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Systematics for the individual assessment of Augmented Reality potentials to support product validation

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Abstract

By integrating multiple disciplines like mechatronics, electronics and software, products become ever complex. The number of product variants increases while the product life cycles are getting shorter. At the same time, individualization and customer orientation are intensified. Often products are specifically designed and produced for customers according to their individual needs and requirements. For multidisciplinary products, a broad spectrum of product features can be of importance to customers in this context. To be successful in the highly competitive markets, companies need to further reduce their development times while fulfilling the individual customer requirements. This demands a continuous and efficient validation during the development. But classic validation approaches like physical prototypes or digital simulations are either not cost- and time-efficient or do not support a subjective validation by the customer. Additionally, an increasing geographical separation and flexible working hours hamper the necessary collaboration of the developers and customers. The existing challenges can be addressed through the innovative visualization and communication technology Augmented Reality (AR). AR provides enormous potentials to support product validation. Products or product features can be validated with AR even across locations based on virtual prototypes. However, the basic complexity of AR in combination with a lack of technology expertise and experience prevents companies from identifying and exploiting the potentials. This work therefore presents a systematic approach for the individual assessment of AR potentials to support product validation. Based on individual requirements, the systematics empowers companies to analyze the potentials on their own and plan AR-based validation accordingly. Thus, the presented work enables the utilization of so far largely unexploited innovative technological potentials.

Keywords: Augmented Reality, product validation, collaboration, customer integration, systematic approach, potential analysis, survey

1 Introduction

Through the combination of different disciplines, today's products combine diverse product features relevant to customers, such as appearance, functionality, behavior, kinematics, and ergonomics. While the number of product variants increases, product life cycles become ever shorter (Gausemeier et al., 2018). Product individualization in combination with increasing time and cost pressure on global markets leads to **new challenges in product development**. Companies need to further shorten their development cycles and bring products faster to market while maintaining or increasing product quality (Dumitrescu et al., 2021). This demands an early and continuous validation with customers to ensure the fulfillment of the requirements and the achievement of the necessary product quality (Albers, Heimicke, et al., 2019). However, classical validation approaches reach their limits ever faster. Physical prototypes are not time- and cost-efficient (Albers, Reinemann, et al., 2019). Digital validation tools such as simulations, on the other hand, do not allow a subjective validation by the customer. Increasing geographical separation and flexible working hours further complicate the necessary collaboration between customers and developers (Gausemeier et al., 2018). For an early and continuous integration of customers into the validation, there is a lack of suitable validation methodologies so far (Dumitrescu et al., 2021). In this respect, the visualization and communication technology **Augmented Reality (AR)** offers innovative possibilities. AR enables the interactive and immersive visualization of digital content embedded in real environments. Digital data and models can be freely overlaid and viewed precisely and true to scale at the future application site. This results in enormous potentials of AR as a validation tool to present virtual prototypes. The focus is not on validating a system as a whole, but rather on validating individual product features (Albers, Reinemann, et al., 2019). AR can fundamentally lead to a better understanding of the development by the customer (Li et al., 2017). This allows customers to provide meaningful feedback to the developers, that is incorporated into the development (Reinemann et al., 2019). In addition to pure visualization, AR enables highly efficient networking of geographically distributed stakeholders and thus efficient and meaningful validation activities even across locations (Porter & Heppelmann, 2017). However, the technological complexity of AR already confronts companies with challenges (Egger & Masood, 2020). In the context of product validation, there is an additional lack of a methodical approach to use AR (Albers, Reinemann, et al., 2019). Companies have great difficulties in identifying the described potentials of AR as a validation tool. Thus, the potentials are hardly exploited by companies so far.

The goal of this work is therefore to enable companies in analyzing and evaluating the potentials of AR as a validation tool on their own for individual validation scenarios. First, a **survey with company representatives** was conducted to better understand the current situation in the companies regarding validation and AR (Chapter 2). According to the needs and requirements that emerged from the survey, the **state of the art and related work** have been investigated (Chapter 3). Based on this investigation, a **systematics for the individual assessment of AR potentials to support product validation** was developed (Chapter 4).

2 Survey on AR in the context of product validation

The survey was conducted in 2021 with 22 company representatives from the engineering sector. They were asked for feedback for certain statements based on a Likert scale from *1* to *5, 1* meaning no agreement at all with the statement and *5* representing total agreement. Figure 1 summarizes the feedback for the main statements. 16 of 22 participants (72.8%) agreed or totally agreed to the statement, that the involvement of customers, both internal and external, is already part of current development projects. Detailed feedback shows that, on the one hand, this integration includes general feedback from potential customers through customer surveys and test markets. On the other hand, specific customers are involved through the discussion of checklists and the exchange of project workbooks. Some participants also stated that their companies try to validate as many product features as possible internally without the integration of the customer to simplify the validation process, for example through simulations or internal feedback sessions. 12 participants (54.6%) stated that the validation is already performed across locations based on digital product models and information. For example, the visualization of CAD models or renderings is shared and discussed in digital meetings. In principle, the observation of 3D models is better suited for the evaluation of many features than corresponding 2D representations (Hou et al., 2009). However, the 3D information is presented two-dimensionally on a screen. This leads to a cognitive distance between the form in which information is provided and the context in which it is applied, which in turn hampers the evaluation of the presented information (Porter & Heppelmann, 2017). Accordingly, 3D visualization of products and product features through AR offers enormous potentials for the validation.

This is basically confirmed by the survey. Companies see potentials of AR in all phases of the development process to support the validation. Asked about potentials for individual product features, the participants highly agreed to the statements, that AR provides potentials for the validation of optics and design (77.3%) as well as the shape (86.34) of a product. In the detailed feedback it was stated multiple times, that AR has particular potentials for these product features when the real environment needs to be considered, e.g. regarding the installation of a machine at the customer's site. In these cases, the customer needs to imagine the product not only in 3D, but at the same time appropriately in the real environment. Potentials of AR for the validation of haptics are rather not seen by the participants. 81.8% disagree to the statement. This basically fits to the fact, that haptics is a special challenge for AR. There is a variety of haptic gloves available as interaction solutions. However, it is not possible to create the feeling of touching and sensing different materials through such gloves. One possibility to validate haptics with AR is through tangible user interfaces, that are based on physical objects. A material probe could be overlaid with a certain design through AR. But such cases often also work without AR. The potentials of AR for the validation of kinematics and dynamics, functionality, and behavior as well as ergonomics were not rated that clear. However, other research work as well as practical examples show that there is potential here as well. This shows that companies are not yet familiar with the potentials of AR for validation. Results of kinematics and dynamics simulations could be visualized spatially positioned at a real system to simplify the interpretation in spatial and logical terms (Li et al., 2017). For functionality, a comprehensive evaluation of different types of prototypes shows advantages of AR over other representation forms (Reinemann et al., 2019). The validation of ergonomics is widely seen in research and already used in practice (Dyck et al., 2020). Accessibility, visibility and motion sequences can be realistically validated through virtual prototypes (Eigner et al., 2014).

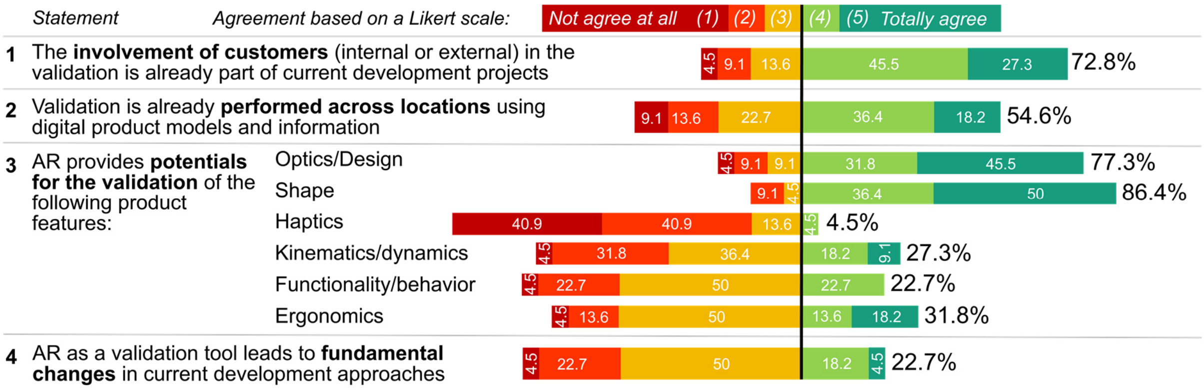


Figure 1. Results of the survey on AR in the context of product validation (n=22).

The feedback for the statements regarding the individual product features shows, that some basic potentials of AR to support validation are already known by the companies. However, due to a lack of a comprehensive understanding of the technology, many of the potentials are not seen. Furthermore, companies are not sure if AR as a validation tool leads to fundamental changes in current development approaches. Asked for details, the participants see an early planning of the validation, the creation of necessary documents and models for the validation and an increased communication between customers and engineers as the main changes. In addition, 8 of 22 participants state, that an AR expert would need to be integrated in the development. This confirms the assumption that companies need support in identifying potentials and planning of AR-based validation.

3 State of the art and related work

The solution for the systematic planning of AR-based validation should be universally applicable and reusable for different products, companies, and industries. So far, no such solution is known. AR-based validation is neither established in industry nor strongly present in research. Some scientific activities deal with the related technology VR in product development (Wolfartsberger, 2019). To enable a generic solution, a suitable processing of the requirements is needed. Thus, approaches for the **analysis and classification of product requirements** were first investigated. The VDI3694 standard for example defines a high-level structure for development specifications (VDI/VDE, 2014). A comprehensive classification of main product features that can be subject of the requirements is given in (Pahl et al., 2007). Lim et al. defined five filtering dimensions for prototypes: appearance, data, functionality, interactivity, spatial structure (Lim et al., 2008). Based on these, Reinemann et al. derived 22 specific filtering dimensions for AR-based prototypes (Reinemann et al., 2019). The dimensions are grouped into visual appearance, nonvisual appearance, functionality, interactivity and meta functionality. The filtering dimensions can be seen as similar to the product features and be addressed by the requirements. A method for planning and developing a product according to the quality characteristics required by the customer is the House-of-Quality (HoQ) (Klein, 1999). The HoQ includes a matrix structure to bring customer requirements in relation to a set of quality features and thus assess the features' importance. A holistic identification and documentation of AR potentials in the context of product validation is required in order to enable companies to fully exploit the potentials. To derive **generic AR potentials**, basic functionalities of AR have been analyzed at first. According to Azuma, AR can be described by three characteristics: the combination of the real with a virtual world, interactivity in real-time, and the three-dimensional registration of virtual content (Azuma, 1997). Furthermore, overviews of AR functionalities are given in (Broll, 2019) and (Billinghurst et al., 2015). In addition, Reinemann defined four functionalities specifically for the support of validation: visualization of meta information, scalability, content variability, and visibility (Reinemann, 2021). The possibility of interactive feedback in form of 3D annotations is described in (Bruno et al., 2019) and (Chang et al., 2017). Some more practical descriptions of AR potentials for validation are given in application reports and research work about certain use cases. Dyck et al. present a mixed mock-up approach to validate assembly processes with AR overlaid on physical cardboard mockups (Dyck et al., 2020). Röltgen and Dumitrescu derived generic AR application scenarios and described them generally and technically in profiles. Two of these scenarios are related to the validation domain: See-before-you-buy and design review (Röltgen & Dumitrescu, 2020). Furthermore, several approaches for the **systematic identification and evaluation of potentials** have been analyzed. A question-based process for the brief evaluation of AR potentials to support maintenance activities is presented in (Palmarini et al., 2017). Röltgen developed a cost-benefit-analysis to assess the potentials of AR for product-service-systems. The potentials are positioned in a portfolio according to their benefit and cost scores to allow an intuitive result interpretation (Röltgen, 2021). Another promising approach is the Agile Practices Impact Model (APIM). It can be used to model the relations between agile practices, organizational goals, and regulations and constraints in a graph structure (Diebold & Zehler, 2015). Based on this graph, an appropriate analysis mechanism could allow the identification of suitable agile practices for a certain application scenario. Furthermore, Reinemann describes a systematic approach for the configuration of AR-based validation environments (Reinemann, 2021). The approach assumes, that it is already decided to use AR for the validation and assists the user in the decision, which product features are to be presented virtually and which as physical prototypes. The analyzed state of the art and related work show, that there is no comprehensive solution for the individual assessment of AR potentials to support product validation available. However, existing approaches can be adapted and combined to form such a solution as described in the following chapter.

4 Systematics to assess AR potentials to support product validation

The systematics empowers companies to individually assess AR potentials to support product validation on their own. It should be usable by companies from different sectors whenever needed in addition to their standard development methodologies. The use of the systematics presupposes that the validation is intended to be carried out in a fundamentally digital form. Based on this assumption, the systematics supports companies in deciding whether AR makes sense as a validation tool for a set of requirements at hand and offers added value compared to alternative digital approaches. Due to the described lack of technology expertise and experience, this question cannot be answered independently by the companies. The systematic approach therefore enables the individual analysis and assessment of the fundamental potentials of AR to support validation based on the given specific requirements. The benefit of AR for the validation of the requirements at hand is assessed and opposed to the corresponding necessary efforts. Thus, the core of the assessment is a **cost-benefit analysis**. Furthermore, a comparison with alternative digital approaches is supported. This allows companies to evaluate whether AR is really necessary or useful to enable a meaningful validation. The alternative approaches include the classic 2D representation of digital data and models on a screen and Virtual Reality as an immersive visualization technology. A comparison with the use of purely physical prototypes is not addressed by the systematics. Accordingly, a decision between purely physical and digitally supported validation should be made in advance.

The idea of the systematics is to rate the potentials of AR to support validation in a generic and static manner and then use these ratings to individually derive conclusions regarding specific requirements. The basis of this approach is the **AR potential assessment graph** (Figure 2). Similar to the APIM (see Section 3), the AR potential assessment graph documents and correlates knowledge relevant for the cost-benefit analysis of AR potentials in the context of validation. The graph consists of a static part and a dynamic part. The static part (visualized in gray in Figure 2) contains the generic definitions and ratings made by technology experts. There are three types of nodes in this part: *AR potentials*, *product features* and *data aspects*. *AR potentials* represent the basic functional possibilities of AR. *Product features* are a generic set of features that can be addressed by the requirements. And *data aspects* contain different types of data that can be necessary to create the virtual prototypes to represent the product features to be validated. The nodes are related to each other via weighted edges. On the edges between each *AR potential* and *product feature* the *benefit* of the potential to support the validation of the feature is rated. Furthermore, the *necessity* of the data aspects to validate the features is defined. The dynamic part of the graph is defined by the user of the systematics (visualized in blue in Figure 2). It contains the *requirements* possibly to be validated with AR as nodes. To achieve a universally usable generic systematics, a generalization of the requirements is necessary. This is achieved by rating the *relevance* of the *product features* for each *requirement*. This approach is inspired by the House-of-Quality (see Section 3). Furthermore, the user defines the *available* as well es the *required level of detail* for each of the *data aspects*. This is later used to analyze the necessary efforts for the data preparation as costs. Based on the graph, an **interactive user tool** for the assessment of the potentials is provided. The user inputs the individual ratings according to the validation scenario at hand. Based on the user inputs and the static graph part, the necessary calculations of the cost-benefit analysis and further analyses are performed. The results are then returned in the tool and interpreted by the user to make a decision. A detailed description of the systematics and its components is given in the following subsections.

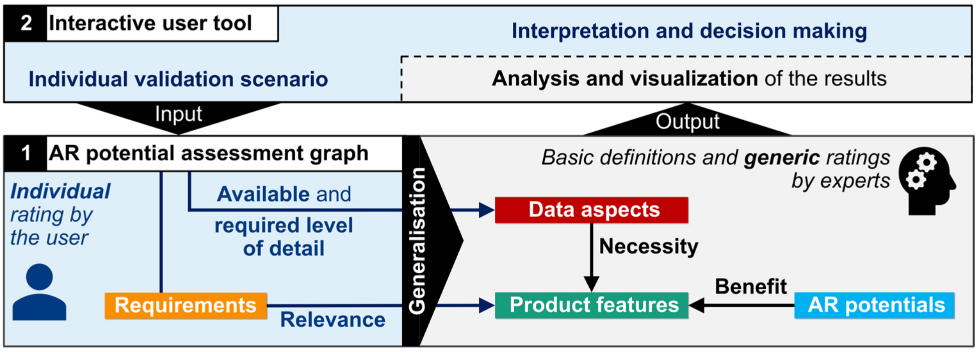


Figure 2. Overview of the systematics for the assessment of AR potentials to support product validation.

4.1 AR potential assessment graph

In addition to the aspects already described, the AR potential assessment graph contains further information like attributes and additional relations. To cover all this in one model the **C**ity-of-**A**ugmented-**R**eality-based-**V**alidation (**CARV**) (Figure 3) has been developed also inspired by the HoQ (see Section 3). In several matrix structures the relations between the different nodes are configured and attributes derived in the CARV. All the information necessary for the decision regarding the use of AR as a validation tool is included in the CARV. Its usage is explained in the following subsections according to the steps indicated in Figure 3.

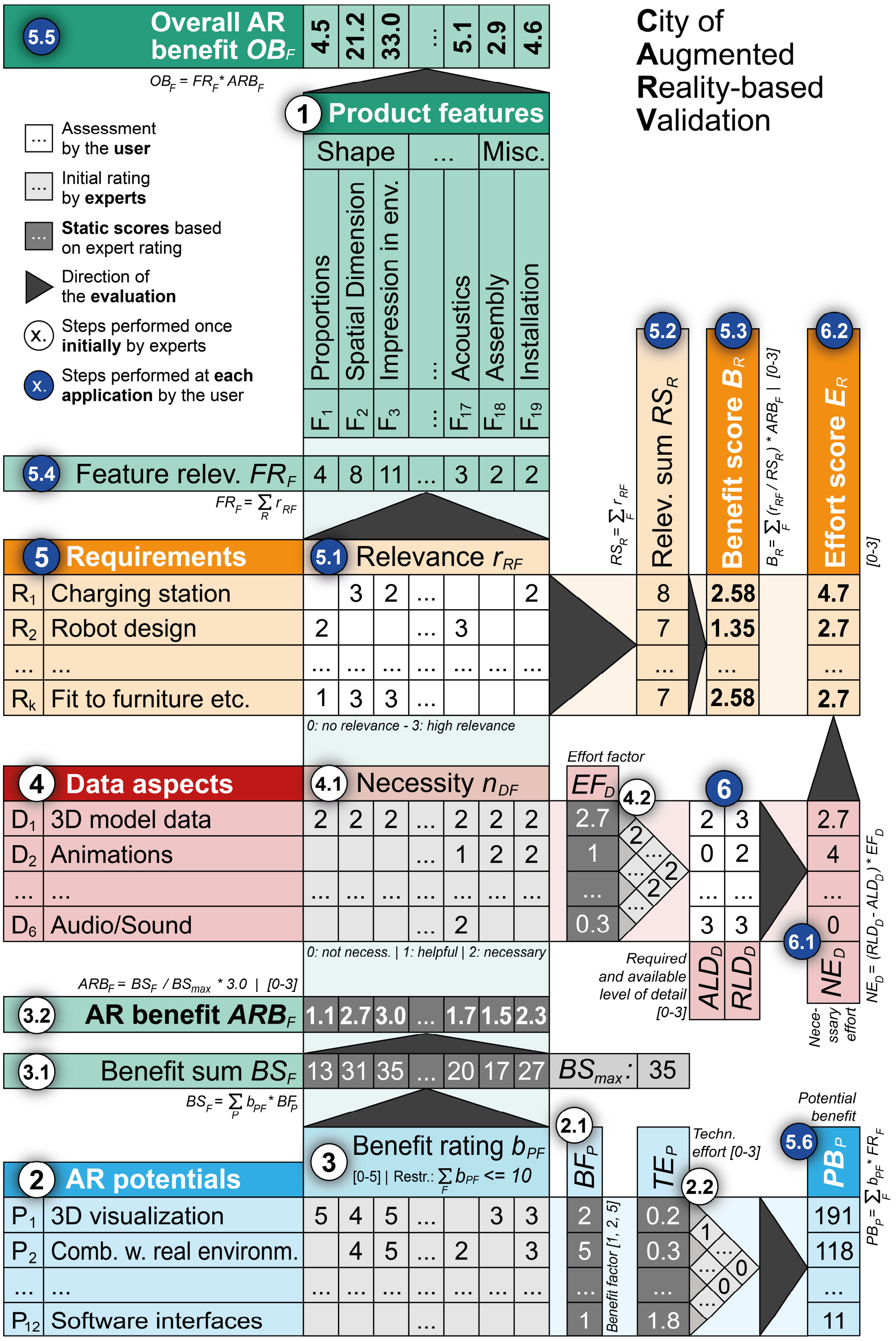
4.1.1 Generic expert ratings

The generic expert ratings are made in the static part of the graph (see Figure 2). The ratings and definitions have initially been made by the authors of this work based on their technology expertise and experience under consideration of the state of the art (Section 3). The ratings have then been discussed with further colleagues and experts and adjusted accordingly.

(1) First 19 generic **product features (F_1-F_{19})** have been defined and documented in the CARV. The product features contain all aspects possibly addressed by the requirements and thus relevant for the validation. They are categorized into shape, optics and design, functionality, interaction, structure, non-visual appearance and miscellaneous (Figure 4). Features not relevant for AR-based validation are not included, e.g., the weight or the hardness. The generic product features have been derived from the works of Pahl et al. and Reinemann et al. (see Chapter 3)

(2) 12 generically derived **AR potentials (P_1-P_{12})** describe the basic functionalities of AR to support the validation regarding the aspects visualization, interaction, connectivity and miscellaneous (Figure 4). **(2.1)** Because not all the AR potentials are unique for AR, a **benefit factor (BF_P)** is assigned to each potential (Figure 4). Only the *combination with the real environment* is a unique potential of AR. A benefit factor of *5* is assigned to it. Some potentials can also be realized with VR, for example the *integration of the user*. These potentials get a benefit factor of *2*. Some potentials like *acoustic output* can even be used with a classical digital

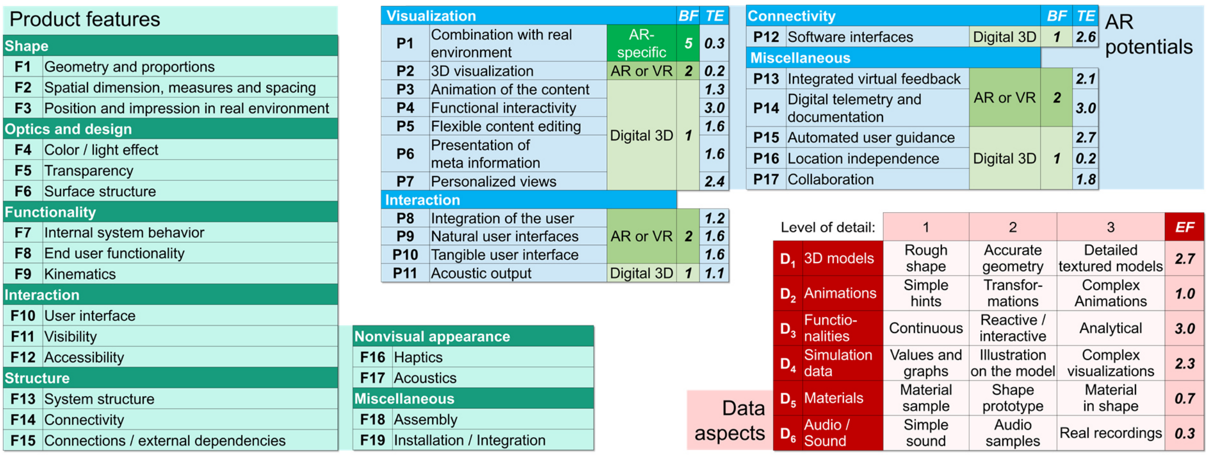
3D visualization. This corresponds to a benefit factor of *1*. **(2.2)** To support the selection of AR potentials to be implemented in the subsequent preparation of the validation software, the **technical effort (*TE_p*)** has been defined and included in the CARV for each AR potential. As Figure 3 indicates, the effort scores have been determined by a qualitative comparison of the efforts for the potentials in a correlation matrix. For each pair of potentials, it is rated which potential has a higher technical effort to be implemented (0: effort for the first potential is higher, 1: effort is similar, 2: effort for the second potential is higher). Summing up the values for each potential allows a relative definition of the technical efforts scaled from *0* to *3* (Figure 4).



		F_1	F_2	F_3	…	F_{17}	F_{18}	F_{19}
R_1	Charging station		3	2	…			2
R_2	Robot design	2			…	3		
…	…	…	…	…	…	…	…	…
R_k	Fit to furniture etc.	1	3	3	…			
D_1	3D model data	2	2	2	…	2	2	2
D_2	Animations				…	1	2	2
…	…	…	…	…	…	…	…	…
D_6	Audio/Sound				…	2		
P_1	3D visualization	5	4	5	…		3	3
P_2	Comb. w. real environm.		4	5	…	2		3
…	…	…	…	…	…	…	…	…
P_{12}	Software interfaces				…			

Figure 3. City of Augmented Reality-based validation (CARV): Matrix-structure for the assessment of AR potentials to support product validation. For simplification, empty cells represent a rating of *0*.

(3) The **benefit rating *b_{PF}*** is defined in a matrix between the *product features* and *AR potentials* through values from *0* to *5*. *0* means the AR potential has no use for the validation of the product feature. *5* indicates a corresponding very high benefit. A restriction is, that for each product feature, the sum of the values must not exceed *10*. This allows a quantitative comparison and scaling of the benefit values for the individual features in step 3.2. As examples, *3D visualization* has a very high benefit for the validation of *proportions* and of the *impression in the real environment*. *Software interfaces*, on the other hand, have no benefit for the validation of the *spatial dimension* or *acoustics*. **(3.1)** For each product feature *F* the **benefit sum BS_F** is determined based on the benefit ratings b_{PF} and the respective benefit factors BF_P. **3.2)** The **AR benefit ARB_F** is determined for each product feature from *0* to *3*. It is important for the evaluation of the AR potentials. The *impression in the real environment* has the highest AR benefit of *3.0*. *Proportions*, on the other hand, only have a benefit of *1.1*.



Product features

Shape	
F1	Geometry and proportions
F2	Spatial dimension, measures and spacing
F3	Position and impression in real environment
Optics and design	
F4	Color / light effect
F5	Transparency
F6	Surface structure
Functionality	
F7	Internal system behavior
F8	End user functionality
F9	Kinematics
Interaction	
F10	User interface
F11	Visibility
F12	Accessibility
Structure	
F13	System structure
F14	Connectivity
F15	Connections / external dependencies
Nonvisual appearance	
F16	Haptics
F17	Acoustics
Miscellaneous	
F18	Assembly
F19	Installation / Integration

AR potentials

Visualization			***BF***	***TE***
P1	Combination with real environment	AR-specific	***5***	***0.3***
P2	3D visualization	AR or VR	***2***	***0.2***
P3	Animation of the content	Digital 3D	***1***	***1.3***
P4	Functional interactivity			***3.0***
P5	Flexible content editing			***1.6***
P6	Presentation of meta information			***1.6***
P7	Personalized views			***2.4***
Interaction				
P8	Integration of the user	AR or VR	***2***	***1.2***
P9	Natural user interfaces			***1.6***
P10	Tangible user interface			***1.6***
P11	Acoustic output	Digital 3D	***1***	***1.1***

Connectivity			***BF***	***TE***
P12	Software interfaces	Digital 3D	***1***	***2.6***
Miscellaneous				
P13	Integrated virtual feedback	AR or VR	***2***	***2.1***
P14	Digital telemetry and documentation			***3.0***
P15	Automated user guidance	Digital 3D	***1***	***2.7***
P16	Location independence			***0.2***
P17	Collaboration			***1.8***

Data aspects

	Level of detail:	1	2	3	***EF***
D_1	3D models	Rough shape	Accurate geometry	Detailed textured models	***2.7***
D_2	Animations	Simple hints	Transformations	Complex Animations	***1.0***
D_3	Functionalities	Continuous	Reactive / interactive	Analytical	***3.0***
D_4	Simulation data	Values and graphs	Illustration on the model	Complex visualizations	***2.3***
D_5	Materials	Material sample	Shape prototype	Material in shape	***0.7***
D_6	Audio / Sound	Simple sound	Audio samples	Real recordings	***0.3***

Figure 4. Overview of the three types of static nodes: *Product features*, *AR potentials* (incl. their benefit factors *BF* and technical effort *TE*) and *data aspects* (incl. their levels of detail and effort factors *EF*)

(4) Six **data aspects (D_1-D_6)** are defined that cover all the possibly necessary data to create the virtual prototypes. For each aspect, three levels of detail are defined (Figure 4). For *3D models*, these are the *rough shape*, the *accurate geometry,* and *detailed textured models*. **(4.1)** The **necessity n_{DF}** of the *data aspects* for the validation of each of the *product features* is rated in a second matrix. *2* means, the aspect is necessary and a *0* that it is not. A *1* indicates that the aspect could be helpful to present the feature. **(4.2)** Similar to the technical effort of the AR potentials, an **effort factor EF_D** is determined based on a correlation matrix. *Functionalities* have the highest preparation effort. *Sound*, on the other hand, is rather easy to prepare.

4.1.2 Assessment by the user

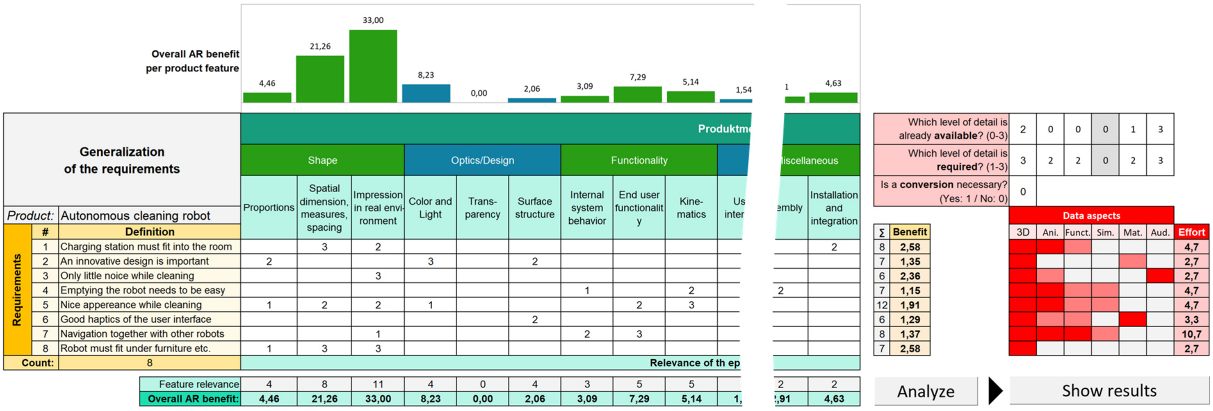
The following steps are performed by the user or based on the user's input each time the systematics is used. They are supported by the interactive user tool presented in Section 4.2.

(5) First, the individual **requirements (R_1-R_k)** that are to be analyzed are entered into the CARV by the user. If all the requirements are analyzed or just a selection is up to the user. Figure 3 includes some exemplary requirements for an autonomous cleaning robot. **(5.1)** By rating the **relevance r_{RF}** of the product features for each requirement, the generalization is performed. The *placement of the charging station* (R_1) for example strongly adresses the product features *spatial dimensions* and *installation* whereas *acoustics* is not important. Based on resulting **relevance sum RS_R (5.2), the benefit score B_R** for each requirement results as the weighted sum of the AR benefit values for all features **(5.3)**. Multiplying the **feature relevance FR_F (5.4)** with the AR benefit ARB_F leads to the **overall AR benefit OB_F (5.5)** for each product feature. **(5.6)** Furthermore, the **potential benefit PB_P** is calculated as the sum of the benefit ratings b_{PF} multiplied with the respective feature relevance FR_F over all features.

(6) The second user input is the rating of the **available level of detail ALD_D** and the **required level of detail RLD_D**, that is required or desired for the validation. **(6.1)** The difference of the two values multiplied with the respective effort factor leads to the **necessary effort NE_D** per aspect. **(6.2)** Based on this, individual **effort scores E_R** can be derived for the requirements.

4.2 Interactive user tool

The interactive user tool is provided as an **Excel file** containing multiple spreadsheets. A first spreadsheet enables the user to provide the necessary input. Figure 5 shows the input spreadsheet on the example of an autonomous cleaning robot. The requirements are entered and the corresponding product feature relevance is rated in the left part. A macro to analyze the input is started via a button. A colored matrix then illustrates the necessity of the data aspects. The user is asked to define the available and required level of detail for the data aspects. For 3D models it also needs to be configured if a conversion from CAD data to tessellated visualization models is necessary. If so, the effort delta is increased by *1*.



Generalization of the requirements

Product: Autonomous cleaning robot

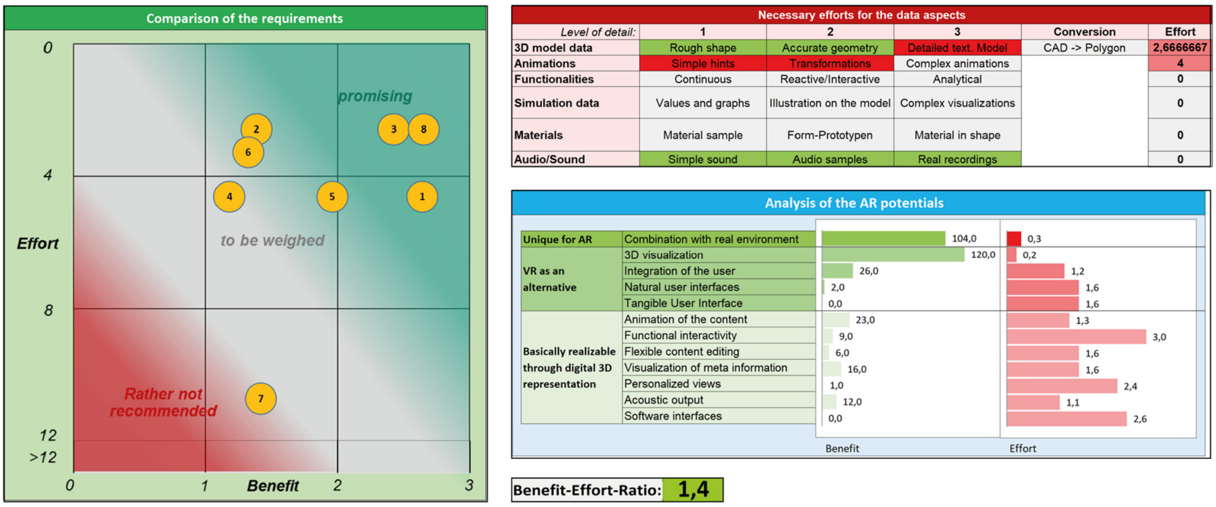
		Produktme										
		Shape			Optics/Design			Functionality				iscellaneous
#	Definition	Proportions	Spatial dimension, measures, spacing	Impression in real envi-ronment	Color and Light	Trans-parency	Surface structure	Internal system behavior	End user functionalit y	Kine-matics	Us inter	embly	Installation and integration
1	Charging station must fit into the room		3	2									2
2	An innovative design is important	2			3		2						
3	Only little noice while cleaning			3									
4	Emptying the robot needs to be easy							1		2		2	
5	Nice appereance while cleaning	1	2	2	1				2	3			
6	Good haptics of the user interface						2						
7	Navigation together with other robots			1				2	3				
8	Robot must fit under furniture etc.	1	3	3									
Count:	8	Relevance of th ep											
	Feature relevance	4	8	11	4	0	4	3	5	5		2	2
	Overall AR benefit:	**4,46**	**21,26**	**33,00**	**8,23**	**0,00**	**2,06**	**3,09**	**7,29**	**5,14**	**1,**	**,91**	**4,63**

	3D	Ani.	Funct.	Sim.	Mat.	Aud.
Which level of detail is already **available**? (0-3)	2	0	0	0	1	3
Which level of detail is **required**? (1-3)	3	2	2	0	2	3
Is a **conversion** necessary? (Yes: 1 / No: 0)	0					

Σ	**Benefit**	Data aspects: 3D	Ani.	Funct.	Sim.	Mat.	Aud.	**Effort**
8	**2,58**	🟥	🟥	▨				**4,7**
7	**1,35**	🟥				▨		**2,7**
6	**2,36**	🟥	▨				🟥	**2,7**
7	**1,15**	🟥	🟥	▨	▨			**4,7**
12	**1,91**	🟥	🟥	▨	▨			**4,7**
6	**1,29**	🟥	▨	▨		🟥		**3,3**
8	**1,37**	🟥	🟥	🟥	▨			**10,7**
7	**2,58**	🟥						**2,7**

Figure 5. Input spreadsheet of the Excel user tool. Left: Relevance of requirements. Right: data aspects.

The results of the analysis are presented in another spreadsheet (Figure 6). The analyzed requirements are visualized in a **portfolio** according to their benefit score B_R and effort score E_R (Figure 6, left). Colored areas indicate, if a requirement is promising to be validated with AR (green) or if AR is rather not recommended (red). In-between AR as a validation tool needs to be weighed individually. The tool allows the selection of a set of requirements to be considered in further evaluations. In the given example, requirements R_1, R_3, R_5, and R_8 are selected. For the selected requirements, the necessary efforts for the preparation of the data aspects are summed up and visualized (Figure 6, top right). For each aspect, it is indicated which level of detail is already available (green) and which level is required (red). The preparation of 3D model data is only calculated once because 3D models can be used for the validation of multiple requirements. The other aspects, e.g. animations, on the other hand, need to be prepared specifically for individual requirements. Thus, these efforts are considered multiple times if necessary. Based on the sum of the benefit scores and the effort scores, the benefit-effort-ratio is determined (Figure 6, bottom center). Values larger than 1 indicate that the benefits outweigh the efforts. The higher the ratio the higher the potentials of AR. To further support the assessment of the AR potentials and especially the comparison to other digital approaches, the potential benefits PB_P and the technical efforts TE_P are visualized in **bar diagrams** (Figure 6, right). High benefit values for the unique AR potential indicate the benefit of AR. If the potentials that are also possible with VR have high values and the unique potentials not, then VR might be considered as an alternative. Same holds for the potentials that can even be realized with a standard 3D representation. To assist the interpretation, a set of **reference profiles** (RP) is provided. Reference profiles describe the basic relation of the potential bars for generic validation scenarios. Figure 7 shows three examples. Bars similar to the ones in RP1 indicate the validation of the *optical appearance in the real environment*. RP2 describes the validation of *ergonomics considering the real surroundings*. In both cases AR-based validation is beneficial. RP3, on the other hand, corresponds to an *immersive and interactive experience* of a product where the real environment does not need to be taken into account. This is also possible with VR and does not necessarily need AR as a validation tool. The analysis of the AR potentials provides helpful information for the subsequent implementation of AR. It indicates which potentials need to be implemented for an AR system to be used as the validation tool.



Necessary efforts for the data aspects

Level of detail:	1	2	3	Conversion	Effort
3D model data	Rough shape	Accurate geometry	Detailed text. Model	CAD -> Polygon	2,6666667
Animations	Simple hints	Transformations	Complex animations		4
Functionalities	Continuous	Reactive/Interactive	Analytical		0
Simulation data	Values and graphs	Illustration on the model	Complex visualizations		0
Materials	Material sample	Form-Prototypen	Material in shape		0
Audio/Sound	Simple sound	Audio samples	Real recordings		0

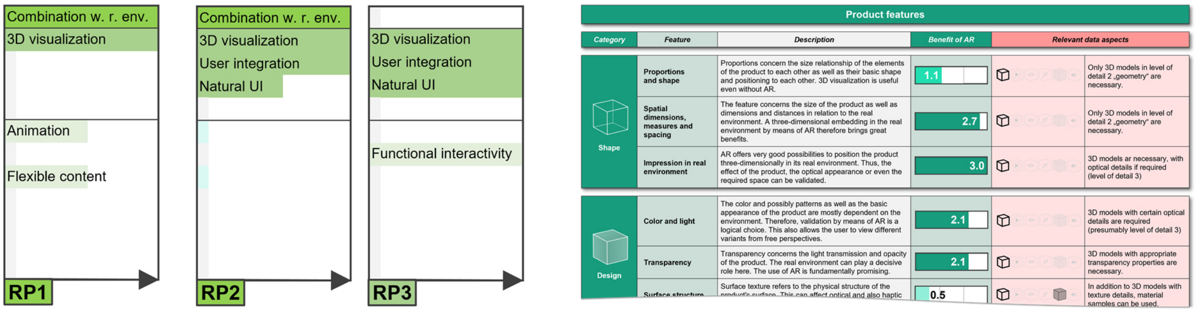
Analysis of the AR potentials

		Benefit	Effort
Unique for AR	Combination with real environment	104,0	0,3
VR as an alternative	3D visualization	120,0	0,2
	Integration of the user	26,0	1,2
	Natural user interfaces	2,0	1,6
	Tangible User Interface	0,0	1,6
Basically realizable through digital 3D representation	Animation of the content	23,0	1,3
	Functional interactivity	9,0	3,0
	Flexible content editing	6,0	1,6
	Visualization of meta information	16,0	1,6
	Personalized views	1,0	2,4
	Acoustic output	12,0	1,1
	Software interfaces	0,0	2,6

Benefit-Effort-Ratio: 1,4

Figure 6. Screenshots of the main elements of the presentation of the results in the Excel-based user tool. Numbered yellow circles correspond to analyzed requirements.

To support the assessment of the AR potentials for the validation, **fact sheets** are provided for the *product features*, the *data aspects* and the *AR potentials*. The fact sheets give an overview including descriptions and related static ratings. Figure 7 shows an excerpt of the fact sheet for the product features. It includes the benefit rating as well as the relevant data aspects for each feature and supports the user in the assessment of the individual requirements.



Product features

Category	Feature	Description	Benefit of AR	Relevant data aspects
Shape	Proportions and shape	Proportions concern the size relationship of the elements of the product to each other as well as their basic shape and positioning to each other. 3D visualization is useful even without AR.	1.1	Only 3D models in level of detail 2 „geometry“ are necessary.
	Spatial dimensions, measures and spacing	The feature concerns the size of the product as well as dimensions and distances in relation to the real environment. A three-dimensional embedding in the real environment by means of AR therefore brings great benefits.	2.7	Only 3D models in level of detail 2 „geometry“ are necessary.
	Impression in real environment	AR offers very good possibilities to position the product three-dimensionally in its real environment. Thus, the effect of the product, the optical appearance or even the required space can be validated.	3.0	3D models ar necessary, with optical details if required (level of detail 3)
Design	Color and light	The color and possibly patterns as well as the basic appearance of the product are mostly dependent on the environment. Therefore, validation by means of AR is a logical choice. This also allows the user to view different variants from free perspectives.	2.1	3D models with certain optical details are required (presumably level of detail 3)
	Transparency	Transparency concerns the light transmission and opacity of the product. The real environment can play a decisive role here. The use of AR is fundamentally promising.	2.1	3D models with appropriate transparency properties are necessary.
	Surface structure	Surface texture refers to the physical structure of the product's surface. This can affect optical and also haptic	0.5	In addition to 3D models with texture details, material samples can be used.

Figure 7. Tools to support the user: exemplary reference profiles (left) and an excerpt of the fact sheet for the product features (right).

5 Conclusion

A systematic approach to support companies in exploiting the potentials of AR for has been developed. The presented systematics empowers companies to individually assess the potentials of AR to support product validation. Static definitions and ratings by experts including generic product features, basic AR potentials, possibly necessary data aspects and relations are used to individually assess the potentials of AR for the validation of a given set of individual requirements. To simplify and support this, an Excel-based interactive user tool is provided.

The assessment includes the benefit as well as the necessary effort to use AR for the validation of the requirements. In addition, the user tool derives and presents an assessment of the basic AR potentials corresponding to the given requirements. This allows a comparison to alternative digital validation approaches and the selection of AR potentials to be implemented for the validation. The results of the assessment, for example the effort-benefit-ratio, do not correspond to concrete decisions. If necessary, the user can track individual calculation steps in the tool. However, the results are only intended to provide meaningful support for the decision-making process. The final decision is still made by the user based on the results, considering further individual factors. The benefits of the system have already been evaluated and confirmed using practical examples of varying complexity, such as the vacuum cleaner robot described above. Based on the assessment of the AR potentials, the configuration and implementation of an AR system to be used as a validation tool need to be conducted in subsequent steps. The support of these steps is currently part of ongoing research. The overall goal is to provide a comprehensive solution to support companies in the planning and preparation of AR-based validation.

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