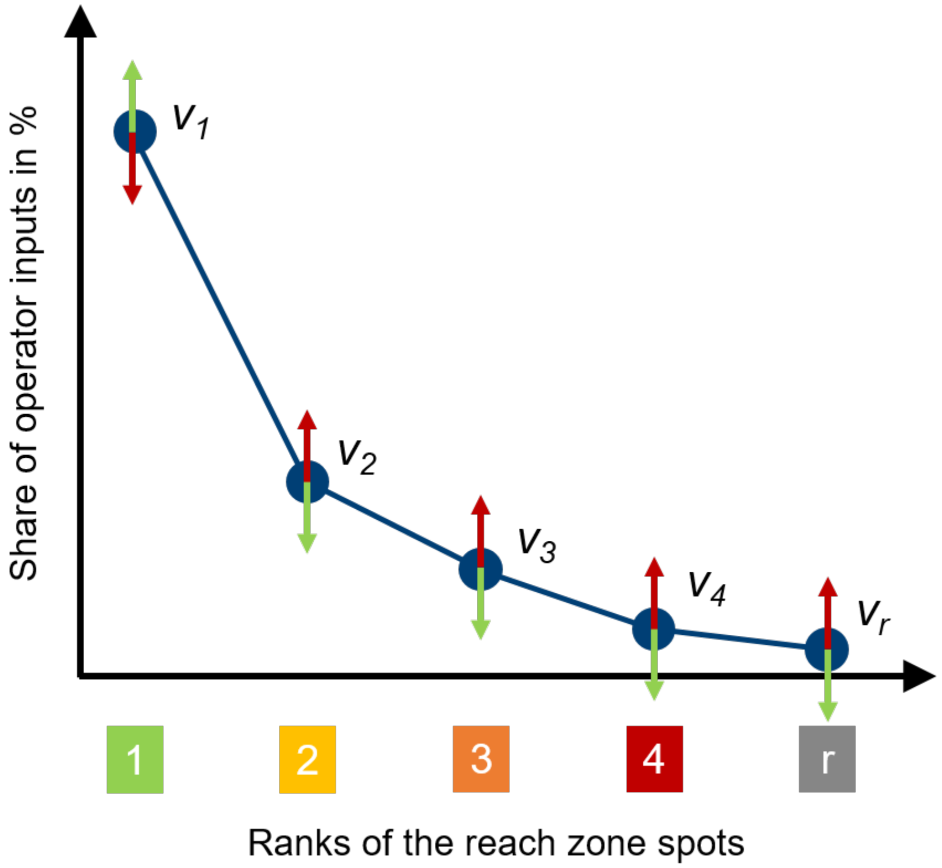


Figure 53: Qualitative target distribution of operator inputs over ranked reach zone spots. The actual distribution positively impacts the evaluation result in the direction of the green arrows and vice versa in the direction of the red arrows.

The actual percentage value a_r of operator inputs in each spot is determined from measurement data. The deviation of the actual distribution from the target distribution is calculated with the following equation

$$OF_{phy} = 1 + (a_1 - v_1) + \sum_{k=2}^{r} (v_k - a_k). \tag{1}$$

The result is an operability factor OF_{phy} representing the physical assessment of the MFA layout. Based on the same operator inputs, it can be compared to OF_{phy} from different MFA layouts. OF_{phy} can be above 1 if the actual distribution over fulfills the target distribution. Based on VDI 2225-3 [60] and thus analogous to OF_{cog}, the physical operability factor OF_{phy} reveals whether the layout of functions on the MFA based on their frequency of use is very good ($OF_{phy} \geq 0.8$), good ($OF_{phy} = 0.7$), or insufficient ($OF_{phy} \leq 0.6$).

Table 3: Proposal for target values v_r based on an 80 % to 20 % split ratio of the looked-at spot and the sum of all higher indexed spots.

Amount of spot ranks	**v_1 in %**	**v_2 in %**	**v_3 in %**	**v_4 in %**	**v_5 in %**
1	100	-	-	-	-
2	80	20	-	-	-
3	80	16	4	-	-
4	80	16	3.2	0.8	-
5	80	16	3.2	0.64	0.16

6 POTENTIAL FOR ADAPTIVE OPERATOR SYSTEMS IN TRACTORS

6.1 Ergonomic fundamentals applied to operating a tractor

Due to its common use as a universal work machine, the tractor is coupled with various implements that differ in their operation. The resulting disadvantages in terms of cognitive ergonomics are described in Chapter 4.3. At this point, this work develops concepts to show how adaptive control systems can overcome these disadvantages.

To achieve added value with an implement, the main function groups of the tractor are crucial. That is why they can be seen as work functions besides comfort functions like air conditioning or entertainment and secondary driving functions like the horn, lights, or windshield wipers. Hence, the derivation of the potential is limited to the four main function groups representing the work functions. A detailed list and description of the four main function groups can be found in Table 1. Within these four main function groups, the potential for adaptivity differs. Hence, a separate analysis is done.

Main function group driving: The driving functions are not directly coupled to the implement itself, so there is no potential for adaptivity.

Main function group TPH: Even though an implement is mechanically coupled to the TPH, the implement itself is not impacted by the TPH's operation, so there is no potential for adaptivity.

Main function group PTO: An implement is mechanically coupled to the PTO to transmit power to the implement to drive some of its functions. Hence, there is the potential to adapt the PTO icon to the actual coupled function of the implement. This icon adaption complies with the dialogue principles described in [62], particularly the suitability for the task. An interactive system is suitable for the task if it supports the users in completing the task, particularly if functionality and dialog are based on the characteristics of the task rather than on the technology used to complete it [62]. Transferring this to the PTO function, an adaptive graphic enables to control a baler, a mower, or the pump of a slurry tanker instead of the PTO as technology.

Main function group hydraulic: The hoses of hydraulic actuators on the implement are coupled to the SCVs on the back or front of the tractor. A hydraulic actuator can be a hydraulic motor that is turned on by opening the coupled SCV with an endless flow. For such a motor, two hoses must be coupled: one for the pressurized flow and one for the unpressurized return flow. Adjusting the flow rate in the settings of the SCV changes the rotations per minute of such a motor. The change of pressurized and unpressurized SCV output changes the rotation direction. Another hydraulic actuator is a hydraulic cylinder that can be extended or retracted. The speed is based on the set SCV flow rate and is proportional to the movement of the assigned control element. To activate the float position of a hydraulic cylinder, the control element has a latch or a separate button nearby. There are single-acting cylinders with one coupled hose and double-acting cylinders with two coupled hoses. The single-acting ones need an external force for either extending or retracting. For an insight into the control of hydraulic actuators, it can be referred back to Figure 15 as an example of a state-of-the-art MFA which shows the following peculiarities.

- The users get no indication of which hydraulic function of the implement is controlled by which of the blue-colored hydraulic control elements. Hence, the first potential for an adaptive feature is an adaptive graphic that shows the actual hydraulic function that is controlled by a specific control element instead of only showing the number or color of a valve. The same principle is mentioned before for the PTO and is also based on [62]. HOERNER [54] describes a clear marking of the assigned function as a perfect design.
- Second, the moving direction of a function driven by a hydraulic cylinder differs. Referring to Chapter 4.2, for an advantageous usability design, the effective part of the function should move in the same direction as the control element. Hence, the second adaptive potential is to adapt the actuating direction of a control element to the direction of the effective part of the implement.

The result: Applying the ergonomic fundamentals to the two high-potential main function groups PTO and hydraulic, the following findings can be recorded:

a) The change of implements entails the need to adapt control elements to the new operating scenario to ensure appropriate ergonomics for the users.
b) Assigned function as an adaptivity feature. The assignment of a function to a control element must be changeable to adapt a control element, as postulated in a).
c) Graphic and color as adaptivity features. Since the assignment of functions to control elements changes, as postulated in b), the graphic and / or color must be changeable to display the currently assigned function to the user.
d) Actuating direction as an adaptivity feature. To align the movement of a control element to the movement of an effective part, the base position of a control element must be changeable.

6.2 Measurement data from operating a tractor

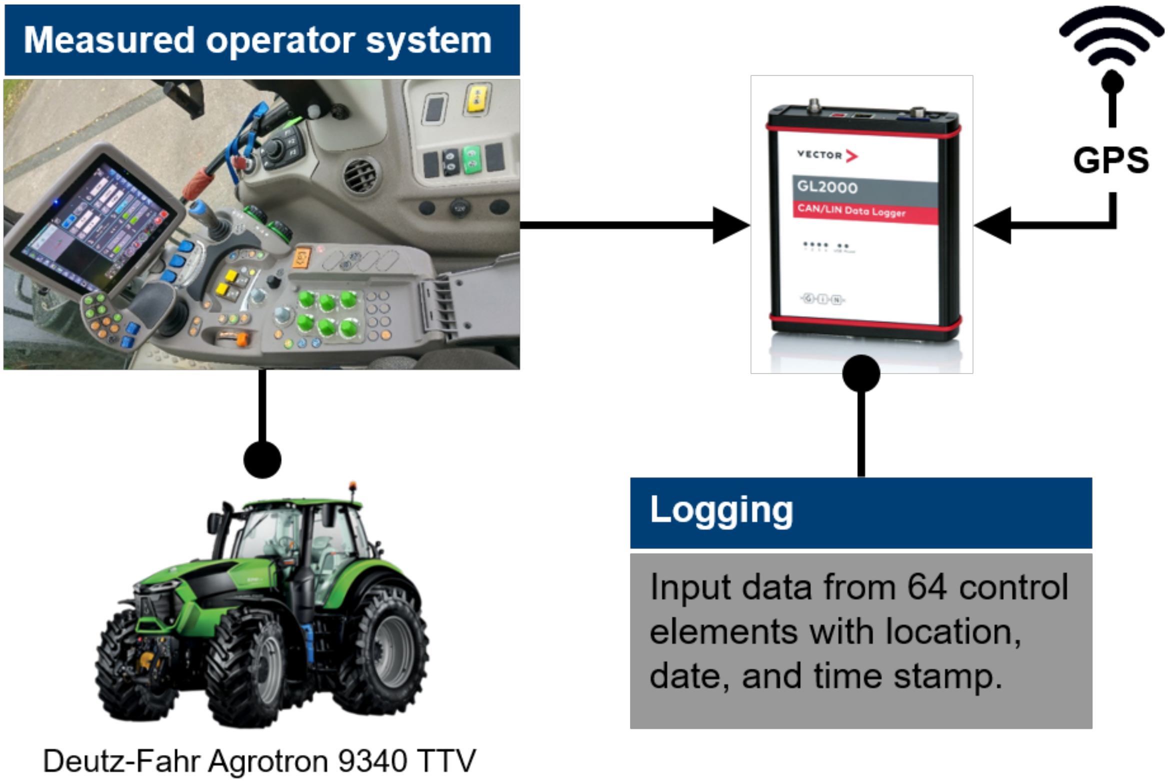


Figure 54: Measuring setup for the operator input logging.

The main hypothesis examined in this work is formulated in Chapter 1. As part of the examination of the main hypothesis, the following sub-thesis is examined in this chapter:

> Not all control elements of a state-of-the-art tractor are needed in each operating scenario.

The proof of this sub-thesis would support the adaptivity features assigned function, availability, and the possibility of reducing the overall number of control elements on an MFA. To prove or disprove this thesis, the PPDAC approach is taken. This approach describes a statistical method with five stages: Problem, plan, data, analysis, and conclusion [63].

1. Problem: The proof or the disproof of the thesis.
2. Plan: Measure the operator inputs via CAN-Bus as depicted in **Figure 54** in one state-of-the-art tractor during one year in different operating scenarios with different drivers.

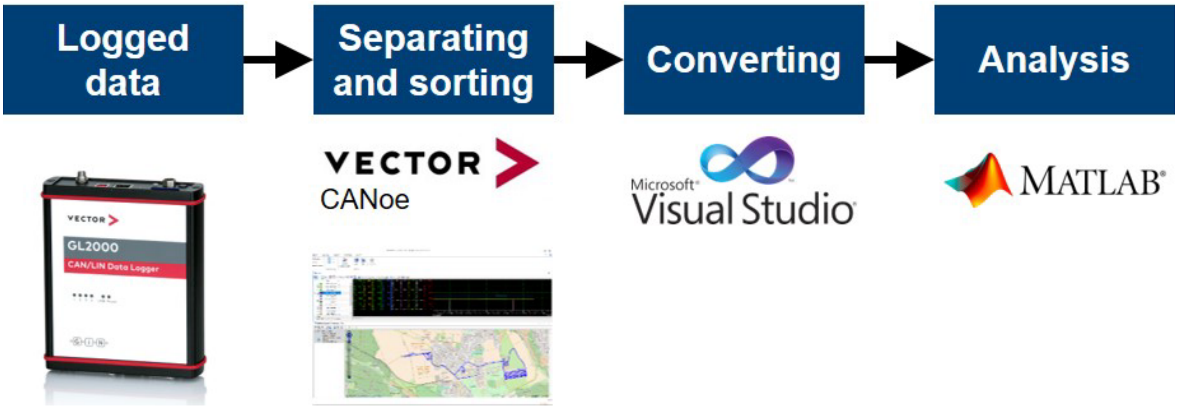


Figure 55: Processing of the measurement data.

3. Data: The measurement data were processed as illustrated in **Figure 55**. **Table 4** in Chapter 6.2.1 gives a sorted overview of the collected data.
4. Analysis: Chapter 6.2.2 describes how the analysis was done with a Matlab algorithm. The results of the analysis are listed in Chapter 6.2.3. and Appendix 12.1.
5. Conclusion: Chapter 6.2.4 comprises the conclusion from the investigation with the answer to the problem, respectively, the sub-thesis. Moreover, additional findings in the results are also listed in this chapter.

6.2.1 Operating scenarios of the measuring runs

Table 4 lists all operating scenarios in which the operator inputs of the drivers were logged. It also shows the associated work scenario, the number of work hours, and the drivers involved in each operating scenario.

Table 4: Overview and sorting of the logged measurement data.

Operating scenario	**Work Scenario**	**Work hours**	**Drivers** (all male)
Deutz-Fahr 9340 TTV Agrotron 	Tractor only	57.57	d1, d2, d3, d4, d5, d6, d7, d8, d9

Operating scenario	**Work Scenario**	**Work hours**	**Drivers** (all male)
Zunhammer MKE14PUL with ISOBUS 	Slurry tanker	75.08	d1, d2, d3
Bergmann TSW 5210 S with ISOBUS 	Universal spreader	21.50	d1, d4
Horsch Terrano 3 FX 	Cultivator	14.78	d1
Kerner Komet K420 	Cultivator	18.00	d1, d5

Operating scenario	**Work Scenario**	**Work hours**	**Drivers** (all male)
Horsch Tiger 4 MT 	Cultivator	36.92	d1, d6
Krone EasyCut 32 CV Float and EasyCut R 320 CV (Side mower) 	Mower	11.78	d1
Krone EasyCut 32 CV Float and EasyCut B 870 CV Collect (Butterfly mower) 	Mower	63.40	d1, d7
Krone MX 400 with ISOBUS 	Loading wagon	43.63	d1, d2, d8

Operating scenario	**Work Scenario**	**Work hours**	**Drivers** (all male)
Krone BigPack 1270 XC with ISOBUS 	Large square baler	15.15	d1, d9
Lemken Juwel 8 with ISOBUS 	Plow	32.12	d1, d3
Lemken Solitair 9 with ISOBUS 	Seeding combination	23.56	d1, d3, d9
Krampe Big Body 750 	Body tipper	35.47	d1, d5

Operating scenario	**Work Scenario**	**Work hours**	**Drivers** (all male)
Wagner WK600 	Body tipper	50.02	d1, d8
14	**10**	**498.98**	**9**

All data were measured in the year 2017. If an operating scenario was done multiple times that year, the data were merged at the end of the measurement phase.

6.2.2 Analysis of the measurement data

All control elements on the MFA of the test tractor (Figure 15), except the parking brake, were analyzed based on CAN-Bus data. The Matlab analysis algorithm can process different types of input signal curves. The signal curve of each control element must be assigned to one of these patterns to count the number of operator inputs correctly. The following types of input signal curves are relevant for the test tractor's MFA.

Non-latching button

Figure 56: A signal curve of a non-latching button. The depicted CE of the analyzed MFA is an example of this type of signal curve.

Referring to **Figure 56**, when the non-latching button is pressed, the value 1 is on the CAN-Bus, and the value 0 when the button is released. Thus, the algorithm counts an input if there is a signal edge in the data where the value goes from 0 to 1. Other events are not considered. With the signal curve in Figure 56, one operator input was counted.

Thumbwheel with one-sided latching point

As illustrated in **Figure 57**, the control element outputs the value N for neutral. The neutral area has the lower tolerance limit C and the upper tolerance limit B. If the signal is outside the neutral area, it triggers the SCV to open in the direction that is linked to above or below the neutral area. The more the signal is outside the neutral area, the more the SVC opens, which connects the SCV proportionally to the movement of the control element. If the control element is moved above the threshold A, it has a latching point and brings the SCV into float position until the user releases the latching point. The values A, B, C, and N can differ from one SCV control element to the other.

First, the algorithm categorizes the signal curve into four sections -1,0,1, and 2, based on the signal value depicted in Figure 57. Second, the algorithm counts the operator inputs. An operator input starts when the signal curve leaves the neutral area and ends when it returns to the neutral area. The algorithm detects the direction in which the SCV is controlled and if the float position is engaged. However, it sums all kinds of inputs into one number of inputs without any distinction. With the signal curve in Figure 57, four inputs were counted.

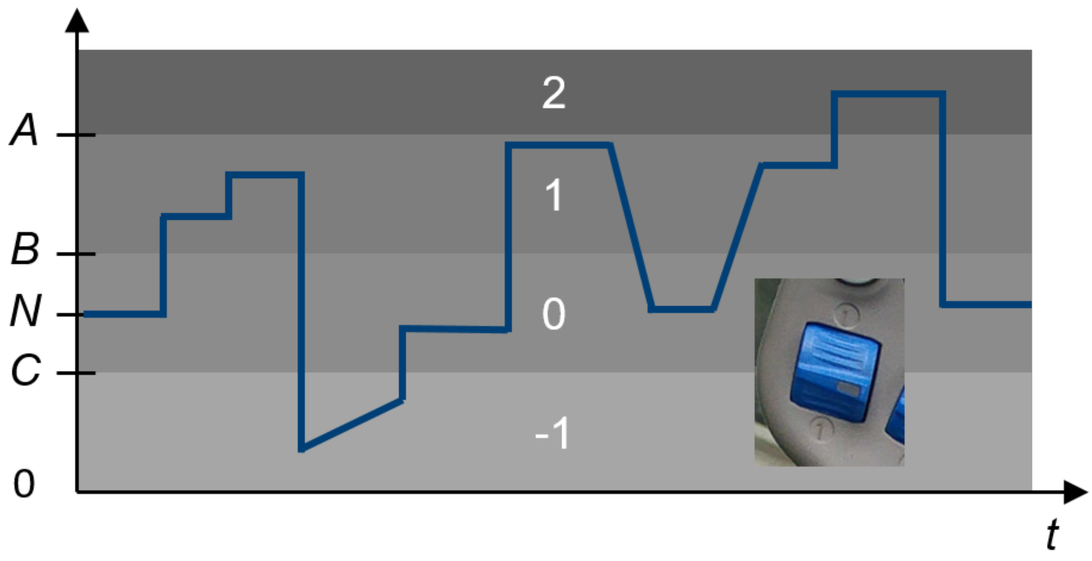


Figure 57: A signal curve of a proportional control element for the SCVs of the tractor. The depicted CE of the analyzed MFA is an example of this type of signal curve.

Rotary controller

As depicted in **Figure 58**, a rotary switch's signal curve ranges from 0 to 1000. The algorithm categorizes the signal curve into the sections 0 (the derivative of the signal curve is 0), -1 (the derivative of the signal curve is negative), and 1 (the derivative of the signal curve is positive). Operator input is counted when a 0-section is followed either by a 1-section or a -1-section. Other events are not considered. With the signal curve in Figure 58, three inputs were counted.

Figure 58: A signal curve of a rotary switch with a value range from 0 to 1000. The depicted CE of the analyzed MFA is an example of this type of signal curve.

Rotary wheel with detents

As shown in **Figure 59**, the pulse wheel sends a pulse with each “click” to increase or decrease a setting value, comparable to a computer mouse wheel. One direction has positive pulses, and the other direction has negative pulses. The algorithm counts a new input if no pulses occur for at least 0.5 s before a new pulse. In Figure 59, the condition $t_1 = t_2 = 0.5$ s applies. Thus, two inputs were counted with the signal curve in Figure 57.

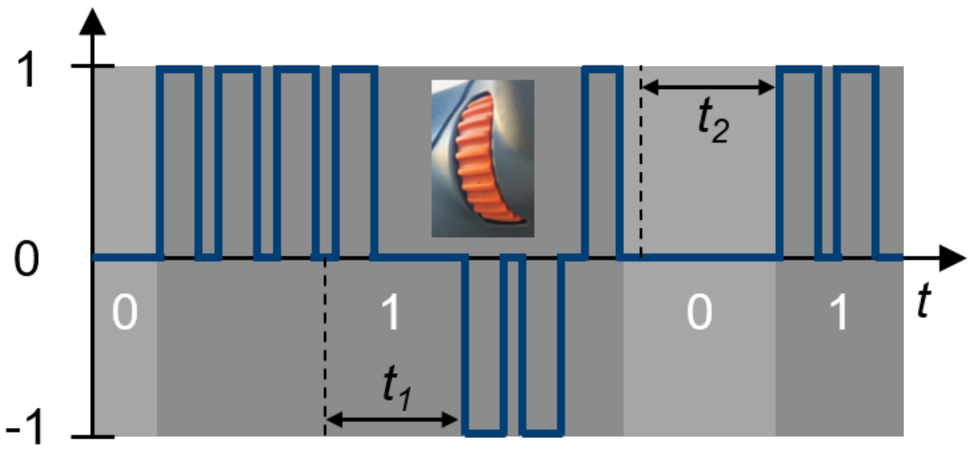


Figure 59: A signal curve of a pulse wheel. The depicted CE of the analyzed MFA is an example of this type of signal curve.

Shuttle shifter

Referring to **Figure 60**, a latching shifter sends discrete signal values based on its position. Every change in the signal value is counted as an input. With the signal curve in Figure 60, four inputs were counted. The first section after the key-on of the tractor is not counted.

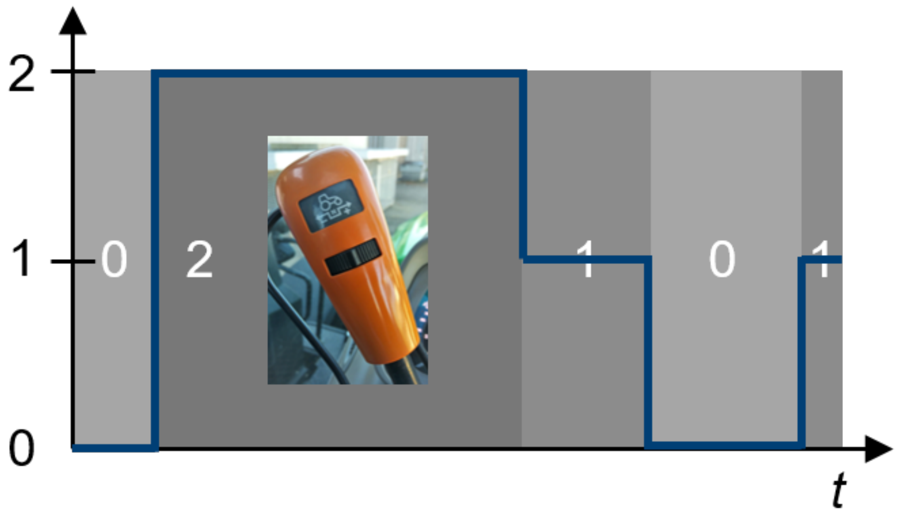


Figure 60: A signal curve of a discrete latching shifter. The depicted CE of the analyzed MFA is an example of this type of signal curve.

The PTO switches are an exception. For safety reasons, these are two-step control elements. However, with the two-step signals, an input was not always clear to detect with the algorithm. Thus, for the front and rear PTO, a status signal of the tractor was used to count the edges from 0 to 1. This counting is only valid when the PTOs are neither part of the headland management nor the AutoPTO for the rear PTO was engaged.

Operator inputs via the screen are only counted when they have an ISOBUS-related input. The ISOBUS input is not further distinguished. All ISOBUS implements were controlled via the Virtual Terminal. The AUX-N functionality with mapping ISOBUS functions to haptic control elements on the MFA was not used.

For the validation of the analysis algorithm, test measurements on the tractor have been conducted. For each of the previously mentioned signal types, a predefined number of operator inputs was conducted on the MFA of the tractor. Then the test measurement file was analyzed with the algorithm to check if the result of the algorithm corresponds to the predefined number of operator inputs. For all these test measurements, a match of 100 % was achieved for each signal type.

6.2.3 Results of the analyzed measurement data

A histogram with the frequency distribution and a heatmap on the MFA show the results of the analyzed measurement data. With the relative frequency (RF), the histograms reveal how often a certain percentage of control elements is used. The number of measured control elements is $n_{tot} = 64$. The number of histogram bins b is set with the following equation from Terrel and Scott [64]

$$b \geq (2n)^{1/3} \tag{2}$$

what yields to $b = 6$. Hence, for the width w of the bins follows

$$w > \frac{i_{high} - i_{low}}{b} \tag{3}$$

where i_{high} is the highest number of operator inputs made with one control element, and i_{low} is the lowest number of operator inputs overall made with one control element.

Even though control elements with an input of $i = 0$ would belong to bin 1, the histograms deliberately show an additional bin 0 to provide information on how many control elements are not used at all. Since n is constant for all measurements, it yields seven linear bins for all histograms, including the additional bin 0. However, the bin width w varies based on i_{high} and i_{low}, which also depend on the length of the measuring runs. Nevertheless, because b is constant, the measuring runs are comparable to each other on a relative basis since the bins always cover the same percentage of the absolute operator inputs. According to the number of operator inputs i of a control element j, the control element is assigned to a bin whose boundaries cover the number of its operator inputs i_j. The height of a bin is the relative frequency of how often the covered range of operator inputs occurs. Expressed differently, it is the percentage share of all control elements for which the number of operator inputs is within the range of that bin. The relative cumulative frequency (RCF) curve reveals the sum of all relative frequencies starting from bin 0 up to a specific bin.

According to a color scale, the heatmaps color every single control element based on its frequency of use. The color scale is logarithmic to achieve a good color differentiation in the low-frequency range. Furthermore, the heatmaps put the frequency of use for every single control element in the context of its position on the MFA. If there was one, the ISOBUS input is shown in the white square on the screen.

Figure 61 clarifies the correlation between the histograms' linear bins and the heatmaps' logarithmic color scale. The lower limit of the color scale is set by the overall lowest number of operator inputs i_{low} made with one CE. The upper limit is set by the overall highest number of operator inputs i_{high} made with one CE. All control elements *j* without an operator input *i* (i = 0) are assigned to bin 0.

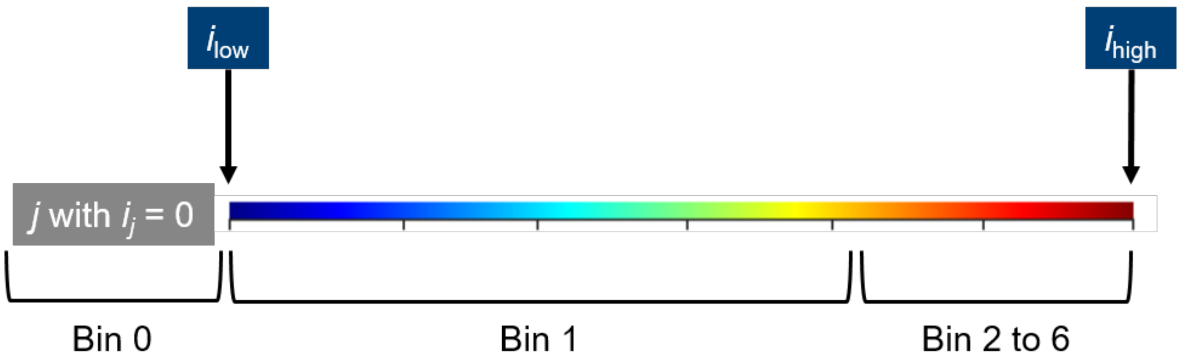


Figure 61: Correlation between the histograms' linear bins and the heatmaps' logarithmic color scale.

In the following, one exemplary operating scenario of each work scenario is listed. The remaining ones are listed in Appendix 12.1.

6.2.3.1 Deutz-Fahr 9340 TTV Agrotron

Overall data for operating a Deutz Fahr 9340 TTV Agrotron during 57.57 work hours:

• Overall operator inputs:	1986
• Operator inputs per minute:	0.57
• Average operator inputs per control element:	31.03
• Average operator inputs per control element without bin 0:	32.03
• Median of operator inputs for all control elements:	7
• Number of CEs for at least 80 % of all operator inputs:	16
• Percentage of CEs for at least 80 % of all operator inputs:	25 %

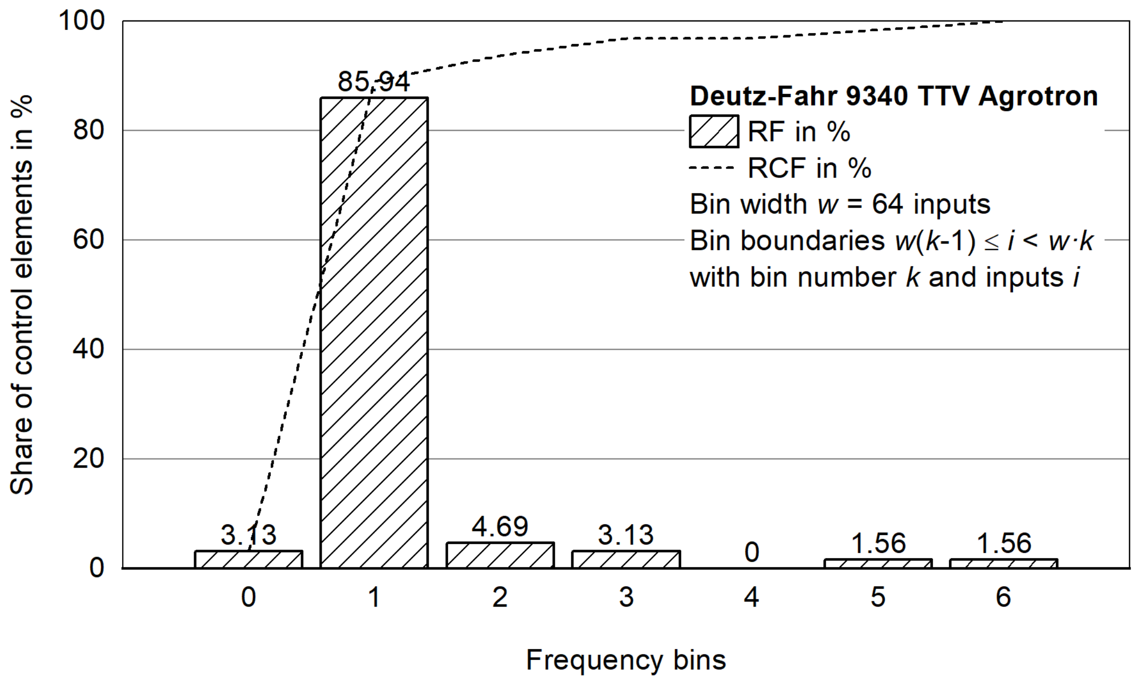


Figure 62: Histogram for the relative and relative cumulative frequency distribution for operating a Deutz Fahr 9340 TTV Agrotron during 57.57 work hours.

Control elements in high-frequency bins of **Figure 62** (code refers to Table 1):

- Bin 2: TPH front - depth control (TPH40),
  TPH front - maximum lifting height (TPH70),
  Fine-tuning of speed limit (DT91)
- Bin 3: Forward direction (D50),
  Backward direction (D50)
- Bin 5: Set maximum speed (DT90)
- Bin 6: Consent button (M20)

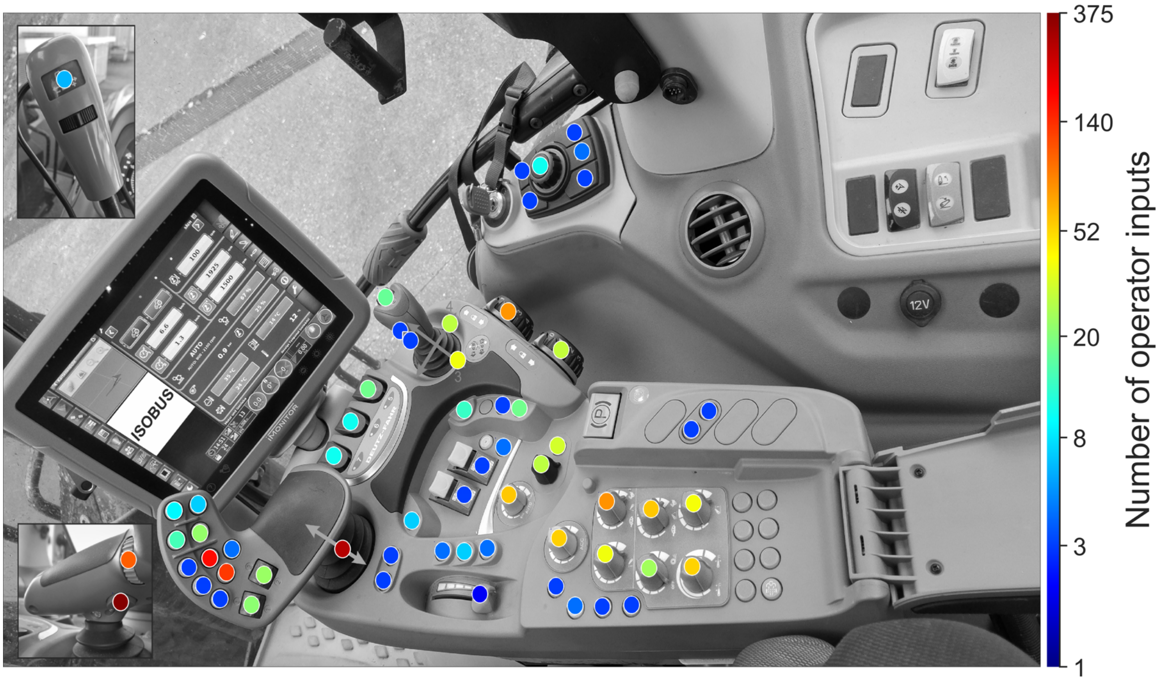


Figure 63: Heatmap for operating a Deutz Fahr 9340 TTV Agrotron during 57.57 work hours.

6.2.3.2 Zunhammer MKE14PUL with ISOBUS

Overall data for operating a Zunhammer MKE14PUL with ISOBUS during 75.08 work hours:

- Overall operator inputs: 8345
- Operator inputs per minute: 1.85
- Average operator inputs per control element: 130.39
- Average operator inputs per control element without bin 0: 166.9
- Median of operator inputs for all control elements: 14.5
- Number of CEs for at least 80 % of all operator inputs: 9
- Percentage of CEs for at least 80 % of all operator inputs: 14 %

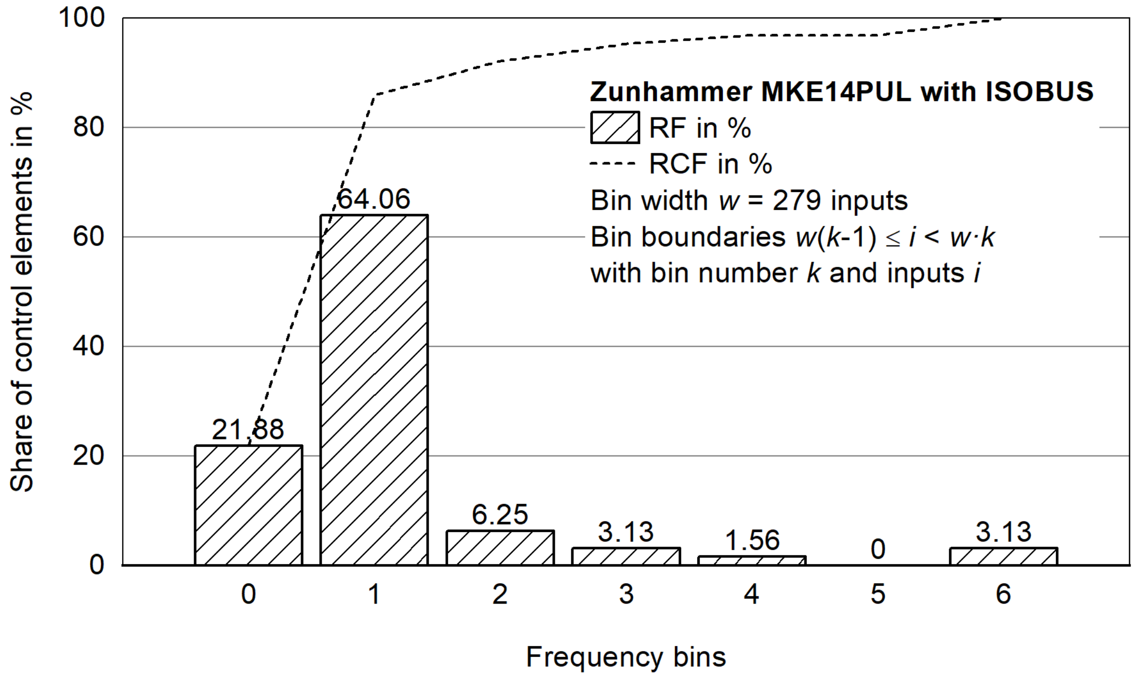


Figure 64: Histogram for the relative and relative cumulative frequency distribution for operating a Zunhammer MKE14PUL with ISOBUS during 75.08 work hours.

Control elements in high-frequency bins of **Figure 64** (code refers to Table 1):

- Bin 2: Control element 3 for an SCV (H10),
  Control element 6 for an SCV (H10),
  PTO rear (PTO10),
  Fine-tuning of speed limit (DT91)

- Bin 3: Control element 2 for an SCV (H10),
  Consent button (M20)
- Bin 4: Control element 4 for an SCV (H10)
- Bin 6: Set maximum speed (DT90),
  ISOBUS input

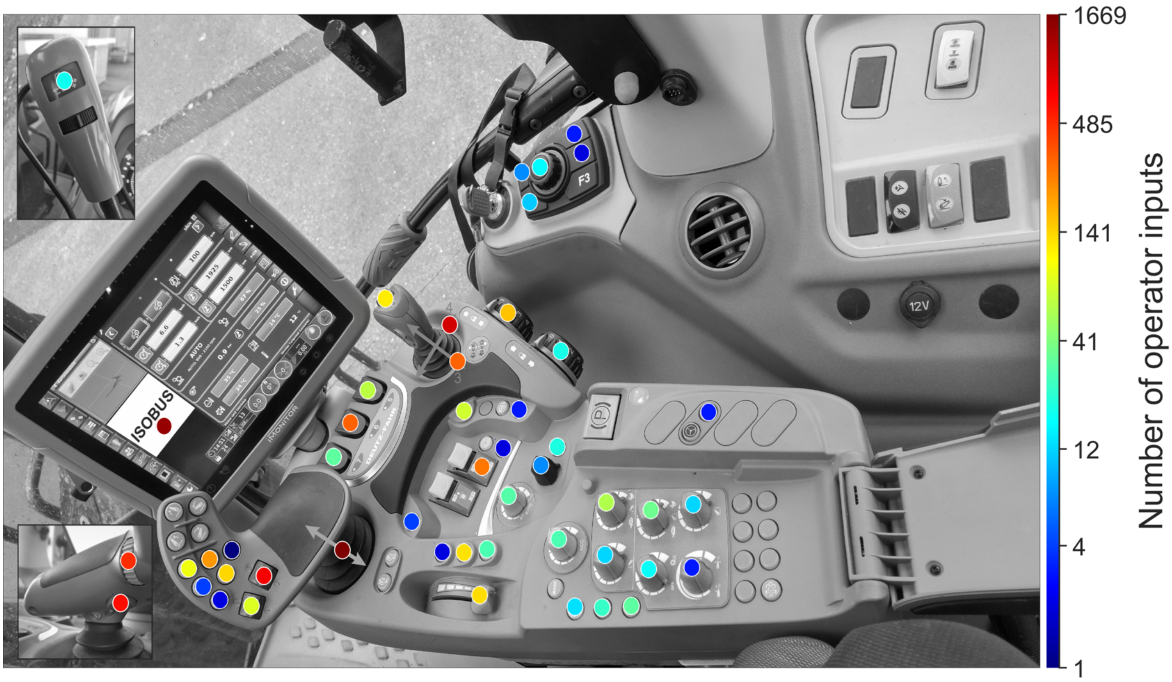


Figure 65: Heatmap for operating a Zunhammer MKE14PUL with ISOBUS during 75.08 work hours.

6.2.3.3 Bergmann TSW 5210 S with ISOBUS

Overall data for operating a Bergmann TSW 5210 S with ISOBUS during 21.5 work hours:

• Overall operator inputs:	997
• Operator inputs per minute:	0.77
• Average operator inputs per control element:	15.58
• Average operator inputs per control element without bin 0:	29.32
• Median of operator inputs for all control elements:	1
• Number of CEs for at least 80 % of all operator inputs:	7
• Percentage of CEs for at least 80 % of all operator inputs:	11 %

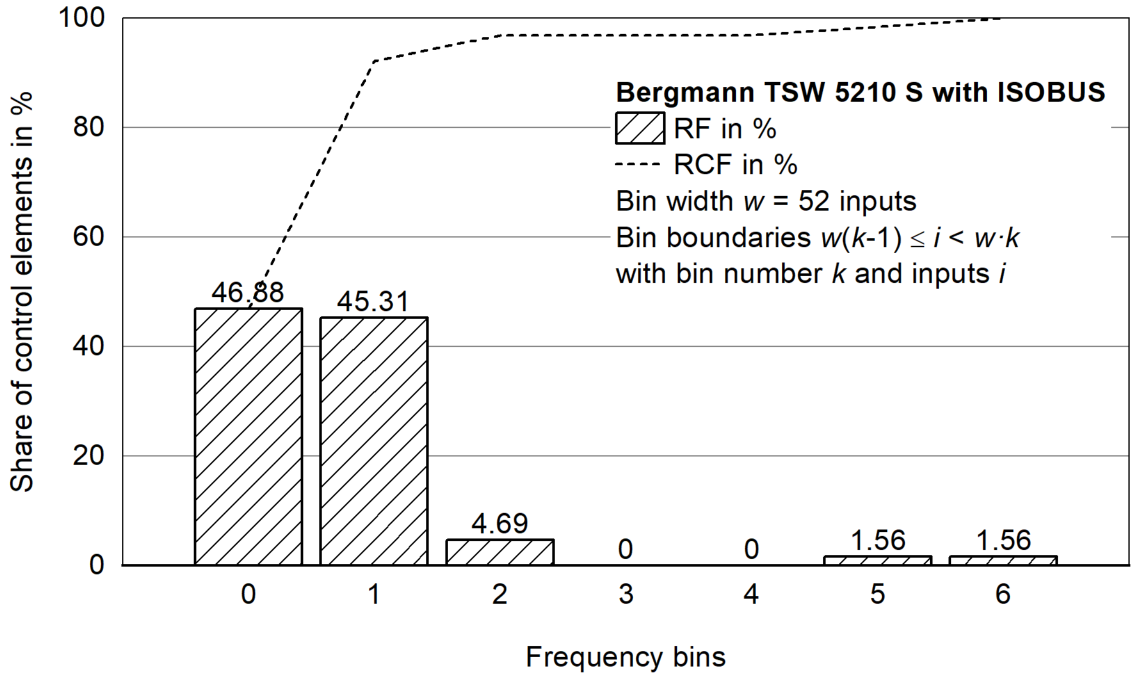


Figure 66: Histogram for the relative and relative cumulative frequency distribution for operating a Bergmann TSW 5210 S with ISOBUS during 21.5 work hours.

Control elements in high-frequency bins of **Figure 66** (code refers to Table 1):

- Bin 2: Forward direction (D50),
  Backward direction (D50),
  Set maximum speed (DT90)
- Bin 5: Consent button (M20)
- Bin 6: ISOBUS input

Figure 67: Heatmap for operating a Bergmann TSW 5210 S with ISOBUS during 21.5 work hours.

6.2.3.4 Horsch Tiger 4 MT

Overall data for operating a Horsch Tiger 4 MT during 36.92 work hours:

- Overall operator inputs: 10260
- Operator inputs per minute: 4.63
- Average operator inputs per control element: 160.31
- Average operator inputs per control element without bin 0: 213.75
- Median of operator inputs for all control elements: 9
- Number of CEs for at least 80 % of all operator inputs: 3
- Percentage of CEs for at least 80 % of all operator inputs: 5 %

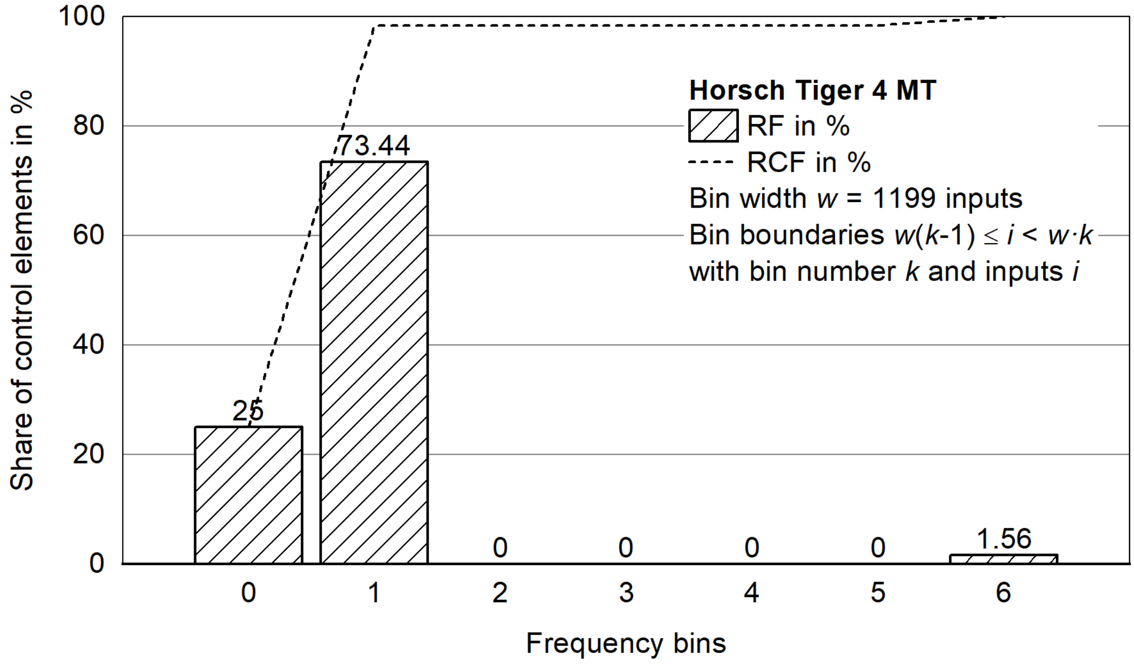


Figure 68: Histogram for the relative and relative cumulative frequency distribution for operating a Horsch Tiger 4 MT during 36.92 work hours.

Control elements in high-frequency bins of **Figure 68** (code refers to Table 1):

- Bin 6: Control element 2 for an SCV (H10)

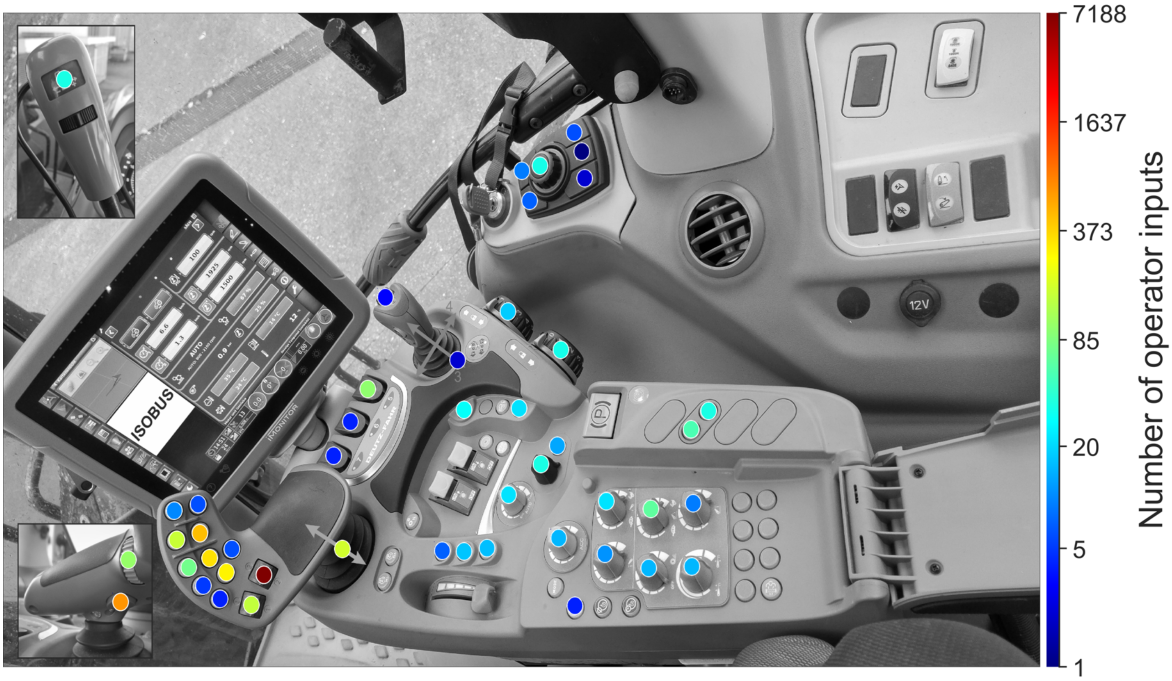


Figure 69: Heatmap for operating a Horsch Tiger 4 MT during 36.92 work hours.

6.2.3.5 Krone EasyCut 32 CV Float and EasyCut B 870 CV

Overall data for operating a Krone EasyCut 32 CV Float and EasyCut B 870 CV during 63.40 work hours:

- Overall operator inputs: 6120
- Operator inputs per minute: 1.61
- Average operator inputs per control element: 97.03
- Average operator inputs per control element without bin 0: 147.86
- Median of operator inputs for all control elements: 6
- Number of CEs for at least 80 % of all operator inputs: 8
- Percentage of CEs for at least 80 % of all operator inputs: 13 %

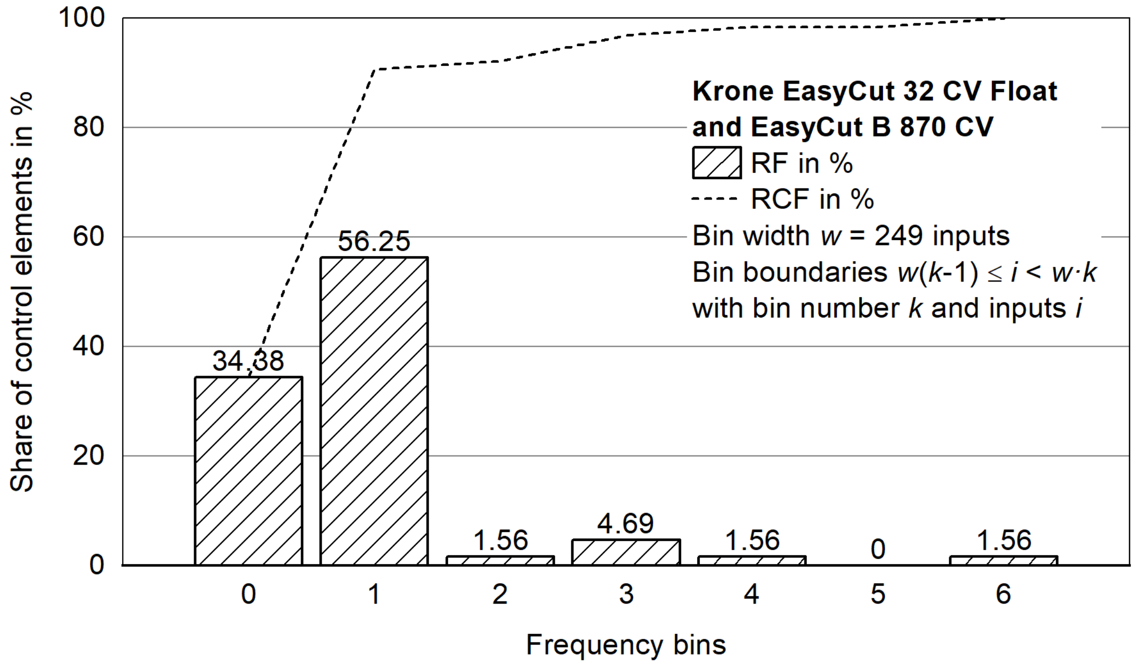


Figure 70: Histogram for the relative and relative cumulative frequency distribution for operating a Krone EasyCut 32 CV Float and EasyCut B 870 CV during 63.40 work hours.

Control elements in high-frequency bins of **Figure 70** (code refers to Table 1):

- Bin 2: Set maximum speed (DT90)
- Bin 3: Control element 2 for an SCV (H10),
  Consent button (M20),
  TPH front - up (TPH20)
- Bin 4: TPH front - down (TPH20)

- Bin 6: Control element 1 for an SCV (H10)

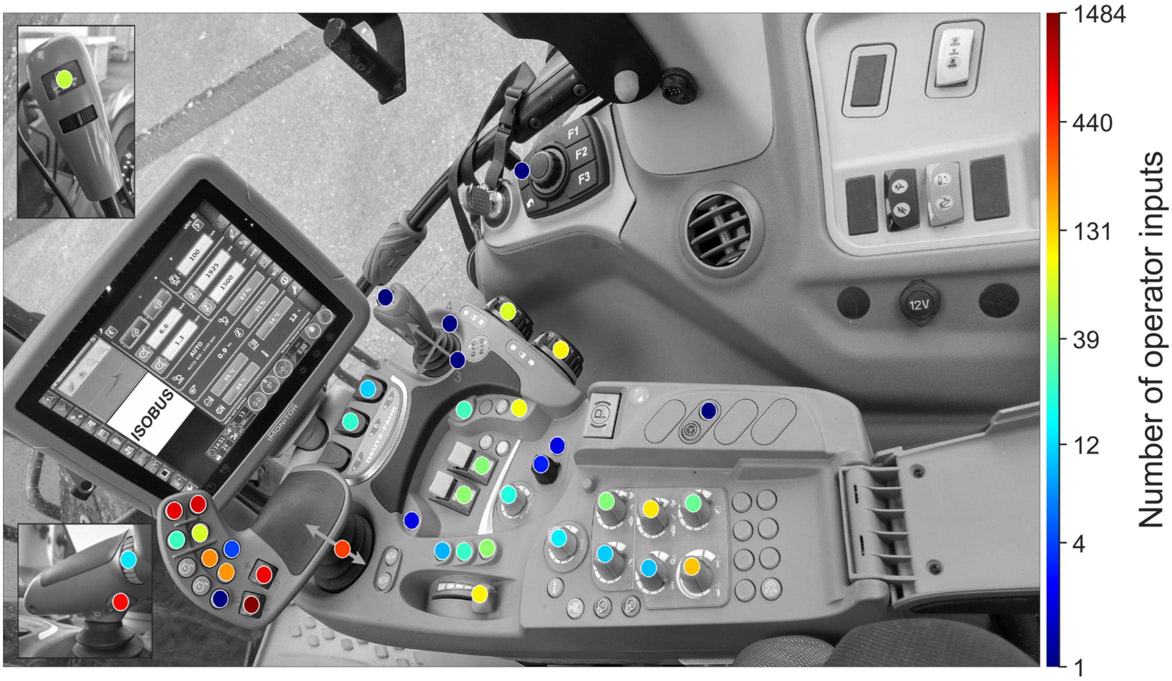


Figure 71: Heatmap for operating a Krone EasyCut 32 CV Float and EasyCut B 870 CV during 63.40 work hours.

Figure 72: Additional control box for EasyCut B 870 CV.

For the butterfly mower EasyCut B 870 CV, an additional control box (**Figure 72**) was required to preselect functions. With the preselection, all functions of the butterfly mower can be executed with only two SCVs. Based on the set combination of the toggle switches, the two SCVs can be used to change from transport to headland position, to lift and lower the left and right mower together or separately, and to lift or lower the cross conveyor belts separately. The potentiometer on the right adjusts the conveyor belts' speed by opening or closing a choke in a hydraulic circuit driven by the PTO.

6.2.3.6 Krone MX 400 with ISOBUS

Overall data for operating a Krone MX 400 with ISOBUS during 43.63 work hours:

- Overall operator inputs: 3458
- Operator inputs per minute: 1.32
- Average operator inputs per control element: 54.03
- Average operator inputs per control element without bin 0: 96.06
- Median of operator inputs for all control elements: 2
- Number of CEs for at least 80 % of all operator inputs: 5
- Percentage of CEs for at least 80 % of all operator inputs: 8 %

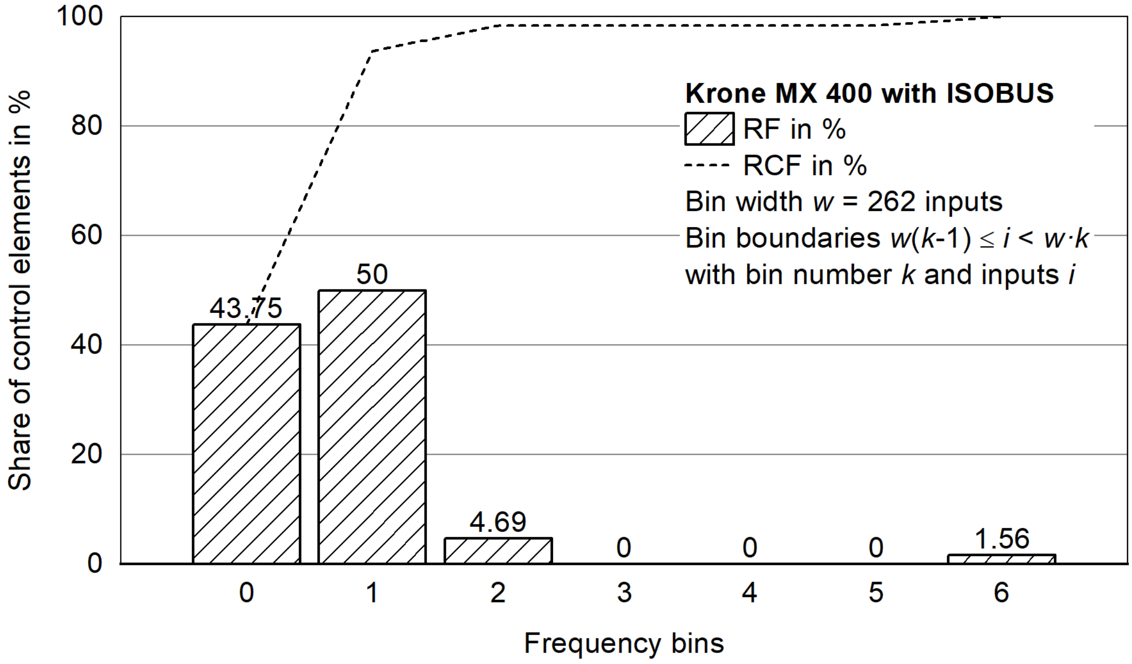


Figure 73: Histogram for the relative and relative cumulative frequency distribution for operating a Krone MX 400 with ISOBUS during 43.63 work hours.

Control elements in high-frequency bins of **Figure 73** (code refers to Table 1):

- Bin 2: Forward direction (D50),
  Consent button (M20),
  Set maximum speed (DT90)
- Bin 6: ISOBUS input

Figure 74: Heatmap for operating a Krone MX 400 with ISOBUS during 43.63 work hours.

6.2.3.7 Krone BigPack 1270 XC with ISOBUS

Overall data for operating a Krone BigPack 1270 XC with ISOBUS during 15.15 work hours:

- Overall operator inputs: 1704
- Operator inputs per minute: 1.87
- Average operator inputs per control element: 26.63
- Average operator inputs per control element without bin 0: 38.73
- Median of operator inputs for all control elements: 8
- Number of CEs for at least 80 % of all operator inputs: 13
- Percentage of CEs for at least 80 % of all operator inputs: 20 %

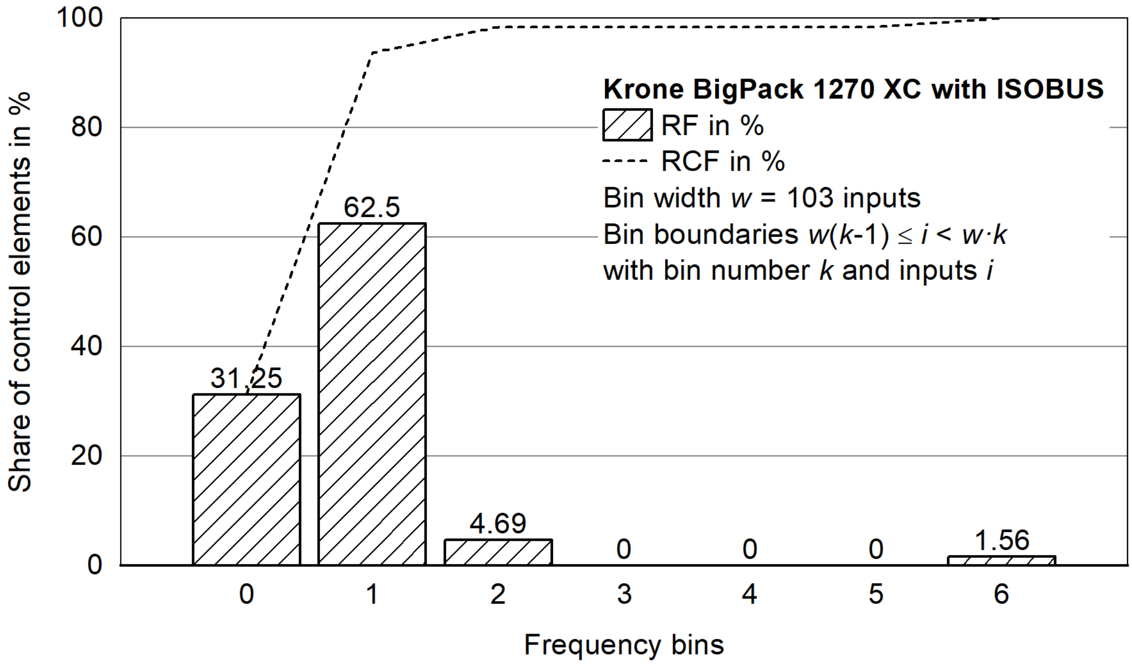


Figure 75: Histogram for the relative and relative cumulative frequency distribution for operating a Krone BigPack 1270 XC with ISOBUS during 15.15 work hours.

Control elements in high-frequency bins of **Figure 75** (code refers to Table 1):

- Bin 2: Consent button (M20),
  Set maximum speed (DT90),
  ISOBUS input
- Bin 6: Control element 1 for an SCV (H10)

Figure 76: Heatmap for operating a Krone BigPack 1270 XC with ISOBUS during 15.15 work hours.

6.2.3.8 Lemken Juwel 8 with ISOBUS

Overall data for operating a Lemken Juwel 8 with ISOBUS during 32.12 work hours:

- Overall operator inputs: 4912
- Operator inputs per minute: 2.55
- Average operator inputs per control element: 76.75
- Average operator inputs per control element without bin 0: 98.24
- Median of operator inputs for all control elements: 6
- Number of CEs for at least 80 % of all operator inputs: 9
- Percentage of CEs for at least 80 % of all operator inputs: 14 %

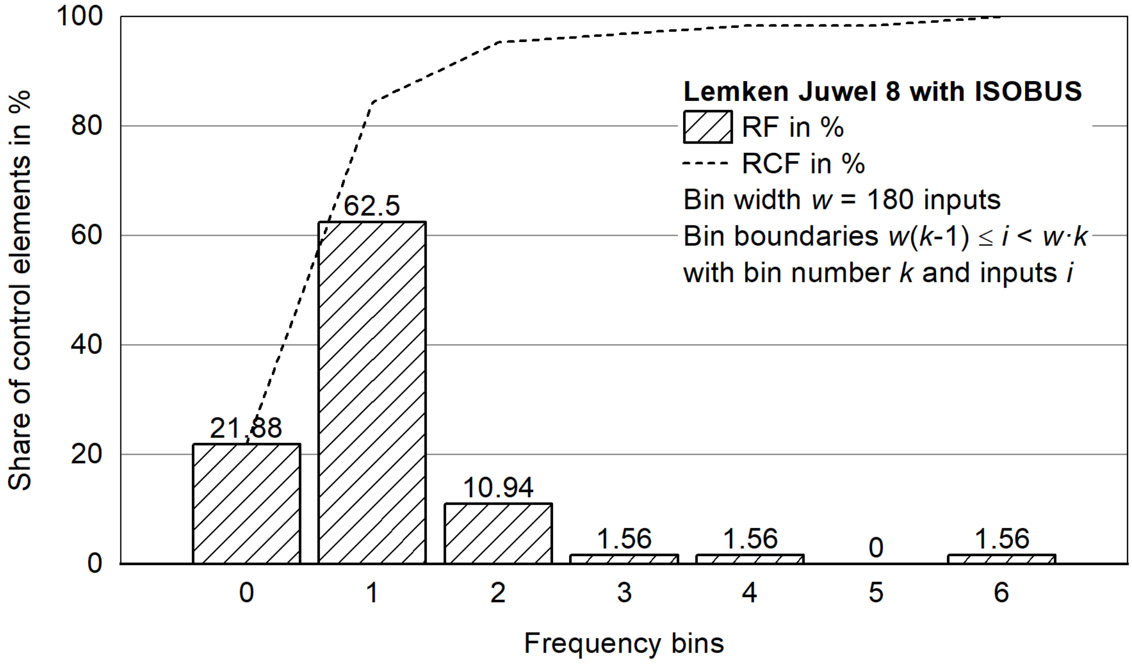


Figure 77: Histogram for the relative and relative cumulative frequency distribution for operating a Lemken Juwel 8 with ISOBUS during 32.12 work hours.

Control elements in high-frequency bins of **Figure 77** (code refers to Table 1):

- Bin 2: Control element 6 for an SCV (H10),
  TPH rear - depth control (TPH40),
  TPH rear - up (TPH20),
  Forward direction (D50),
  Backward direction (D50),
  Set maximum speed (DT90),
  Fine-tuning of speed limit (DT91)

- Bin 3: ISOBUS input
- Bin 4: Consent button (M20)
- Bin 6: TPH rear - down (TPH20)

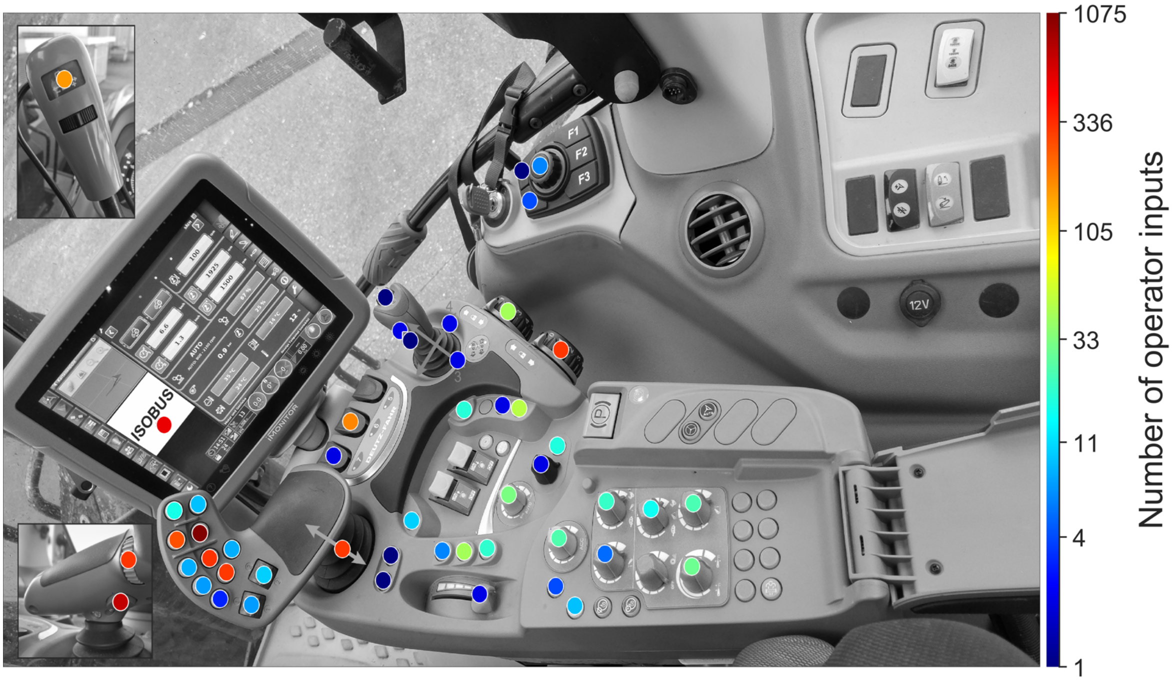


Figure 78: Heatmap for operating a Lemken Juwel 8 with ISOBUS during 32.12 work hours.

6.2.3.9 Lemken Solitair 9 with ISOBUS

Overall data for operating a Lemken Solitair 9 with ISOBUS during 23.56 work hours:

- Overall operator inputs: 4532
- Operator inputs per minute: 3.21
- Average operator inputs per control element: 70.81
- Average operator inputs per control element without bin 0: 100.71
- Median of operator inputs for all control elements: 9
- Number of CEs for at least 80 % of all operator inputs: 11
- Percentage of CEs for at least 80 % of all operator inputs: 17 %

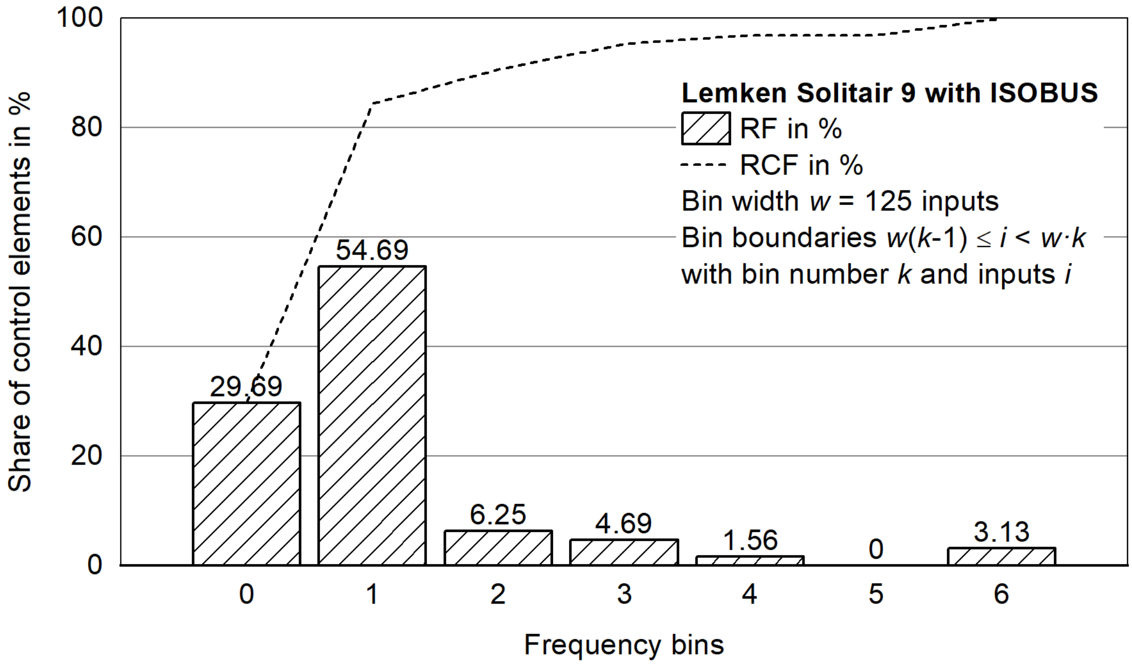


Figure 79: Histogram for the relative and relative cumulative frequency distribution for operating a Lemken Solitair 9 with ISOBUS during 23.56 work hours.

Control elements in high-frequency bins of **Figure 79** (code refers to Table 1):

- Bin 2: TPH front - depth control (TPH40),
  TPH rear - down (TPH20),
  Automatic steering system (A30),
  PTO rear (PTO10)

- Bin 3: Forward direction (D50),
  Backward direction (D50),
  Fine-tuning of speed limit (DT91)
- Bin 4: Forward-neutral-backward shuttle lever (D50)
- Bin 6: Headland management (A10),
  Consent button (M20)

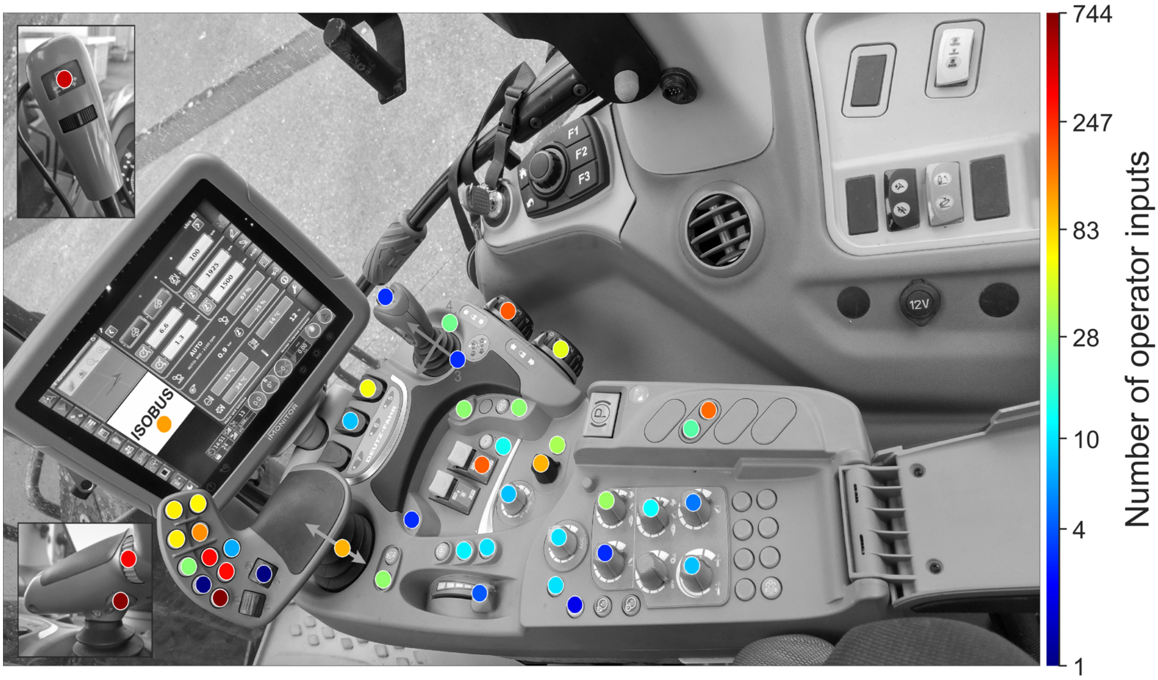


Figure 80: Heatmap for operating a Lemken Solitair 9 with ISOBUS during 23.56 work hours.

6.2.3.10 Krampe Big Body 750

Overall data for operating a Krampe Big Body 750 during 35.47 work hours:

• Overall operator inputs:	3932
• Operator inputs per minute:	1.85
• Average operator inputs per control element:	61.44
• Average operator inputs per control element without bin 0:	103.47
• Median of operator inputs for all control elements:	1
• Number of CEs for at least 80 % of all operator inputs:	6
• Percentage of CEs for at least 80 % of all operator inputs:	9 %

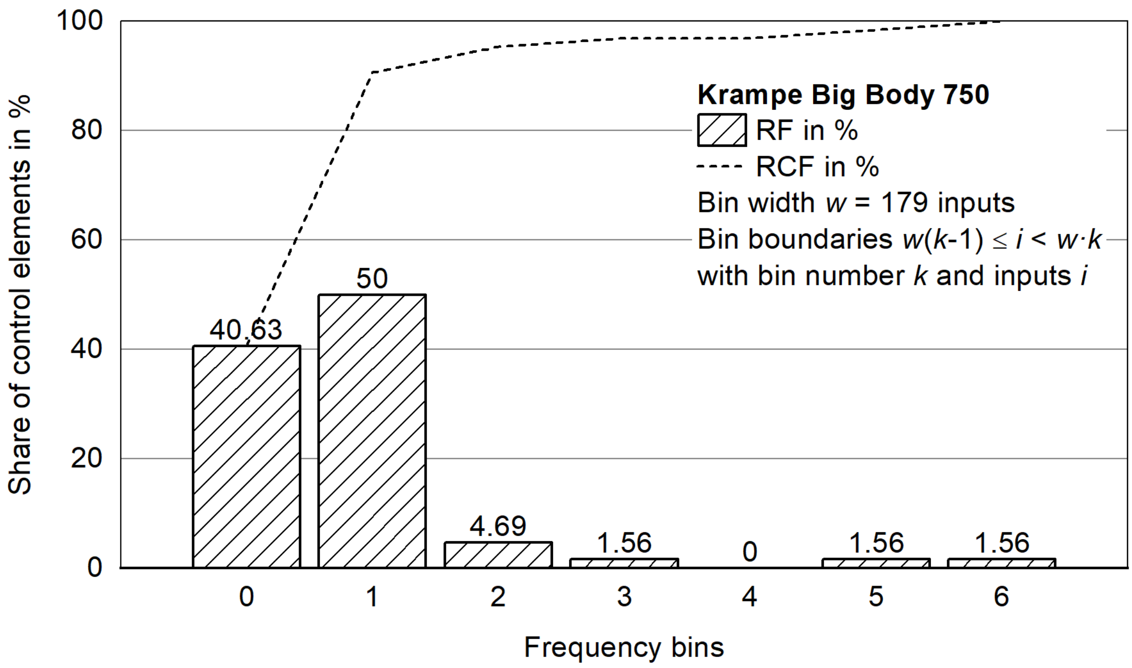


Figure 81: Histogram for the relative and relative cumulative frequency distribution for operating a Krampe Big Body 750 during 35.47 work hours.

Control elements in high-frequency bins of **Figure 81** (code refers to Table 1):

- Bin 2: Control element 1 for an SCV (H10),
  Control element 4 for an SCV (H10),
  Control element 5 for an SCV (H10)
- Bin 3: Control element 3 for an SCV (H10)
- Bin 5: Set maximum speed (DT90)
- Bin 6: Control element 2 for an SCV (H10)

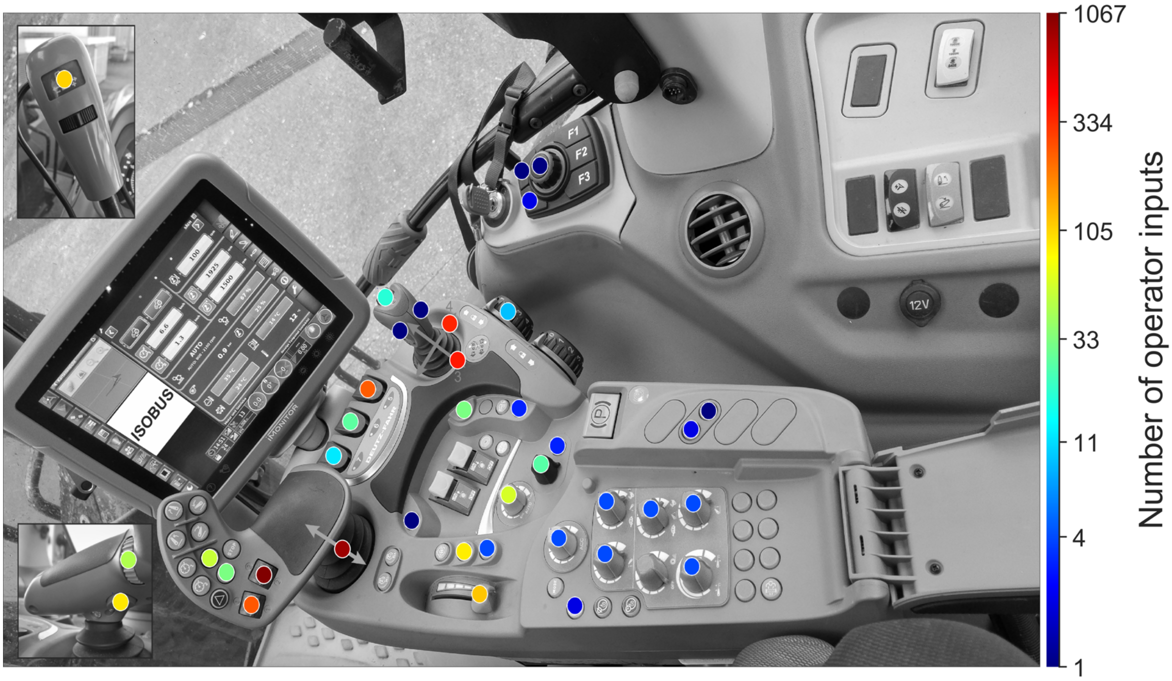


Figure 82: Heatmap for operating a Krampe Big Body 750 during 35.47 work hours.

6.2.4 Conclusion from the investigation

Chapters 6.2.3 and 12.1 show the pure results of the measurement data based on the analysis described in Chapter 6.2.2. For the upcoming interpretation, some context of how the MFA was used is necessary. The test tractor had eight SCVs that could be freely assigned to one of the eight SCV control elements (H10). The front TPH could be controlled either with two buttons on the very top of the thumb control panel of the joystick or with one of the eight SCV control elements (H10). The drivers could change both the assignment of SCVs to control elements (H10) and the assignment of the front TPH at any time. Table 4 lists all nine drivers involved in the measurement phase. However, the measurement data were analyzed without distinguishing between the different drivers. Although the configuration of the MFA may vary from driver to driver within its few degrees of freedom, it was assumed that the number and type of operator inputs vary only a little or not at all. This assumption is justified since all drivers need to control the tractor and implement in the same way to achieve value-added results in the field. The following findings are based on the measurement data collected and analyzed in this work.

1) In all measured operating scenarios with an implement, several control elements are not used. The share of bin 0 is always above 20 % of the total amount of CEs with n_{tot} = 64.
2) The share of bin 0 ranges from 21.88 % (Lemken Juwel 8 and Zunhammer MKE14PUL) to 46.88 % (Bergmann TSW 5210 S and Kerner Komet 420).

$$0.2 \cdot n_{tot} < n_0 < 0.45 \cdot n_{tot} \tag{4}$$

3) In each operating scenario, at least 80 % of the control elements do not have more operator inputs than those covered by bin 1.

$$\sum_{k=0}^{1} n_k > 0.8 \cdot n_{tot} \tag{5}$$

4) The high-frequency bins 2 to 6 cover at least 80 % of all operator inputs i_{tot} with never more than 20 % of the control elements n_{tot}.

$$\sum_{k=2}^{6} n_k < 0.2 \cdot n_{tot} \tag{6}$$

$$\sum_{k=2}^{6} i_k \geq 0.8 \cdot i_{tot} \tag{7}$$

5) Based on frequency, two groups of control elements can be divided: control elements to execute functions (high-frequency) and control elements to set up functions (low-frequency).
6) The CEs in the high-frequency bins differ from operating scenario to operating scenario.
7) Rear TPH down is much more often pressed than rear TPH up in operating scenarios with the rear TPH in use.

Explanation and consequences for 1) and 2)

Returning to the sub-thesis stated at the beginning of Chapter 6.2 that not all control elements of a state-of-the-art tractor are needed in each operating scenario, the analysis results in Chapters 6.2.3 and 12.1 prove this sub-thesis: In all 14 operating scenarios bin 0 is not empty. Excluding the tractor-only scenario with a share of 3.13 % for bin 0, the share of bin 0 ranges from 21.88 % (Lemken Juwel 8 and Zunhammer MKE14PUL) to 46.88 % (Bergmann TSW 5210 S and Kerner Komet 420). The number of haptic control elements on the MFA could be reduced by 20 % since the share of bin 0 is always above 20 %.

Considering the volatile amount of non-used control elements ranging from 22 % to 47 %, the adaptivity feature availability is a solution. This means CEs can be hidden, locked, or deactivated if not assigned to a function.

Explanation and consequences for 3) and 4)

A noticeable finding in all operating scenarios: At least 80 % of the control elements are assigned to bin 0 or 1. This leads to a very right-skewed data distribution with a mean always higher than the median. The uneven distribution is also confirmed by the result that never more than 20 % of the control elements cover at least 80 % of all operator inputs.

Explanation and consequences for 5)

Control elements in the high-frequency bins are mostly used to execute a function, whereas control elements in the low-frequency bins 0 and 1 are mostly used to set up a function. Hence, another conclusion following these measurement data is that functions most likely needed on every headland turn should be linked to haptic control elements placed at an easy-to-reach position for the driver. Functions to set up a tractor or an implement function, like the lowering speed of the TPH, do not necessarily need to be linked to haptic control elements. These findings give more leeway in the conception of operator systems. If space and cost must be reduced, these low-frequency functions can be linked to a software-based surface on a screen. The approach of the assign method described in Chapter 5.2 complies with these findings.

Explanation and consequences for 6)

Different operating scenarios cause different frequencies with which several functions are used. For instance, when plowing, the PTO is not needed. However, with a slurry tanker, the PTO is used on every headland turn. Hence, the adaptivity feature assigned function is advantageous to assign the high-frequency functions of an operating scenario to the control elements with the best ergonomic positions on the MFA. In Appendix 12.2, Table 23 shows the bin occurrence of the measured control elements across all operating scenarios. This analysis confirms that the frequency with which control elements respectively functions are used differs from operating scenario to operating scenario. Particularly focusing on the control elements for the SCVs, it becomes obvious.

Explanation and consequences for 7)

Remarkable is that rear TPH down is much more often pressed than rear TPH up in operating scenarios with the TPH in use. Since a press on rear TPH up or down is always all the way up or down, the number of inputs should be almost equal. However, the assumption can be made that the drivers have no feedback about lowering the TPH. Thus, it is pressed multiple times to double-check if the TPH is actually in the lowest position.

6.3 Derived concept for adaptive operator systems and its features

Based on the findings in the previous Chapters 6.1 and 6.2, **Figure 83** shows the derived concept for adaptive operator systems in tractors. Depending on the implement that is used with the tractor, the adaptivity features of the control elements allow the tractor's operator system to adapt to the operating requirements of that specific implement. In this work, the adaptivity features assigned function, graphic, color, actuating direction, and availability are considered.

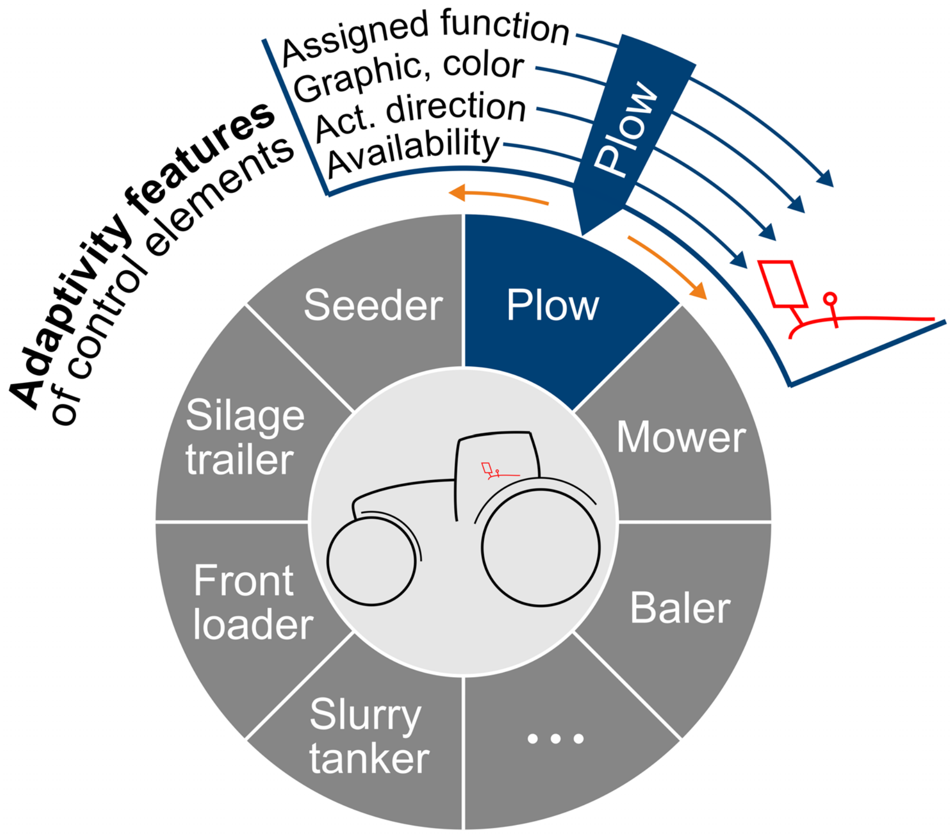


Figure 83: Derived concept for adaptive operator systems in tractors. The adaptivity features of control elements allow the operator system to adapt to changing operating scenarios.

The adaptivity feature "assigned function" is only feasible in combination with "graphic" or at least "color" to indicate to users the adaption of a control element to another function. Chapter 3 also describes additional adaptivity features like shape, actuating torque, or actuating force which could be considered in further studies in this field.

7 SPECIFICATION OF THE ADAPTIVE OPERATOR SYSTEM

The layer method from Chapter 5.1 is used to specify the adaptive operator system. According to the method's first step, the individual requirements of each operating scenario are stacked as layers on the base layout of the AOS. **Figure 84** depicts a concept for the base layout with red-framed reach zone spots and within numbered placeholder fields (1.1, 1.2, 1.3, 2.1, 2.2, 2.3, and 3.X) for the adaptive control elements.

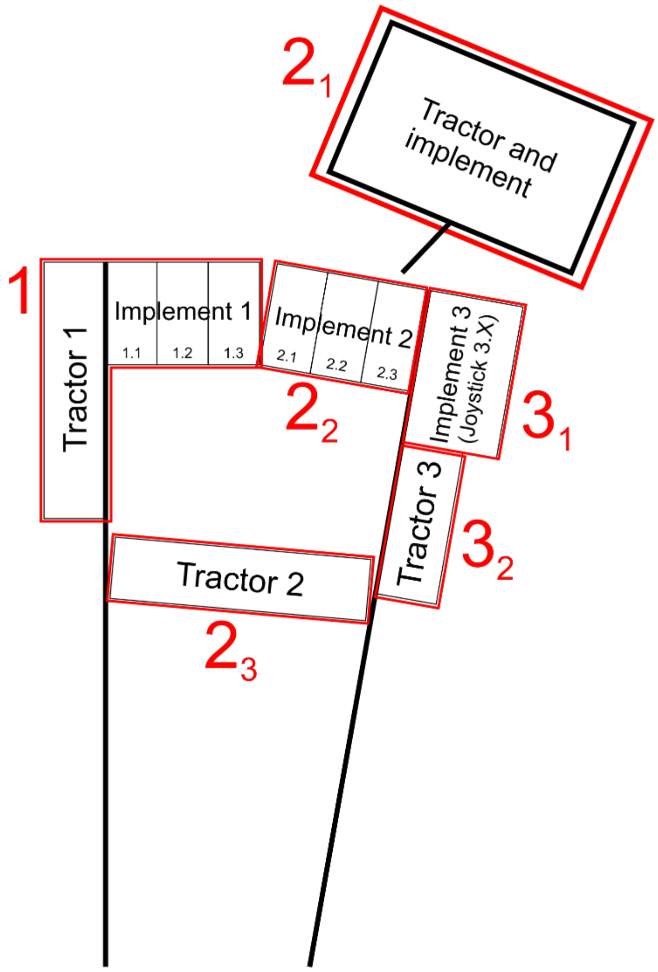


Figure 84: Concept for the base layout of the AOS with adaptive control elements and red-framed reach zone spots.

As derived in Chapter 6.1, the main function groups PTO and hydraulics have the potential for adaptivity features because they are directly related to the implement. The main function groups driving and TPH are related to the tractor. Hence, in this chapter, only the PTO and hydraulic functions are considered for the assignment to adaptive control elements.

7.1 Individual layers of the operating scenarios

Based on the operating scenarios listed in Chapter 6.2.1, the following layers will be used to specify the requirements for the adaptive control elements. These layers comprise all PTO and hydraulic-related functions of the implements that shall be assigned to a haptic adaptive control element. According to the assignment method introduced in Chapter 5.2, these are work mode or readjustment functions of the implements. The target field numbers in the first column of **Tables 5 to 18** refer to the placeholder field numbers in Figure 84.

Layer Deutz-Fahr 9340 TTV Agrotron

Table 5: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Deutz-Fahr 9340 TTV Agrotron.

Target field	Name of the function	Basic input characteristic
1.1	Front PTO	On / off
1.2	Rear PTO	On / off

Layer Zunhammer MKE14PUL with ISOBUS

Table 6: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Zunhammer MKE14PUL with ISOBUS.

Target field	Name of the function	Basic input characteristic
1.1	Substrate pump (Rear PTO)	On / off
1.2	Trailing shoes	Up / down
1.3	Folding boom	Forth / back
2.1	Constant hydraulic flow	On / off
2.2	Trailing axle	Open / close
2.3	Support leg	Up / down

Layer Bergmann TSW 5210 S with ISOBUS

Table 7: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Bergmann TSW 5210 S with ISOBUS.

Target field	Name of the function	Basic input characteristic
1.1	Spreader (Rear PTO)	On / off
1.2	Dosing wall	Up / down
1.3	Scraper floor automatic	On / off
2.1	Scraper floor manual	Forth / back
2.2	Trailing axle	Open / close
2.3	Spread pattern limiter	Up / down

Layer Horsch Terrano 3 FX

Table 8: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Horsch Terrano 3 FX.

Target field	Name of the function	Basic input characteristic
1.1	Working depth adjustment	Up / down
1.2	Edge discs	On / off
1.3	Toplink cylinder	Forth / back

Layer Kerner Komet K420

Table 9: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Kerner Komet K420.

Target field	Name of the function	Basic input characteristic
1.1	Frame wings	Up / down
1.2	Toplink cylinder	Forth / back
1.3	Spring load stone protection	More / less

Layer Horsch Tiger 4 MT

Table 10: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Horsch Tiger 4 MT.

Target field	Name of the function	Basic input characteristic
1.1	Working depth adjustment	Up / down
1.2	Disc system	Up / down
1.3	Frame wings	Up / down

Layer Krone EasyCut 32 CV Float and EasyCut R 320 CV

Table 11: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Krone EasyCut 32 CV Float and EasyCut R 320 CV.

Target field	Name of the function	Basic input characteristic
1.1	Front mower transport < > mowing	Up / down
1.2	Rear mower headland < > mowing	Up / down
1.3	Front mower (Front PTO)	On / off
2.1	Rear mower (Rear PTO)	On / off
2.2	Rear mower headland < > transport	Up / down
2.3	Toplink cylinder	Forth / back

Layer Krone EasyCut 32 CV Float and EasyCut B 870 CV

Table 12: Requirements specification for basic input characteristics of adaptive control elements in the operating scenario Krone EasyCut 32 CV Float and EasyCut B 870 CV.

Target field	Name of the function	Basic input characteristic
1.1	Front mower transport < > mowing	Up / down
1.2	Rear mower a) transport < > headland b) headland < > mowing c) conveyor belts (ref. Figure 72)	Up / down
1.3	Front mower (Front PTO)	On / off
2.1	Rear mower (Rear PTO)	On / off
2.2	Toplink cylinder	Forth / back

Layer Krone MX 400 with ISOBUS

Table 13: Requirement specification for basic input characteristics of adaptive control elements in the operating scenario Krone MX 400 with ISOBUS.

Target field	Name of the function	Basic input characteristic
1.1	Pick up	Up / down
1.2	Loading wagon (Rear PTO)	On / off
1.3	Scraper floor	Forth / back
2.1	Folding drawbar	Up / down
2.2	Trailing axle	Open / close

Layer Krone BigPack 1270 XC with ISOBUS

Table 14: Requirement specification for basic input characteristics of adaptive control elements in the operating scenario Krone BigPack 1270 XC with ISOBUS.

Target field	Name of the function	Basic input characteristic
1.1	Pick up	Up / down
1.2	Baler (Rear PTO)	On / off
1.3	Trailing axle	Open / close
2.1	Support leg	Up / down

Layer Lemken Juwel 8 with ISOBUS

Table 15: Requirement specification for basic input characteristics of adaptive control elements in the operating scenario Lemken Juwel 8 with ISOBUS.

Target field	Name of the function	Basic input characteristic
1.1	Turn plow	Turn CW / CCW
1.2	Tow arm	Open / close
1.3	Plow support wheel	Up / down
2.1	Toplink cylinder	Forth / back
2.2	Plow width	More / less
2.3	Furrow width	More / less

Layer Lemken Solitair 9 with ISOBUS

Table 16: Requirement specification for basic input characteristics of adaptive control elements in the operating scenario Lemken Solitair 9 with ISOBUS.

Target field	Name of the function	Basic input characteristic
1.1	Rotary harrow (Rear PTO)	On / off
1.2	Fan	On / off
1.3	Colter pressure	More / less
2.1	Toplink cylinder	Forth / back

Due to an automatic steering system, the track markers were not used.

Layer Krampe Big Body 750

Table 17: Requirement specification for basic input characteristics of adaptive control elements in the operating scenario Krampe Big Body 750.

Target field	Name of the function	Basic input characteristic
1.1	Body tipper	Up / down
1.2	Body tailgate	Up / down
1.3	Body cover	Open / close
2.1	Trailing axle	Open / close

Layer Wagner WK600

Table 18: Requirement specification for basic input characteristics of adaptive control elements in the operating scenario Wagner WK600.

Target field	Name of the function	Basic input characteristic
1.1	Body tipper	Up / down
1.2	Body tailgate	Up / down
1.3	Trailing axle	Open / close
2.1	Support leg	Up / down

7.2 Overall specification based on the layers

Table 19 summarizes and weights the basic input characteristics from Chapter 7.1 for each placeholder field as the overall specification for adaptive control elements on the AOS.

Table 19: Summarized and weighted requirements for basic input characteristics to be provided by adaptive control elements on the AOS. The numbering of the columns refers to Figure 84.

	1.1	1.2	1.3	2.1	2.2	2.3	3.X
Deutz Fahr 9340 TTV Agrotron	on / off	on / off					
Zunhammer MKE14PUL ISOBUS	on / off	up / down	forth / back	on / off	open / close	up / down	
Bergmann TSW 5210 S ISOBUS	on / off	up / down	on / off	forth / back	open / close	up / down	
Horsch Terrano 3 FX	up / down	on / off	forth / back				
Kerner Komet K420	up / down	forth / back	more / less				
Horsch Tiger 4 MT	up / down	up / down	up / down				
Krone EasyCut 32 CV Float + R 320 CV	up / down	up / down	on / off	on / off	up / down	forth / back	
Krone EasyCut 32 CV Float + B 870 CV	up / down	up / down	on / off	on / off	forth / back		
Krone MX 400 ISOBUS	up / down	on / off	forth / back	up / down	open / close		
Krone BigPack 1270 XC ISOBUS	up / down	on / off	open / close	up / down			
Lemken Juwel 8 ISOBUS	turn cw / ccw	open / close	up / down	forth / back	more / less	more / less	
Lemken Solitair 9 ISOBUS	on / off	on / off	more / less	forth / back			
Krampe Big Body 750	up / down	up / down	open / close	open / close			
Wagner WK600	up / down	up / down	open / close	up / down			
weighted summary	up / down 9	up / down 7	forth / back 3	up / down 3	open / close 3	up / down 2	
	on / off 4	on / off 5	open / close 3	on / off 3	up / down 1	forth / back 1	
	turn cw / ccw 1	forth / back 1	on / off 3	forth / back 3	more / less 1	more / less 1	
		open / close 1	up / down 2	open / close 1	forth / back 1		
			more / less 2				

8 THE ADAPTIVE OPERATOR SYSTEM

Based on the overall specification in Chapter 7, technical concepts have been elaborated in iterative loops for adaptive control elements and control modules, followed by the realization and integration into the system. The final design as illustrated in **Figure 85** is described in detail in this chapter and evaluated in Chapter 9. It was first published in [65].

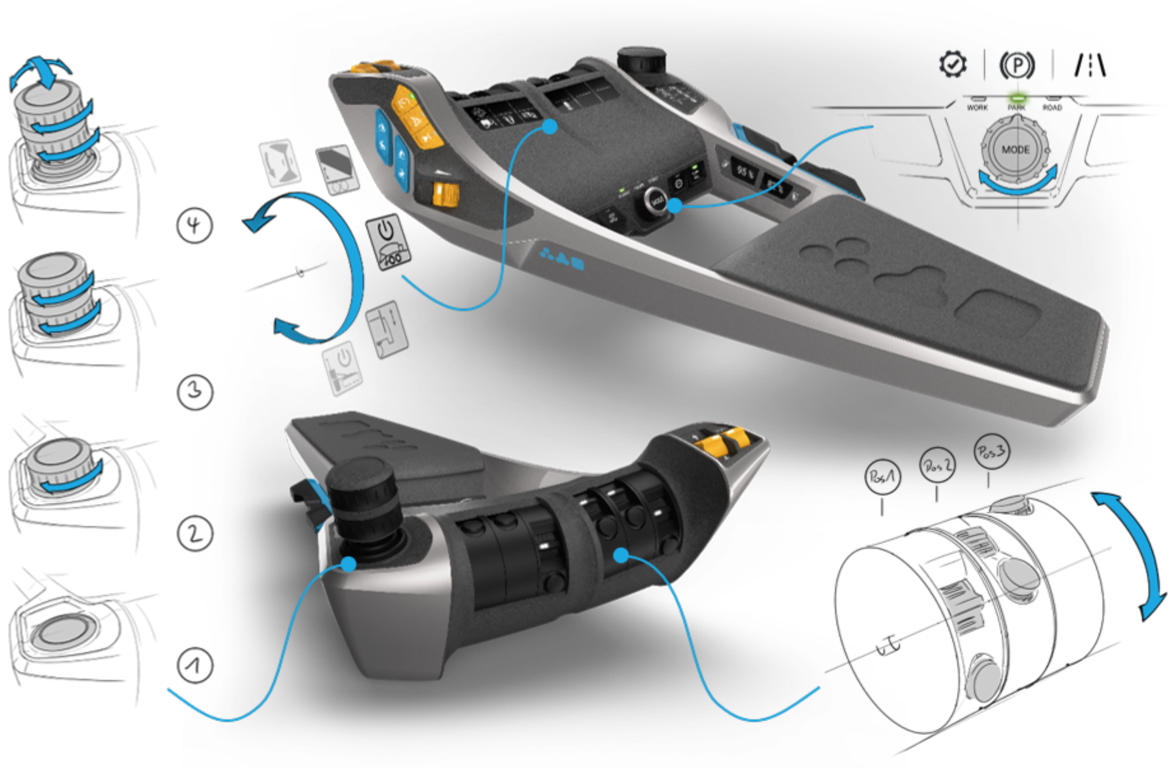


Figure 85: The adaptive operator system and its adaptive features at a glance. [65]

8.1 The overall design

As depicted in **Figure 86,** the AOS features six areas, whereas A, E, and F are tractor-related, and areas B, C, and D are implement-related.

The side flank of area A is to be controlled with the thumb and the two wheels on top with the index finger and middle finger. With the same hand position, area B can be controlled with the index finger, middle finger, and ring finger. This design ensures the control of the tractor and the implement functions simultaneously while having the hand in the most advantageous position. The driver does not have to reach around, which HOENER [54] also demands. For area C, the hand moves to the right to control the rollers with the index, middle, and ring fingers. Based on the specification, a multi-axis joystick was not required for the adaptive operator system. However, with other operating scenarios not investigated in this work, a multi-axis joystick might be needed since it is standard on state-of-the-art MFAs. Hence, a multi-axis joystick that can change its availability was integrated into area D. The joystick can be controlled with a grasping or clasping grip depending on its availability positions described later. Area E features two paddles and associated screens for the depth control of the front and rear TPH. The paddles can be controlled with a grasping grip. A rotary switch and four buttons are available in area F.

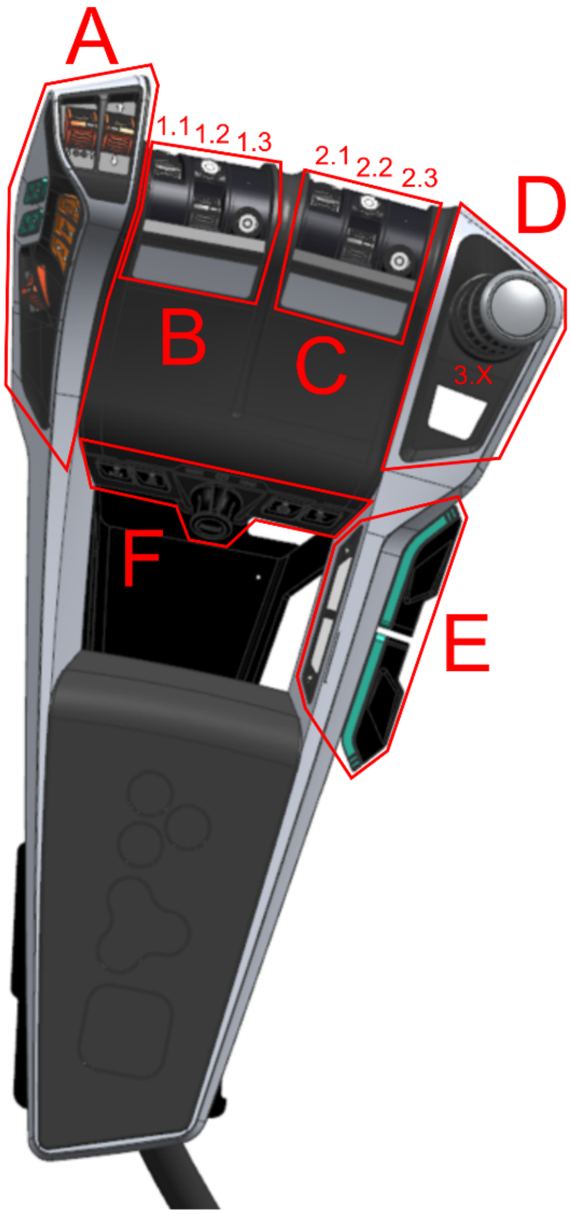


Figure 86: Top view of the adaptive operator system with area markings.

8.2 Tractor-related areas

Areas A, E, and F are tractor-related areas. Based on the assignment method in Chapter 5.2, all work mode or road mode functions have been placed in area A, as shown in **Figure 87**.

The two paddles in area E belong to the depth control of the TPH in the front and the back. The depth control is part of the readjustment control phase (Figure 46). Thus, the depth control function is assigned to haptic control elements. It is meant to have the lower links of the TPH in the hand while setting the maximum depth. Screens show the set depth with a percentage value, whereas 0 % is the lowest position. Below 0 % is a latching point to bring the lower links of the TPH into the float position.

In area F, the four buttons are assigned to the suspension of the front axle, auto PTO, gearbox modes, and all SCVs in float position. These functions are part of the "change road mode <> work mode" control phase (Figure 46). Hence, these functions are assigned to haptic control elements.

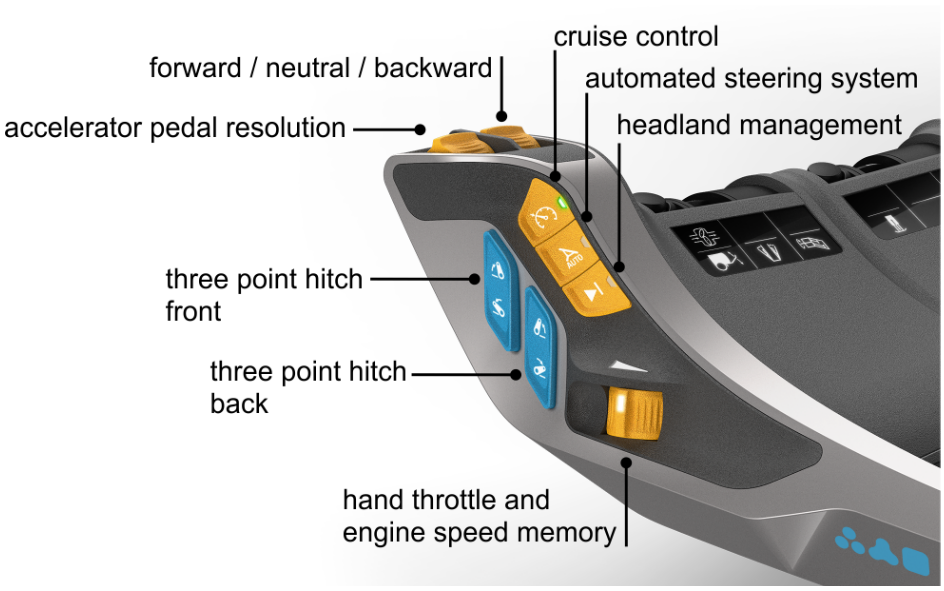


Figure 87: All work mode and road mode-related tractor functions are assigned to haptic control elements in area A.

In this concept, all tractor functions not assigned to haptic control elements in areas A, E, or F but have been on the MFA before, when referring to Figure 16, are assigned to the screen. This decision is based on the assignment method and yields more clarity on the AOS.

8.3 Implement-related areas

The application of the layer method, described in Chapter 7, results in Table 19, which is the overall specification for the adaptive control elements based on the considered operating scenarios. All deep blue-marked requirements in **Table 20** could be fully realized with the adaptive control elements introduced in the following. However, the later described rollers can not fully realize the open / close characteristic requirements. As a compromise, the open / close characteristic was moved to the more suitable and later described rotary switches of the retractable joystick. In addition, these rotary switches are also suitable for a more / less characteristic.

To express this in numbers: 61 requirements are listed in Table 19, from which 53 requirements could be fully realized on the AOS as specified. The eight open / close requirements are half fulfilled since they were moved to 3.X, which equals four points. Hence, 57 out of 61 corresponds to a degree of fulfillment of the requirements of 93 %.

Table 20: Degree of fulfillment of the requirements specification for the adaptive control elements. Deep blue: fulfilled, bright blue: half fulfilled.

	1.1	1.2	1.3	2.1	2.2	2.3	3.X
weighted summary	up / down 9	up / down 7	forth / back 3	up / down 3	open / close 3	up / down 2	
	on / off 4	on / off 5	open / close 3	on / off 3	up / down 1	forth / back 1	
	turn cw / ccw 1	forth / back 1	on / off 3	forth / back 3	more / less 1	forth / back 1	
		open / close 1	up / down 2	open / close 1	forth / back 1		
			more / less 2				

8.3.1 The rollers

Areas B (1.1, 1.2, 1.3) and C (2.1, 2.2, 2.3) feature a roller package comprising three rollers and associated screens. The rollers are meant to be assigned to hydraulic functions and the PTOs. Each roller has a thumbwheel for proportional movement with a latching point for hydraulic float position. Also, each roller has a button. Independent from other rollers, a roller can change between three different positions (**Figure 88**):

1) Base position 1: Thumbwheel up / down and one button
2) Base position 2: Thumbwheel forth / back and one button
3) Base position 3: Only one button

The associated screens show the icons of the functions assigned to the button or the thumbwheel of a roller. Hence, these rollers feature all four adaptivity features from Figure 83: Assigned function, graphic, availability, and actuating direction.

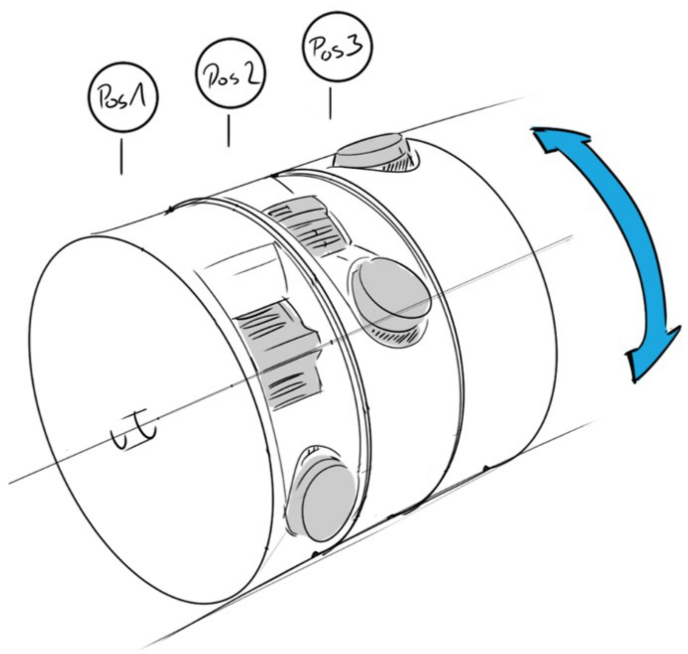


Figure 88: A roller package comprising three rollers that can change between three base positions. [65]

Regarding possible basic input characteristics from Figure 44, the button on a roller is used for on / off. The thumbwheel is used for up / down (base position 1), forth / back (base position 2), and according to Figure 38, for more / less in both base positions.

The turn CW / CCW requirement for the headland turn of the plow can also be realized with these rollers since that turn of the plow is to the very right or the very left. For that, rollers 1.1 and 1.2 are in base position 3 to only show their button. Then button 1.1 turns the plow to the left, and button 1.2 turns the plow to the right. As a consequence, all other requirements have to move one position to the right. However, this does not cause any disadvantage because the two initial more / less requirements on 2.2 and 2.3 were moved to 3.1 and 3.2 in the plow scenario, see Chapter 12.3.

For the rollers, a patent has been filed in Germany [66]. Based on the German priority, the patent has now been granted in Europe and is pending in the United States of America.

8.3.2 The retractable joystick

For front loader work, state-of-the-art tractors feature a joystick on their MFAs; see Figure 15, Figure 12, and Figure 10. However, tractors are not used for front-loader work all the time. Hence, this AOS features a retractable joystick. Regarding possible basic input characteristics from Figure 44, the joystick itself features forth / back, right / left, and pivot cw / ccw. In addition, up to two rotary switches can be used for turn cw / ccw, more / less, or open / close. The open / close input characteristic with these rotary switches is related to open / close a bottle lid. This characteristic can be used for a trailing axle that must be opened and closed. It can also be used for the third hydraulic circuit during front loader work, for instance, to open or close a bale fork.

The retractable joystick in area D (3.X) features four base positions, depicted in **Figure 89**:

1) Base position 1: Completely hidden
2) Base position 2: One rotary switch available
3) Base position 3: Two rotary switches available
4) Base position 4: Two-axle joystick with two rotary switches available

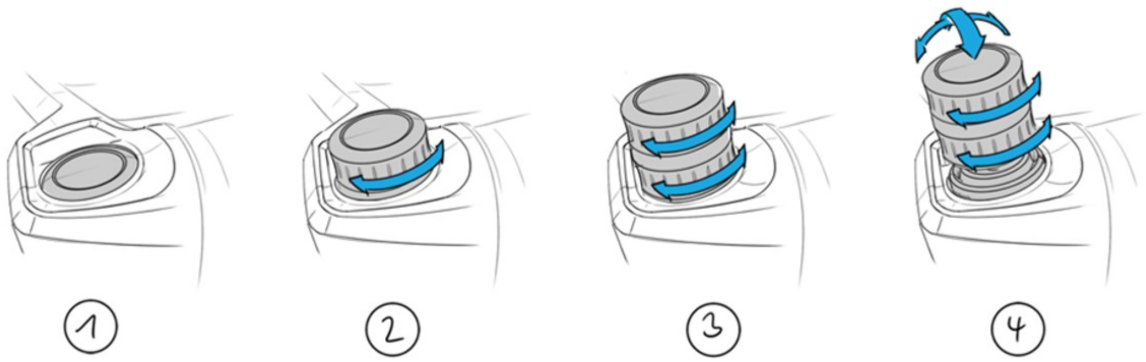


Figure 89: Base positions and related input options of the retractable joystick. [65]

An associated screen shows the icons of the functions assigned to the joystick and its rotary switches. Hence, this retractable joystick features three adaptivity features from Figure 83: Assigned function, graphic, and availability.

Regarding the assigned fields of the tables in Appendix 12.3, field 3.1 refers to the upper rotary switch of the joystick, field 3.2 to the lower one, field 3.3 refers to forth / back, and 3.4 to left / right of the joystick from the driver's perspective.

8.3.3 The rotary switch

Referring to the operating phases in Figure 46, this rotary switch, located in the middle of area F, changes from work mode to road mode and vice versa or engages the parking brake. It is based on the adaptivity feature assigned function since it enables or disables only the functions needed in the current operating scenario. For instance, when working with a plow, changing from road mode to work mode would enable the hydraulics and the TPH, whereas when working with a slurry tanker it would only enable the hydraulics since the TPH is not needed and thus stays disabled.

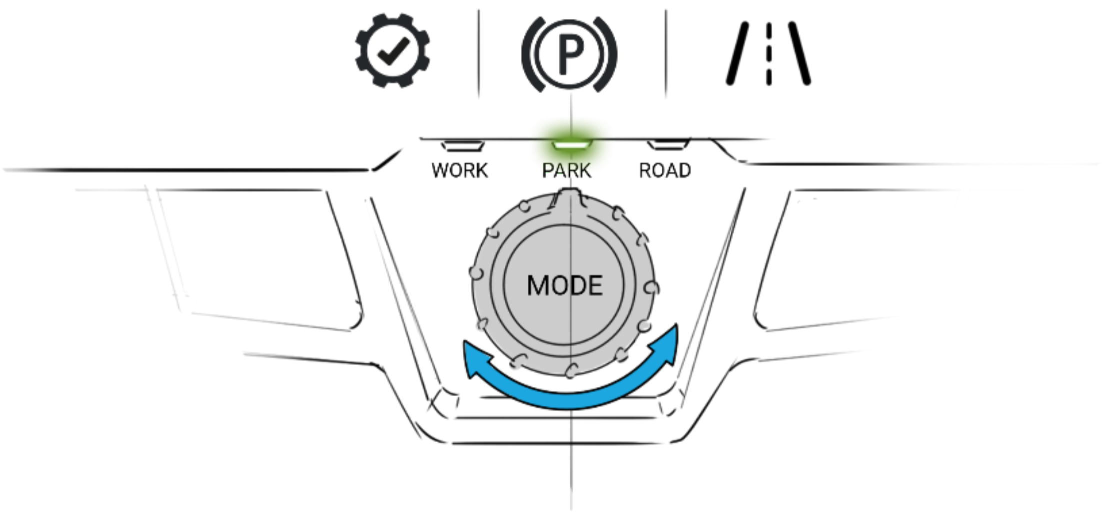


Figure 90: The rotary switch changes between work mode and road mode and engages the parking brake. It is based on the adaptivity feature assigned function since it disables or enables only the necessary functions in the current operating scenario. [65]

8.4 Operating scenario-based function assignment

Appendix 12.3 lists the function assignments for hydraulic functions and the PTOs in each operating scenario. The assigned field numbers refer to Figure 86. If a field number is not listed, no functions are assigned. If no function is assigned to the joystick (3.X), it is in base position 1. If no function is assigned to a roller (field numbers 1.1 to 2.3), it is in base position 3.

9 EVALUATION OF THE ADAPTIVE OPERATOR SYSTEM

9.1 Cognitive factors

The UASW evaluation method from Chapter 5.3.1 is used to determine the cognitive factors of the adaptive operator system and the state-of-the-art operator system (SOAOS) of the test tractor which is described in Chapter 2.4.3. The result of the factors in each operating scenario and the comparison of both OSs are listed in **Table 21**. For both operator systems, the procedure was done in the same way as illustrated in Figure 48:

- The considered operating scenarios are the ones listed and described in Chapter 6.2.1.

From each operating scenario, all UASW groups based on the main function groups PTO and hydraulics have been evaluated with the scheme as shown in Table 2.

- The resulting cognitive operability factors of the evaluated UASW groups are listed in **Tables 38 to 51** in Appendix 12.4.
- As an equally weighted average of the individual factors of the UASW groups, the overall cognitive operability factor of each operating scenario is listed in the bottom line of the tables in Appendix 12.4 and is at the same time the one listed in Table 21 for each operating scenario.
- The bottom line of Table 21 is the non-weighted average of the cognitive operability factors of all operating scenarios for each OS.

Concerning ISOBUS functions, the following differences are considered in the evaluation of the state-of-the-art operator system and the adaptive operator system:

- With the SOAOS, all ISOBUS functions were controlled via the screen and not mapped to haptic control elements.
- Up to five ISOBUS function pairs could be mapped to the adaptive control elements on the AOS. For instance, support leg up / down counts as one function pair.

Table 21: Cognitive operability factors OF_{cog} of the state-of-the-art and the adaptive operator system based on the evaluated operating scenarios. In accordance with VDI 2225-3 [60], a green result means very good, orange good, and red insufficient.

Operating scenario	$OF_{cog,SOAOS}$	$OF_{cog,AOS}$
Deutz-Fahr 9340 TTV Agrotron	1.00	1.00
Zunhammer MKE14PUL with ISOBUS	0.46	0.92
Bergmann TSW 5210 S with ISOBUS	0.74	0.93
Horsch Terrano 3 FX	0.42	0.70
Kerner Komet K420	0.61	1.00
Horsch Tiger 4 MT	0.83	1.00
Krone EasyCut 32 CV Float and EasyCut R 320 CV (Side mower)	0.67	1.00
Krone EasyCut 32 CV Float and EasyCut B 870 CV Collect (Butterfly mower)	0.73	1.00
Krone MX 400 with ISOBUS	0.76	1.00
Krone BigPack 1270 XC with ISOBUS	0.82	1.00
Lemken Juwel 8 with ISOBUS	0.83	1.00
Lemken Solitair 9 with ISOBUS	0.58	0.88
Krampe Big Body 750	0.69	1.00
Wagner WK600	0.69	1.00
Non-weighted average	**0.70**	**0.96**

To prove or disprove the directional main hypothesis, that was formulated in Chapter 1, a statistical analysis is conducted. It is analyzed if $OF_{cog,AOS}$ is significantly higher than $OF_{cog,SOAOS}$ across all 14 evaluated operating scenarios. **Figure 91** shows the cognitive operability factors of the SOAOS and the AOS in a box plot. Like the difference of the non-weighted averages in Table 21, the visual check of the box plot suggests an improvement in cognitive ergonomics of the AOS compared to the SOAOS. Since the cognitive OFs are not normally distributed, as assessed by the Shapiro-Wilk-test [67] with $p < 0.05$, the Mann-Whitney-U-test [68] is used to check for a statistically significant improvement in cognitive ergonomics with a significance level of $\alpha = 0.05$.

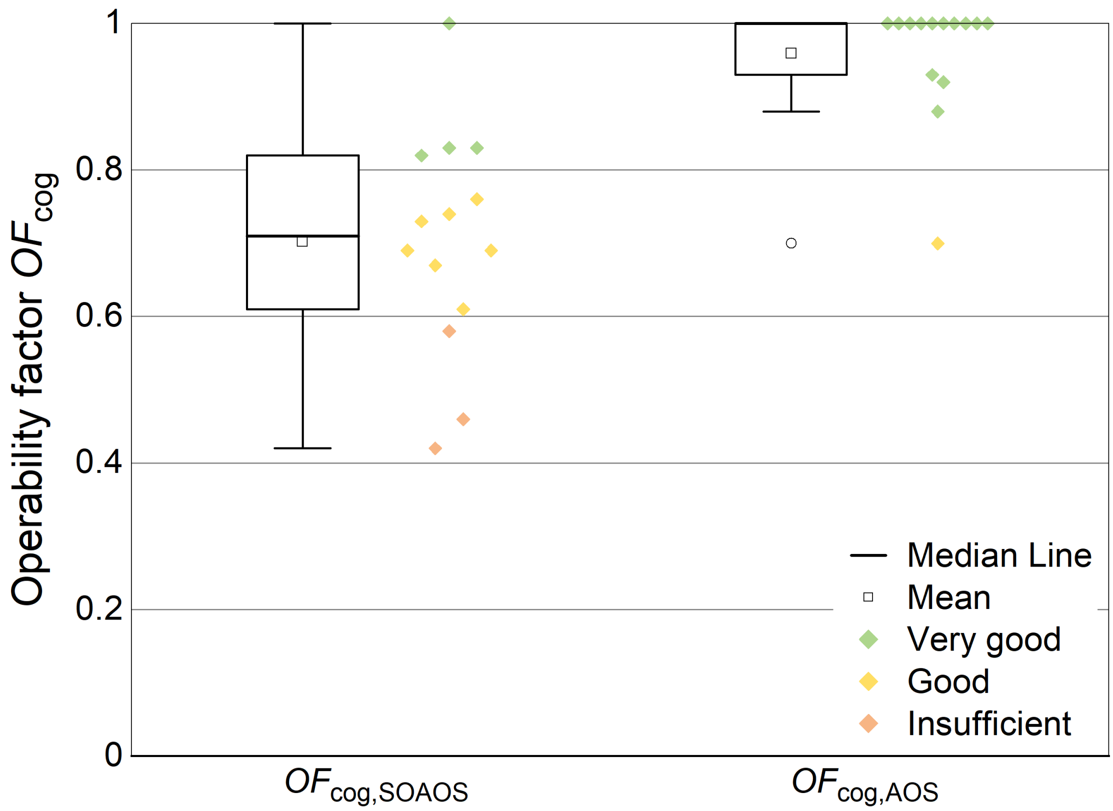


Figure 91: Box plot of the cognitive operability factors $OF_{cog,SOAOS}$ and $OF_{cog,AOS}$. The coloring of the data points is in accordance with VDI 2225-3 [60].

The result of the Mann-Whitney-U-test [68] was a statistically significant higher cognitive OF of the AOS ($M_{Rank} = 20.43$) compared to the SOAOS ($M_{Rank} = 8.57$), $U = 15$, $Z = -3.935$, $p < 0.001$, $r_{es} = 0.74$. According to COHEN [69] with $r_{es} > 0.5$ the effect size is large.

Hence, based on the applied evaluation methods, the AOS provides a statistically significant improvement in cognitive ergonomics compared to the SOAOS.

9.2 Physical factors

First - Reach zone check

According to Chapter 5.3.2., in the first step, the spots method checks the compliance with a reach zone. Based on the reach zone from DIN EN ISO 6682 [10], the AOS's layout was checked with reference to the SIP.

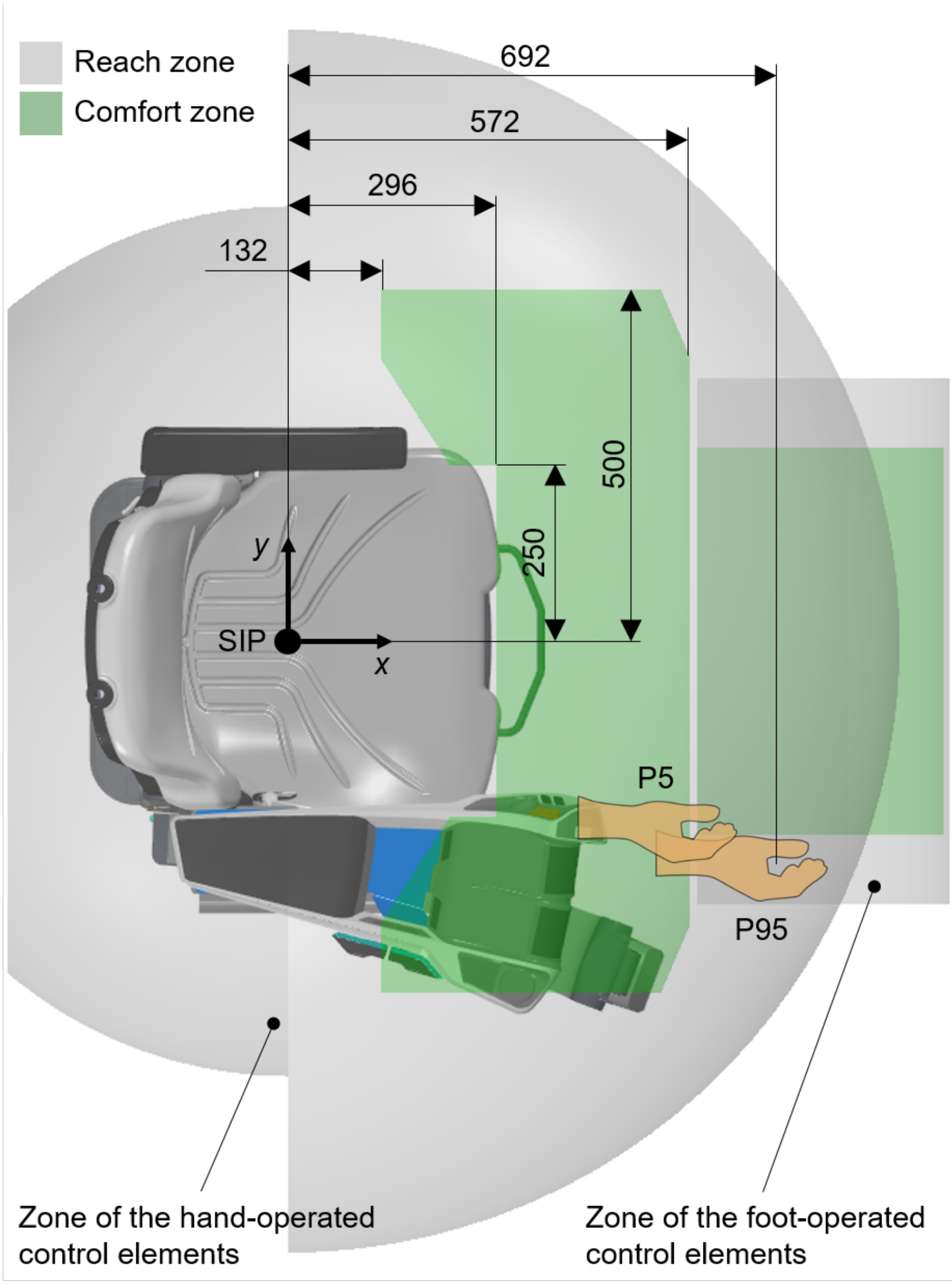


Figure 92: With reference to the SIP, the check of the AOS's layout using the comfort zone (green) and reach zone (gray) from DIN EN ISO 6682 and the maximum grip range in the x-direction of the right hand of the small (P5) and large (P95) machine operator of the underlying DIN EN ISO 3411. All dimensions in mm.

Figure 92 illustrates the reach zone check, particularly with the overall reach zone (gray) and the comfort zone (green). All control elements are within the gray reach zone. They are even within the green comfort zone except for one depth control paddle. The screen, of which only the mount in front of the AOS is shown, is entirely within the reach zone and half within the comfort zone. Since the available space in the comfort zone is fully utilized, the little overlap of one paddle and half of the screen into the reach zone is acceptable. The comfort zone right in front of the seat can not be used for MFA to not interfere with the driver's right leg.

Second - Subdivision in reach zone spots

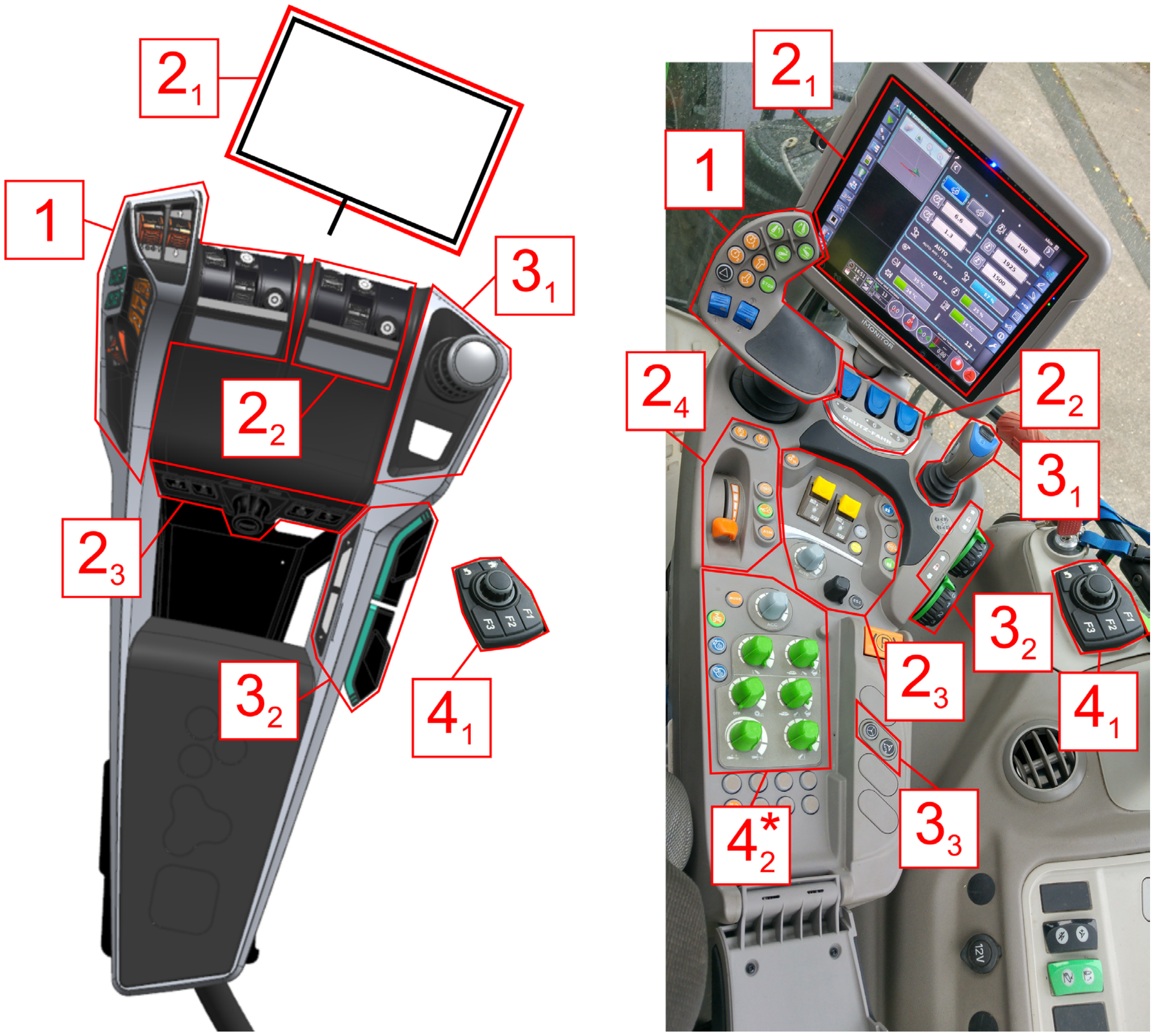


Figure 93: The adaptive (left) and the state-of-the-art operator system (right) are subdivided into reach zone spots. The smaller the number of a spot, the better the ergonomic rank. Even though spot 4_2* is in the radius of rank 3, it is ranked 4 because it is under a flip cover.

Based on the scheme from Figure 52, the OSs to compare have been subdivided into reach zone spots, as illustrated in **Figure 93**. The higher the number of a spot, the lower the ergonomic rank. A list of the control elements in each spot on each OS can be found in Appendix 12.5.

Third - Calculating the deviation from the target distribution

Referring to Table 3, with four defined spot ranks (1 to 4), the target values v_r for the target distribution are v_1 = 80 %, v_2 = 16 %, v_3 = 3.2 %, and v_4 = 0.8 %. The deviation of the actual distribution from the target distribution is calculated with Equation 1. The resulting physical operability factors of each operating scenario for the two compared OSs are listed in **Table 22** with a non-weighted average of these physical operability factors for each OS in the bottom line.

The measurement data described in Chapter 6.2.1 yield the actual distribution for the state-of-the-art OS. All ISOBUS functions were controlled via the screen and not mapped to haptic control elements.

These measurement data are also taken to analyze the adaptive operator system for comparability. Hence, the data are treated as if the same operator inputs would have been made with the AOS but from their newly assigned reach zone spot as listed in the appendix in **Table 52**. With the adaptive operator system, up to five ISOBUS function pairs are assigned to the adaptive control elements.

The measurement data lack information on how the total ISOBUS inputs are divided among the individual ISOBUS functions in each operating scenario. Hence, if the measured ISOBUS inputs were assigned to adaptive control elements in more than one reach zone spot on the AOS, the following assumption was necessary: All individual ISOBUS functions have the same input frequency, namely the measured overall ISOBUS inputs divided by the amount of individual ISOBUS functions. This assumption leads to a more conservative evaluation of the AOS since it gives more weight to less-used functions in less advantageous reach zone spots. The assumption was applied with Bergmann TSW 5210 S, Krone MX 400, Krone BigPack 1270 XC, and Lemken Juwel 8.

The measurement data contain information on how often each of the eight CEs for the SCVs was used. However, it does not contain any information on how the measured inputs of the CEs for the SCVs are divided among the individual hydraulic functions in each operating scenario. Hence, if the hydraulic functions were assigned to adaptive control elements in more than one reach zone spot on the AOS, the following assumption was necessary: All individual hydraulic functions have the same input frequency, namely the measured overall hydraulic inputs divided by the amount of individual hydraulic functions. This assumption leads to a more conservative evaluation of the AOS since it gives more weight to less-used functions in less advantageous reach zone spots. The assumption was applied with Zunhammer MKE14PUL, Krampe Big Body 750, and Wagner WK600.

Table 22: Physical operability factors OF_{phy} of the state-of-the-art and the adaptive operator system based on the evaluated operating scenarios. In accordance with VDI 2225-3 [60], a green result means very good, orange good, and red insufficient.

Operating scenario	$OF_{phy,SOAOS}$	$OF_{phy,AOS}$
Deutz-Fahr 9340 TTV Agrotron	0.58	0.71
Zunhammer MKE14PUL with ISOBUS	0.36	0.82
Bergmann TSW 5210 S with ISOBUS	0.38	1.02
Horsch Terrano 3 FX	1.17	1.26
Kerner Komet K420	1.06	1.09
Horsch Tiger 4 MT	1.28	1.31
Krone EasyCut 32 CV Float and EasyCut R 320 CV (Side mower)	0.30	1.16
Krone EasyCut 32 CV Float and EasyCut B 870 CV Collect (Butterfly mower)	1.08	1.15
Krone MX 400 with ISOBUS	0.23	0.62
Krone BigPack 1270 XC with ISOBUS	0.56	0.80
Lemken Juwel 8 with ISOBUS	0.81	0.88
Lemken Solitair 9 with ISOBUS	0.82	1.11
Krampe Big Body 750	0.66	0.97
Wagner WK600	0.67	0.86
Non-weighted average	**0.71**	**0.98**

To prove or disprove the directional main hypothesis, that was formulated in Chapter 1, a statistical analysis is conducted. It is analyzed if $OF_{\mathrm{phy,AOS}}$ is significantly higher than $OF_{\mathrm{phy,SOAOS}}$ across all 14 evaluated operating scenarios. **Figure 94** shows the physical operability factors of the SOAOS and the AOS in a box plot. Like the difference of the non-weighted averages in Table 22, the visual check of the box plot suggests an improvement in physical ergonomics of the AOS compared to the SOAOS. The physical OFs are normally distributed, as assessed by the Shapiro-Wilk-test [67] with $p > 0.05$. The homogeneity of variance is confirmed by the Levene-test [70] with $p > 0.05$. The hypothesis is directional. Hence, an independent one-tailed t-test [71] is used to check for a statistically significant improvement in physical ergonomics with a significance level of $\alpha = 0.05$.

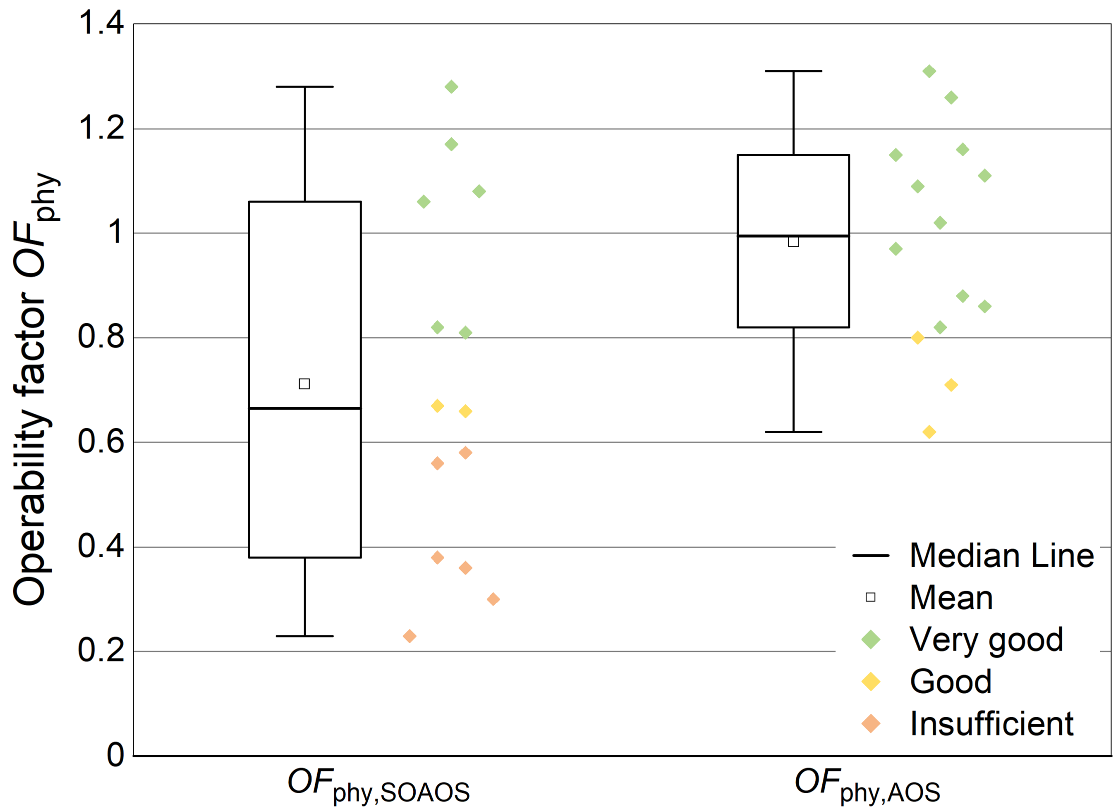


Figure 94: Box plot of the physical operability factors $OF_{\mathrm{phy,SOAOS}}$ and $OF_{\mathrm{phy,AOS}}$. The coloring of the data points is in accordance with VDI 2225-3 [60].

The result of the independent one-tailed t-test was a statistically significant higher physical OF of the AOS ($M = 0.98$, $SD = 0.21$) compared to the SOAOS ($M = 0.71$, $SD = 0.34$), $t(26) = 2.55$, $p = 0.008$, $d = 0.97$. According to COHEN [69] with d > 0.8 the effect size is large.

Hence, based on the applied evaluation methods, the AOS provides a statistically significant improvement in physical ergonomics compared to the SOAOS.

10 DISCUSSION AND OUTLOOK

The conflicting goals of the versatile use of a tractor and ergonomic operability can be solved with adaptive operating systems. With state-of-the-art operator systems (Chapter 2.4), the first approaches towards this direction are taken. However, these approaches are limited to buttons with generic icons. Usually, these buttons can be assigned to a selection of functions. Furthermore, the possibility to change the assignment of hydraulic valve controllers to different SCVs is also state of the art. Sometimes the current SCV assignment is indicated by a valve-related color lighting on or next to the hydraulic valve control element, like on the Fendt One system described in Chapter 2.4.2.

Considering this from a cognitive ergonomics perspective, adaptive operating systems are particularly advantageous for tractors since they improve the implement-specific operability by adapting the operator system to the implement. These advantages become clear when linking the UASW model from SCHMID [46] in Figure 36 with the theory of the conceptual model from NORMAN [49] in Figure 40. If control elements harmonize with their displays and assigned functions, the operator system can transmit a suitable system image to the users. A proper system image makes it easier for the users to build a better conceptual model of the then self-explaining system. As of today, as depicted in Figure 41, the system image of an implement can not be transmitted to the users - unfortunately, also not with free assignable buttons with generic icons. Instead, users must build their conceptual model of the implement through the system image made by the tractor designer. This additional cognitive load can be avoided by bridging the gap between an implement’s system image and the users with adaptive operator systems.

From a physical ergonomics perspective, adaptive operator systems also provide advantages. The versatile use of tractors entails a large number of functions. A permanent assignment of these functions to control elements requires correspondingly much space and thus leads to more space-taking operator systems. On the other hand, adaptive operator systems provide only the necessary functions in a context-based manner assigned to the control elements according to their frequency of use. This results in fewer control elements, better reachability, and fewer hand position changes.

The above consideration of adaptive control systems and the derived advantages led to the following directional main hypothesis as formulated in Chapter 1:

> If a tractor’s operator system adapts itself to an operating scenario, then both cognitive and physical ergonomics improve.

The approach to prove or disprove this main hypothesis in this work was first to analyze the potential for adaptive operator systems in tractors.

One part was a theoretical potential analysis of operating state-of-the-art tractors based on a Deutz-Fahr Agrotron 9340 TTV manufactured in 2015 that can be seen as generally applicable to today’s tractors. The analysis brought up a high potential for adaptivity of control elements for the two main function groups PTO and hydraulics.

Another part of the examination of the main hypothesis was taking measurements with the above-mentioned Deutz-Fahr Agrotron 9340 TTV in the field. Measurements have been taken and analyzed for 14 operating scenarios listed in Table 4. Even though these operating scenarios cover a wide range of agricultural work, all findings have to be seen under the limitation of these 14 measured operating scenarios. Strongly summarized, it was found that very few control elements are used for the vast majority of operator inputs. From operating scenario to operating scenario, these very few control elements differ. Another finding is that there are control elements in every operating scenario that are not used at all. This finding proves the sub-thesis as formulated in Chapter 6.2:

> Not all control elements of a state-of-the-art tractor are required in each operating scenario.

Chapters 6.2.3 and 6.2.4 include the detailed results and interpretation of the measurement data. Hence, both the theoretical (Chapter 6.1) and the in-field measurement analysis (Chapter 6.2) show the potential for adaptive operator systems in tractors.

With the layer method and the assign method, Chapter 5 introduces two new methods that support the specification of adaptive operator systems alongside the development process based on the V-model. In Chapter 7, both methods have been used to specify the adaptive operator system developed during this work. For the evaluation part of the development process based on the V-model two methods are introduced and applied: Besides the description of the UASW method, Chapter 5 introduces a new method to evaluate the physical factors of an operating system - the spots method. The adaptive operator system of this work was evaluated with these two methods in Chapter 9.

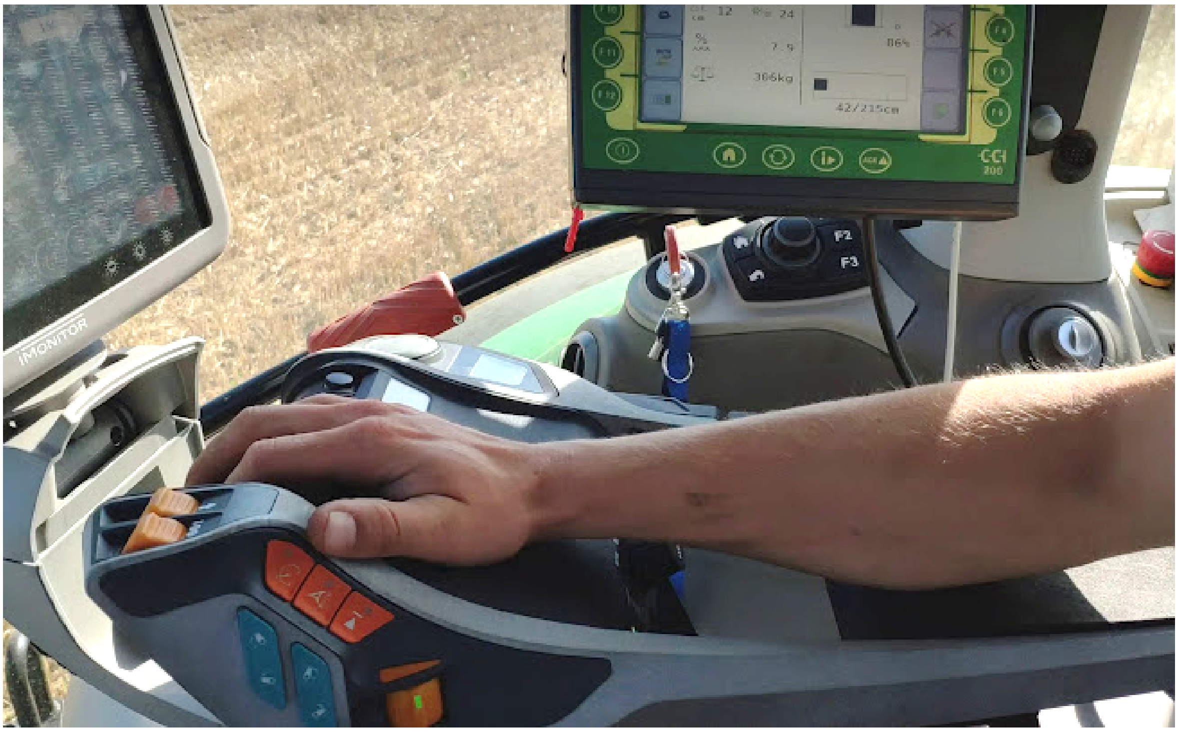


Figure 95: In-field use of the adaptive operator system with a Krone BigPack 1270 XC with ISOBUS.

The adaptive operator system developed during this work is described in Chapter 8. It is the first time that a holistic adaptive operator system is introduced in a tractor. Moreover, this AOS is fully functional and was used during in-field tests with the Deutz-Fahr 9340 TTV Agrotron test tractor as depicted in **Figure 95**. It was driven by five drivers in the operating scenarios Deutz-Fahr 9340 TTV Agrotron, Kerner Komet K420, Zunhammer MKE14PUL with ISOBUS, Krone BigPack 1270 XC with ISOBUS, and Lemken Juwel 8 with ISOBUS. It was well accepted by all drivers who wished to see market availability as soon as possible. The adaptive features causing better usability and a reduced number of control elements were evaluated as very positive. Two drivers wished for a stronger differentiation in the coloring of the control elements. As depicted in Chapter 8, the coloring of the control elements' material was very much restrained in the design of the AOS. Since color is an adaptivity feature, it can only be realized with built-in RGB lighting or colored icons in the adaptive control elements' screens.

The evaluation of the AOS based on the UASW method (cognitive factors) and spots method (physical factors) is conducted in Chapter 9. It was done to prove or disprove the directional main hypothesis from Chapter 1 that if a tractor's operator system adapts itself to an operating scenario, then both cognitive and physical ergonomics improve. The resulting cognitive and physical operability factors in comparison of the state-of-the-art operator system and the adaptive operator system in Tables 21 and 22 prove the directional main hypothesis:

- In cognitive ergonomics, the non-weighted average operability factor of the AOS with 0.96 (very good) is a statistically significant improvement with a large effect compared to the SOAOS with 0.70 (good).
- In physical ergonomics, the non-weighted average operability factor of the AOS with 0.98 (very good) is a statistically significant improvement with a large effect compared to the SOAOS with 0.71 (good).

These findings are explainable since the cognitive requirements per se can be fulfilled as soon as a proper adaptive control element is available. With physical ergonomics, the more functions that need to be controlled in an operating scenario, the lower the probability that all will fit in the ergonomically higher-ranked spots. Hence, it is all the more important that high-frequent functions are assigned to control elements in ergonomically better-ranked spots. Even though the UASW method generally allows for a small amount of subjective blur when conducting the evaluation, the results show significant improvements with the adaptive operator system, so potential blur can be neglected. With the spots method, a slight blurring is caused in some operating scenarios by the assumptions that were made to allocate the measured ISOBUS and hydraulic inputs to the spots on the adaptive operator system as described in Chapter 9.2. However, these assumptions are justifiable since they reveal more conservative evaluation results that still show a significant improvement with the adaptive operator system compared to the state-of-the-art operator system. No assumptions were made when applying the spots method to the state-of-the-art operator system.

Regarding drivers of different skill levels, the afore-listed findings show that both a low-skilled temporary driver and a high-skilled professional driver can benefit from adaptive operator systems. As already explained with the model from NORMAN [49], adaptive operator systems allow the transfer of the implement's system image to the tractor's operator system. Thus, the low-skilled driver can understand the implement designer's conceptual model much easier. Moreover, fewer control elements provide a much clearer operator system. In addition to the ergonomic advantages already mentioned, the high-skilled driver will particularly benefit from the frequency-based assignment of functions to control elements, since this reduces the amount of movement on the MFA and thus increases the efficiency of the operation of a tractor.

In conclusion, this work demonstrates that adaptive operator systems significantly improve the cognitive and physical ergonomics of operating tractors through outstanding usability and user experience. The applied methods for the specification and evaluation of adaptive operator systems in the development process based on the V-model have proven to be very suitable.

Based on the results and findings of this work, a patent has been filed in Germany [72] for adaptive operator systems and their adaptation to an implement using adaptivity features. Based on the German priority, the patent has been granted in Europe and the United States of America.

The outlook for the next steps includes measuring and analyzing additional operating scenarios. Within these additional operating scenarios, cognitive and physical operability factors for the adaptive operator system can be evaluated to see if the results and findings of this work can be further confirmed.

Further steps are possible in the development of additional adaptive control elements, each covering as many of the basic input characteristics in Figure 44 as possible. For this, also other adaptivity features than those in Figure 83 can be considered, such as torque, force, or shape.

The use of artificial intelligence (AI) offers additional potential for the further development of adaptive operator systems in tractors. AI is a set of technologies that enable computers to perform a variety of advanced functions, including the ability to see, understand and translate spoken and written language, analyze data, make recommendations, and more [73]. With adaptive operator systems, AI can help to optimize the implement manufacturer's frequency-based standard assignment of functions to control elements. For this, the actual frequency of use of functions in an operating scenario is continuously analyzed. If the AI detects a high-frequency function that is assigned to a control element in a low-ranked ergonomic spot, but could be assigned to a control element in a high-ranked spot by changing with a low-frequency function, it recommends this optimization of the assignment to the driver. The driver then only has to confirm the change. Moreover, AI can be used to recognize input patterns on the headland turn and suggest thereon-based headland sequences to the driver. The recognized patterns can also be used to monitor if the users forget a function input during a headland turn and notify them accordingly.

However, besides ergonomics, other influencing factors must be considered in future steps to make it to the market with adaptive operator systems in tractors and unleash their full potential. Hence, not only the adaptive operator system itself must be considered, but the whole system comprising the tractor, its adaptive operator system, and the implement. All three entities must interact with each other. The concept could be that the implement manufacturer defines a configuration of how its implement is to be controlled in the best way. This information is transmitted to the tractor. There, an algorithm matches the requirements from the implement's configuration with the available adaptive control elements on the tractor. Then, the system adjusts the adaptive operator system accordingly. With this procedure, the system image from the implement designer is provided to the driver. Hence, the driver faces an almost self-explaining and thus intuitive operator system.

From a technological perspective, the industry must agree on a universal communication protocol to connect the tractors' adaptive operator systems to the implements - independently from the manufacturer. Preferably this protocol is based on the ISOBUS standard. The follow-up research project aISA 2.0 includes both the conceptual elaboration of the entire system and the technological development [74]. The author of this work is part of the research project aISA 2.0.

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12 APPENDIX

12.1 Appendix of Chapter 6.2.3

12.1.1 Horsch Terrano 3 FX

Overall data for operating a Horsch Terrano 3 FX during 14.47 work hours:

- Overall operator inputs: 2127
- Operator inputs per minute: 2.45
- Average operator inputs per control element: 33.23
- Average operator inputs per control element without bin 0: 57.49
- Median of operator inputs for all control elements: 2
- Number of CEs for at least 80 % of all operator inputs: 7
- Percentage of CEs for at least 80 % of all operator inputs: 11 %

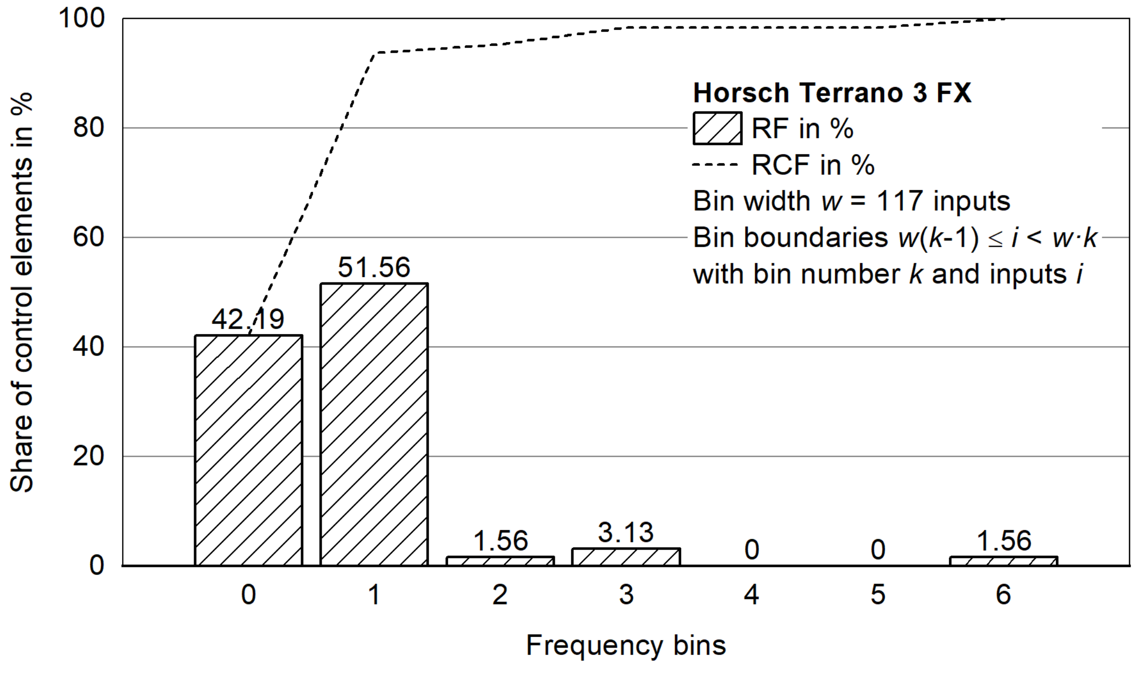

Figure 96: Histogram for the relative and relative cumulative frequency distribution for operating a Horsch Terrano 3 FX during 14.47 work hours.

Control elements in high-frequency bins of **Figure 96** (code refers to Table 1):

- Bin 2: Consent button (M20)

- Bin 3: TPH rear - up (TPH20),
  Set maximum speed (DT90)
- Bin 6: TPH rear - down (TPH20)

Figure 97: Heatmap for operating a Horsch Terrano 3 FX during 14.47 work hours.

12.1.2 Kerner Komet K420

Overall data for operating a Kerner Komet K420 during 18 work hours:

- Overall operator inputs: 3480
- Operator inputs per minute: 3.22
- Average operator inputs per control element: 54.38
- Average operator inputs per control element without bin 0: 102.35
- Median of operator inputs for all control elements: 2
- Number of CEs for at least 80 % of all operator inputs: 7
- Percentage of CEs for at least 80 % of all operator inputs: 11 %

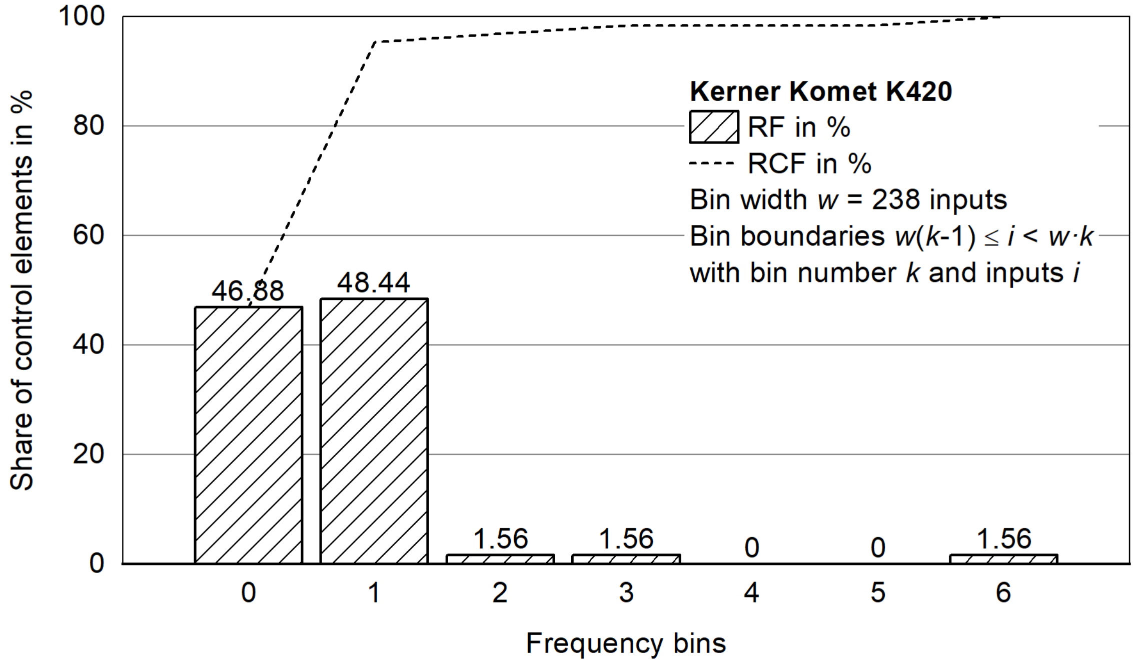

Figure 98: Histogram for the relative and relative cumulative frequency distribution for operating a Kerner Komet K420 during 18 work hours.

Control elements in high-frequency bins of **Figure 98** (code refers to Table 1):

- Bin 2: TPH rear - up (TPH20)
- Bin 3: Set maximum speed (DT90)
- Bin 6: TPH rear - down (TPH20)

Figure 99: Heatmap for operating a Kerner Komet K420 during 18 work hours.

12.1.3 Krone EasyCut 32 CV Float and EasyCut R 320 CV

Overall data for operating a Krone EasyCut 32 CV Float and EasyCut R 320 CV during 11.78 work hours:

- Overall operator inputs: 1938
- Operator inputs per minute: 2.74
- Average operator inputs per control element: 30.28
- Average operator inputs per control element without bin 0: 49.69
- Median of operator inputs for all control elements: 6
- Number of CEs for at least 80 % of all operator inputs: 11
- Percentage of CEs for at least 80 % of all operator inputs: 17 %

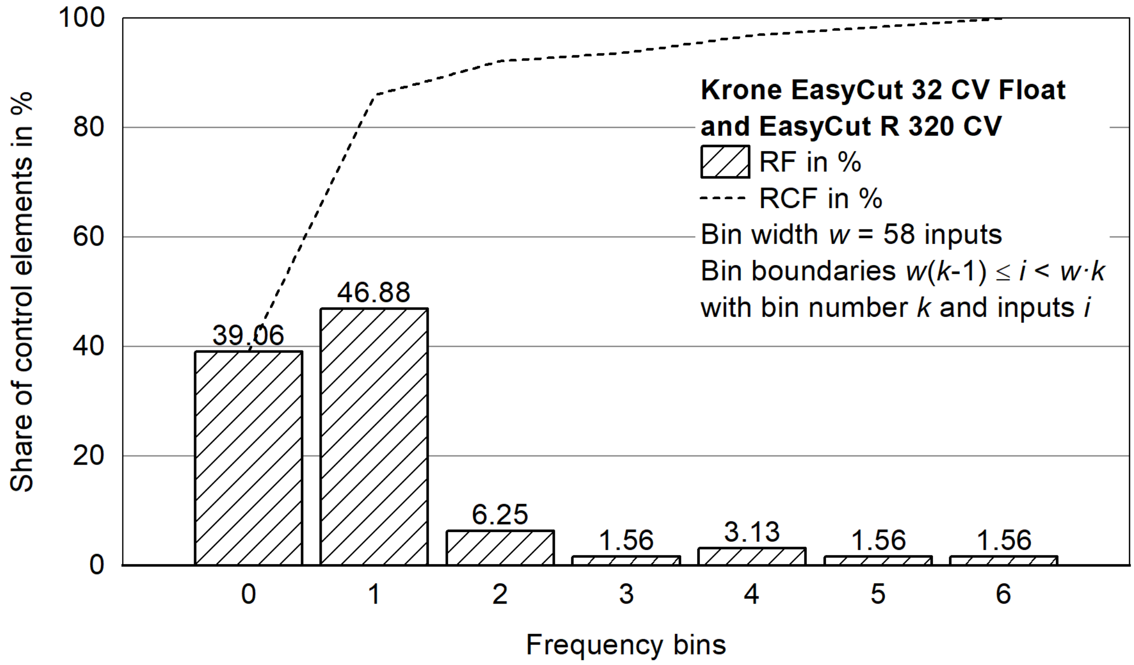

Figure 100: Histogram for the relative and relative cumulative frequency distribution for operating a Krone EasyCut 32 CV Float and EasyCut R 320 CV during 11.78 work hours.

Control elements in high-frequency bins of **Figure 100** (code refers to Table 1):

- Bin 2: Control element 1 for an SCV (H10),
  Forward direction (D50),
  Backward direction (D50),
  TPH front - down (TPH20)
- Bin 3: Control element 8 for an SCV (H10)

- Bin 4: Control element 4 for an SCV (H10),
  Consent button (M20)
- Bin 5: Control element 3 for an SCV (H10)
- Bin 6: Forward-neutral-backward shuttle lever (D50)

Figure 101: Heatmap for operating a Krone EasyCut 32 CV Float and EasyCut R 320 CV during 11.78 work hours.

12.1.4 Wagner WK600

Overall data for operating a Wagner WK600 during 50.02 work hours:

- Overall operator inputs: 4146
- Operator inputs per minute: 1.38
- Average operator inputs per control element: 64.78
- Average operator inputs per control element without bin 0: 101.12
- Median of operator inputs for all control elements: 6
- Number of CEs for at least 80 % of all operator inputs: 13
- Percentage of CEs for at least 80 % of all operator inputs: 20 %

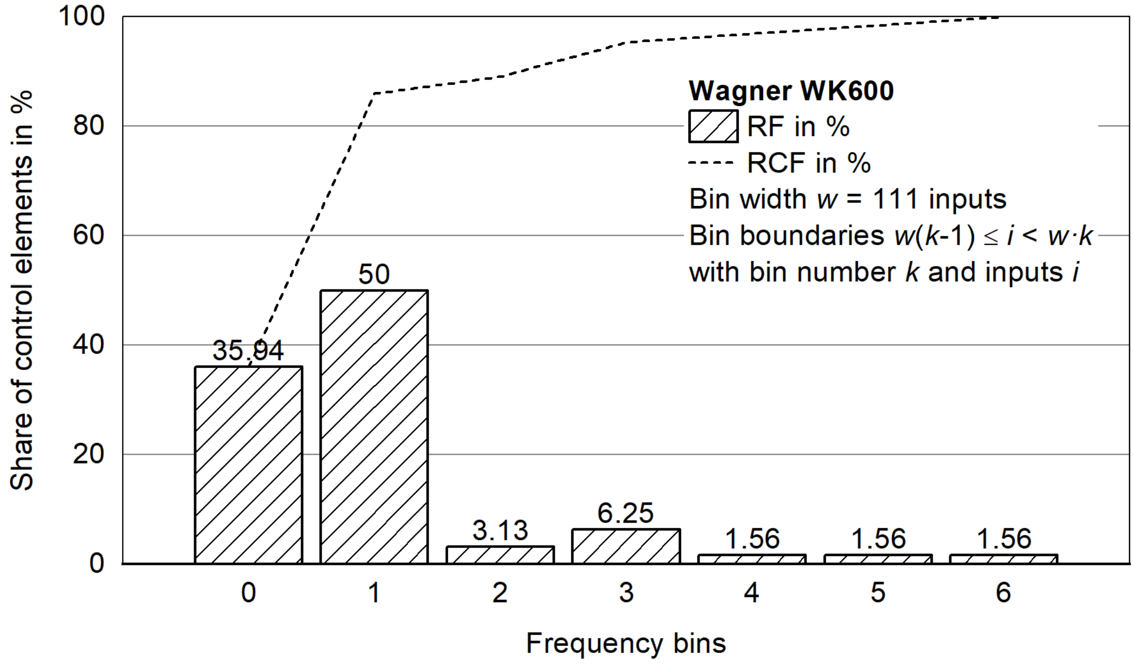

Figure 102: Histogram for the relative and relative cumulative frequency distribution for operating a Wagner WK600 during 50.02 work hours.

Control elements in high-frequency bins of **Figure 102** (code refers to Table 1):

- Bin 2: Control element 3 for an SCV (H10),
  Control element 5 for an SCV (H10)
- Bin 3: Control element 2 for an SCV (H10),
  Backward direction (D50),
  Set maximum speed (DT90),
  Fine-tuning of speed limit (DT91)
- Bin 4: Forward direction (D50)

- Bin 5: Control element 1 for an SCV (H10)
- Bin 6: Consent button (M20)

Figure 103: Heatmap for operating a Wagner WK600 during 50.02 work hours.

12.2 Appendix of Chapter 6.2.4

Table 23: Bin occurrence of the measured control elements across all operating scenarios.

Control element	Bin 0	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
Forward direction (D50)	-	true	true	true	true	-	-
Backward direction (D50)	-	true	true	true	-	-	-
Forward-neutral-backward shuttle lever (D50)	-	true	-	-	true	-	true
Idle running (D60)	true	true	-	-	-	-	-
Hand throttle (DT10)	true	true	-	-	-	-	-
Four-wheel drive (DT20)	true	true	-	-	-	-	-
Differential lock (DT30)	true	true	-	-	-	-	-
Automatic drive train management (DT40)	-	true	-	-	-	-	-
Cruise control 1 (DT50)	true	true	-	-	-	-	-
Cruise control 2 (DT50)	true	true	-	-	-	-	-
Engine speed memory 1 (DT60)	true	true	-	-	-	-	-
Engine speed memory 2 (DT60)	true	true	-	-	-	-	-
Transmission mode (DT70)	true	true	-	-	-	-	-
Unlock / lock front suspension (DT80)	true	true	-	-	-	-	-
Set maximum speed (DT90)	-	true	true	true	-	true	true
Fine-tuning of speed limit (DT91)	-	true	true	true	-	-	-
Trailer stretch (DT100)	true	true	-	-	-	-	-
Acceleration intensity (DT110)	-	true	-	-	-	-	-

Control element	**Bin 0**	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin 6**
Engine speed range (DT120)	-	true	-	-	-	-	-
Unlock / lock TPHs (TPH10)	-	true	-	-	-	-	-
TPH rear - up (TPH20)	true	true	true	true	-	-	-
TPH rear - down (TPH20)	true	true	true	-	-	-	true
TPH front - up (TPH20)	true	true	-	true	-	-	-
TPH front - down (TPH20)	true	true	true	-	true	-	-
TPHs stop (TPH30)	true	true	-	-	-	-	-
TPH rear - depth control (TPH40)	true	true	true	-	-	-	-
TPH front - depth control (TPH40)	-	true	true	-	-	-	-
TPH rear - traction and position control (TPH50)	true	true	-	-	-	-	-
TPH rear - lowering speed (TPH60)	-	true	-	-	-	-	-
TPH front - lowering speed (TPH60)	-	true	-	-	-	-	-
TPH rear - maximum lifting height (TPH70)	-	true	-	-	-	-	-
TPH front - maximum lifting height (TPH70)	-	true	true	-	-	-	-
TPH rear - slip control (TPH80)	true	true	-	-	-	-	-
PTO rear (PTO10)	true	true	true	-	-	-	-
PTO front (PTO10)	true	true	-	-	-	-	-
PTO rear - automode (PTO30)	true	true	-	-	-	-	-
Control element 1 for an SCV (H10)	true	true	true	-	-	true	true

Control element	**Bin 0**	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin 6**
Control element 2 for an SCV (H10)	-	true	-	true	-	-	true
Control element 3 for an SCV (H10)	true	true	true	true	-	true	-
Control element 4 for an SCV (H10)	true	true	true	-	true	-	-
Control element 5 for an SCV (H10)	true	true	true	-	-	-	-
Control element 6 for an SCV (H10)	true	true	true	-	-	-	-
Control element 7 for an SCV (H10)	true	true	-	-	-	-	-
Control element 8 for an SCV (H10)	true	true	-	true	-	-	-
Shortcut hydraulic oil flow rate (H20)	true	true	-	-	-	-	-
Shortcut hydraulic oil flow timing (H30)	true	true	-	-	-	-	-
Unlock / lock SCVs (H50)	-	true	-	-	-	-	-
Headland management (A10)	true	true	-	-	-	-	true
Automatic steering system (A30)	true	true	true	-	-	-	-
Activate easy steering (A50)	true	true	-	-	-	-	-
Esc-button dashboard (M10)	-	true	-	-	-	-	-
Dial dashboard (M10)	-	true	-	-	-	-	-
Consent button (M20)	-	true	true	true	true	true	true
ISOBUS input	true	true	true	true	-	-	true
P1 small joystick	true	true	-	-	-	-	-
P2 small joystick	true	true	-	-	-	-	-

Control element	**Bin 0**	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin 6**
P3 small joystick	true	true	-	-	-	-	-
F1	true	true	-	-	-	-	-
F2	true	true	-	-	-	-	-
F3	true	true	-	-	-	-	-
Home-button	true	true	-	-	-	-	-
Back / esc button	true	true	-	-	-	-	-
Push dial iMonitor	true	true	-	-	-	-	-
Dial iMonitor	true	true	-	-	-	-	-

12.3 Appendix of Chapter 8.4

Deutz-Fahr 9340 TTV Agrotron

Table 24: Assignment of adaptive functions in the operating scenario Deutz-Fahr 9340 TTV Agrotron.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	3	Front PTO	On / off
1.2	3	Rear PTO	On / off

Zunhammer MKE14PUL with ISOBUS

Table 25: Assignment of adaptive functions in the operating scenario Zunhammer MKE14PUL with ISOBUS.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Substrate pump (Rear PTO)	On / off
1.1	1	Trailing shoes	Up / down
1.2	2	Folding boom	Forth / back
1.3	2	Constant hydraulic flow	On / off
2.1	1	Support leg	Up / down
3.1	2	Trailing axle	Open / close

Bergmann TSW 5210 S with ISOBUS

Table 26: Assignment of adaptive functions in the operating scenario Bergmann TSW 5210 S with ISOBUS.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Spreader (Rear PTO)	On / off
1.1	1	Dosing wall	Up / down

Assigned field	Base position	Name of the function	Basic input characteristic
1.2	2	Scraper floor automatic	On / off
1.2	2	Scraper floor manual	Forth / back
1.3	1	Spread pattern limiter	Up / down
3.1	2	Trailing axle	Open / close

Terrano 3 FX

Table 27: Assignment of adaptive functions in the operating scenario Horsch Terrano 3 FX.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Working depth adjustment	Up / down
1.2	2	Edge discs	On / off
1.3	2	Toplink cylinder	Forth / back

Kerner Komet K420

Table 28: Assignment of adaptive functions in the operating scenario Kerner Komet K420.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Frame wings	Up / down
1.2	2	Toplink cylinder	Forth / back
3.1	2	Spring load stone protection	More / less

Horsch Tiger 4 MT

Table 29: Assignment of adaptive functions in the operating scenario Horsch Tiger 4 MT.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Working depth adjustment	Up / down
1.2	1	Disc system	Up / down
1.3	1	Frame wings	Up / down

Krone EasyCut 32 CV Float and EasyCut R 320 CV

Table 30: Assignment of adaptive functions in the operating scenario Krone EasyCut 32 CV Float and EasyCut R 320 CV.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Front mower transport < > mowing	Up / down
1.2	1	Rear mower headland < > mowing	Up / down
1.1	1	Front mower (Front PTO)	On / off
1.2	1	Rear mower (Rear PTO)	On / off
1.3	1	Rear mower headland < > transport	Up / down
2.1	2	Toplink cylinder	Forth / back

Krone EasyCut 32 CV Float and EasyCut B 870 CV

Table 31: Assignment of adaptive functions in the operating scenario Krone EasyCut 32 CV Float and EasyCut B 870 CV.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Front mower transport < > mowing	Up / down
1.2	1	Rear mower a) transport < > headland b) headland < > mowing c) conveyor belts (ref. Figure 72)	Up / down
1.1	1	Front mower (Front PTO)	On / off
1.2	1	Rear mower (Rear PTO)	On / off
1.3	2	Toplink cylinder	Forth / back

Krone MX 400 with ISOBUS

Table 32: Assignment of adaptive functions in the operating scenario Krone MX 400 with ISOBUS.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	1	Pick up	Up / down
1.1	1	Loading wagon (Rear PTO)	On / off
1.2	2	Scraper floor	Forth / back
1.3	1	Folding drawbar	Up / down
3.1	2	Trailing axle	Open / close

Krone BigPack 1270 XC with ISOBUS

Table 33: Assignment of adaptive functions in the operating scenario Krone BigPack 1270 XC with ISOBUS.

Assigned field	**Base position**	**Name of the function**	**Basic input characteristic**
1.1	1	Pick up	Up / down
1.1	1	Baler (Rear PTO)	On / off
3.1	2	Trailing axle	Open / close
1.2	1	Support leg	Up / down

Lemken Juwel 8 with ISOBUS

Table 34: Assignment of adaptive functions in the operating scenario Lemken Juwel 8 with ISOBUS.

Assigned field	**Base position**	**Name of the function**	**Basic input characteristic**
1.1	3	Turn plow left	Turn CW / CCW
1.2	3	Turn plow right	Turn CW / CCW
1.3	3	Tow arm	Open / close
2.1	1	Plow support wheel	Up / down
2.2	2	Toplink cylinder	Forth / back
3.1	3	Plow width	More / less
3.2	3	Furrow width	More / less

Lemken Solitair 9 with ISOBUS

Table 35: Assignment of adaptive functions in the operating scenario Lemken Solitair 9 with ISOBUS.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	2	Rotary harrow (Rear PTO)	On / off
1.1	2	Fan	On / off
1.2	3	Colter pressure	More / less
1.3	2	Toplink cylinder	Forth / back

Due to an automatic steering system, the track markers were not used.

Krampe Big Body 750

Table 36: Assignment of adaptive functions in the operating scenario Krampe Big Body 750.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	3	Body tipper	Up / down
1.2	3	Body tailgate	Up / down
1.3	3	Body cover	Open / close
3.1	2	Trailing axle	Open / close

Wagner WK600

Table 37: Assignment of adaptive functions in the operating scenario Wagner WK600.

Assigned field	Base position	Name of the function	Basic input characteristic
1.1	3	Body tipper	Up / down
1.2	3	Body tailgate	Up / down
3.1	2	Trailing axle	Open / close
1.3	3	Support leg	Up / down

12.4 Appendix of Chapter 9.1

Table 38: Evaluation sheet for Deutz-Fahr 9340 TTV Agrotron.

Name of the function	Basic input characteristic	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Front PTO	On / off	1.00	1.00
Rear PTO	On / off	1.00	1.00
	Overall OF_{cog}	1.00	1.00

Table 39: Evaluation sheet for Zunhammer MKE14PUL with ISOBUS.

Name of the function	Basic input characteristic	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Substrate pump (Rear PTO)	On / off	0.75	1.00
Trailing shoes	Up / down	0.17	1.00
Folding boom	Forth / back	0.50	1.00
Constant hydraulic flow	On / off	0.25	0.50
Trailing axle	Open / close	0.25	1.00
Support leg	Up / down	0.83	1.00
	Overall OF_{cog}	0.46	0.92

Table 40: Evaluation sheet for Bergmann TSW 5210 S with ISOBUS.

Name of the function	Basic input characteristic	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Spreader (Rear PTO)	On / off	0.75	1.00
Dosing wall	Up / down	0.50	0.60
Scraper floor automatic	On / off	1.00	1.00
Scraper floor manual	Forth / back	0.50	1.00
Trailing axle	Open / close	0.88	1.00
Spread pattern limiter	Up / down	0.83	1.00
	Overall OF_{cog}	0.74	0.93

Table 41: Evaluation sheet for Horsch Terrano 3 FX.

Name of the function	Basic input characteristic	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Working depth adjustment	Up / down	0.50	0.60
Edge discs	On / off	0.25	0.50
Toplink cylinder	Forth / back	0.50	1.00
	Overall OF_{cog}	0.42	0.70

Table 42: Evaluation sheet for Kerner Komet K420.

Name of the function	Basic input characteristic	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Frame wings	Up / down	0.83	1.00
Toplink cylinder	Forth / back	0.50	1.00
Spring load stone protection	More / less	0.50	1.00
	Overall OF_{cog}	0.61	1.00

Table 43: Evaluation sheet for Horsch Tiger 4 MT.

Name of the function	Basic input characteristic	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Working depth adjustment	Up / down	0.83	1.00
Disc system	Up / down	0.83	1.00
Frame wings	Up / down	0.83	1.00
	Overall OF_{cog}	0.83	1.00

Table 44: Evaluation sheet for Krone EasyCut 32 CV Float and EasyCut R 320 CV.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Front mower transport < > mowing	Up / down	0.58	1.00
Rear mower headland < > mowing	Up / down	0.58	1.00
Front mower (Front PTO)	On / off	0.75	1.00
Rear mower (Rear PTO)	On / off	0.75	1.00
Rear mower headland < > transport	Up / down	0.83	1.00
Toplink cylinder	Forth / back	0.50	1.00
	Overall OF_{cog}	0.67	1.00

Table 45: Evaluation sheet for Krone EasyCut 32 CV Float and EasyCut B 870 CV.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Front mower transport < > mowing	Up / down	0.83	1.00
Rear mower a) transport < > headland b) headland < > mowing c) conveyor belts (ref. Figure 72)	Up / down	0.83	1.00
Front mower (Front PTO)	On / off	0.75	1.00
Rear mower (Rear PTO)	On / off	0.75	1.00
Toplink cylinder	Forth / back	0.50	1.00
	Overall OF_{cog}	0.73	1.00

Table 46: Evaluation sheet for Krone MX 400 with ISOBUS.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Pick up	Up / down	0.83	1.00
Loading wagon (Rear PTO)	On / off	0.75	1.00
Scraper floor	Forth / back	0.50	1.00
Folding drawbar	Up / down	0.83	1.00
Trailing axle	Open / close	0.88	1.00
	Overall OF_{cog}	0.76	1.00

Table 47: Evaluation sheet for Krone BigPack 1270 XC with ISOBUS.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Pick up	Up / down	0.83	1.00
Baler (Rear PTO)	On / off	0.75	1.00
Trailing axle	Open / close	0.88	1.00
Support leg	Up / down	0.83	1.00
	Overall OF_{cog}	0.82	1.00

Table 48: Evaluation sheet for Lemken Juwel 8 with ISOBUS.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Turn plow	Turn CW / CCW	0.65	1.00
Tow arm	Open / (close)	1.00	1.00
Plow support wheel	Up / down	0.90	1.00
Toplink cylinder	Forth / back	0.50	1.00
Plow width	More / less	0.95	1.00
Furrow width	More / less	0.95	1.00
	Overall OF_{cog}	0.83	1.00

Table 49: Evaluation sheet for Lemken Solitair 9 with ISOBUS.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Rotary harrow (Rear PTO)	On / off	0.75	1.00
Fan	On / off	0.25	0.50
Toplink cylinder	Forth / back	0.50	1.00
Colter pressure	More / less	0.83	1.00
	Overall OF_{cog}	0.58	0.88

Table 50: Evaluation sheet for Krampe Big Body 750.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Body tipper	Up / down	0.83	1.00
Body tailgate	Up / down	0.83	1.00
Body cover	Open / close	0.83	1.00
Trailing axle	Open / close	0.25	1.00
	Overall OF_{cog}	0.69	1.00

Table 51: Evaluation sheet for Wagner WK600.

Name of the function	**Basic input characteristic**	$OF_{cog,SOAA}$	$OF_{cog,AOS}$
Body tipper	Up / down	0.83	1.00
Body tailgate	Up / down	0.83	1.00
Trailing axle	Open / close	0.25	1.00
Support leg	Up / down	0.83	1.00
	Overall OF_{cog}	0.69	1.00

12.5 Appendix of Chapter 9.2

Referring to Figure 93, Table 52 lists all control elements and their assignment to the spots on the state-of-the-art and on the adaptive operator system.

Table 52: Available control elements and their spot assignment on the state-of-the-art and on the adaptive operator system.

Control element	**Spot on the SOAOS**	**Spot on the AOS**
Forward direction (D50)	Spot 1	Spot 1
Backward direction (D50)	Spot 1	Spot 1
Forward-neutral-backward shuttle lever (D50)	Steering wheel	Steering wheel
Idle running (D60)	Spot 2_3	Spot 1
Hand throttle (DT10)	Spot 2_4	Spot 1
Four-wheel drive (DT20)	Spot 2_4	Spot 2_1
Differential lock (DT30)	Spot 2_4	Spot 2_1
Automatic drive train management (DT40)	Spot 2_4	Spot 2_1
Cruise control 1 (DT50)	Spot 1	Spot 1
Cruise control 2 (DT50)	Spot 1	Spot 2_1
Engine speed memory 1 (DT60)	Spot 2_4	Spot 1
Engine speed memory 2 (DT60)	Spot 2_4	Spot 2_1
Transmission mode (DT70)	Spot 4_2	Spot 2_3
Unlock / lock front suspension (DT80)	Spot 4_2	Spot 2_3
Set maximum speed (DT90)	Spot 1	Spot 1
Fine-tuning of speed limit (DT91)	Spot 1	Spot 1
Trailer stretch (DT100)	Spot 2_3	Spot 2_1
Acceleration intensity (DT110)	Spot 4_2	Spot 2_1
Engine speed range (DT120)	Spot 2_3	Spot 2_1
Unlock / lock TPHs (TPH10)	Spot 2_3	Spot 2_3
TPH rear - up (TPH20)	Spot 1	Spot 1

Control element	**Spot on the SOAOS**	**Spot on the AOS**
TPH rear - down (TPH20)	Spot 1	Spot 1
TPH front - up (TPH20)	Spot 1	Spot 1
TPH front - down (TPH20)	Spot 1	Spot 1
TPHs stop (TPH30)	Spot 1	Spot 1
TPH rear - depth control (TPH40)	Spot 3_2	Spot 3_2
TPH front - depth control (TPH40)	Spot 3_2	Spot 3_2
TPH rear - traction and position control (TPH50)	Spot 4_2	Spot 2_1
TPH rear - lowering speed (TPH60)	Spot 4_2	Spot 2_1
TPH front - lowering speed (TPH60)	Spot 4_2	Spot 2_1
TPH rear - maximum lifting height (TPH70)	Spot 4_2	Spot 2_1
TPH front - maximum lifting height (TPH70)	Spot 4_2	Spot 2_1
TPH rear - slip control (TPH80)	Spot 4_2	Spot 2_1
PTO rear (PTO10)	Spot 2_3	Variable
PTO front (PTO10)	Spot 2_3	Variable
PTO rear - automode (PTO30)	Spot 2_3	Spot 2_3
Control element 1 for an SCV (H10)	Spot 1	Variable
Control element 2 for an SCV (H10)	Spot 1	Variable
Control element 3 for an SCV (H10)	Spot 3_1	Variable
Control element 4 for an SCV (H10)	Spot 3_1	Variable
Control element 5 for an SCV (H10)	Spot 2_2	Variable
Control element 6 for an SCV (H10)	Spot 2_2	Variable
Control element 7 for an SCV (H10)	Spot 2_2	Variable
Control element 8 for an SCV (H10)	Spot 3_1	Variable
Shortcut hydraulic oil flow rate (H20)	Spot 4_2	Not available

Control element	**Spot on the SOAOS**	**Spot on the AOS**
Shortcut hydraulic oil flow timing (H30)	Spot 4_2	Not available
Unlock / lock SCVs (H50)	Spot 2_3	Spot 2_3
Headland management (A10)	Spot 1	Spot 1
Automatic steering system (A30)	Spot 3_3	Spot 1
Activate easy steering (A50)	Spot 3_3	Spot 2_1
Esc-button dashboard (M10)	Spot 2_3	Not available
Dial dashboard (M10)	Spot 2_3	Not available
Consent button (M20)	Spot 1	Spot 1
ISOBUS input	Spot 2_1	Variable
P1 small joystick	Spot 3_1	Not available
P2 small joystick	Spot 3_1	Not available
P3 small joystick	Spot 3_1	Not available
F1	Spot 4_1	Spot 4_1
F2	Spot 4_1	Spot 4_1
F3	Spot 4_1	Spot 4_1
Home-button	Spot 4_1	Spot 4_1
Back / esc button	Spot 4_1	Spot 4_1
Push dial iMonitor	Spot 4_1	Spot 4_1
Dial iMonitor	Spot 4_1	Spot 4_1