PRODUCTION MANAGEMENT

Maturity model for determining digitalization levels within different product lifecycle phases

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Abstract

Maintaining pace with ongoing changes due to digitalization is challenging for manufacturing companies. For successful implementation of digitalization, manufacturing companies must consider their existing technical systems, organizational structures, and processes, as well as social aspects. With the support of a maturity model, a company-specific digitalization level can be evaluated to provide manufacturing companies with an initial insight into their particular status quo; this can serve as a starting point for future optimization and digitalization projects. Furthermore, the results of such an analysis allow objective comparison of different areas within the company and with competitors. In this paper, the "Integrierte Arbeitssystemgestaltung in digitalisierten Produktionsunternehmen" (InAsPro) maturity model is presented, which considers the *Development*, *Production*, and *Assembly* product lifecycle phases, as well as *Aftersales*, and assesses their digitalization level focusing on the four dimensions of *Technology*, *Organization*, *Social Issues*, and *Corporate Strategy*. The maturity model's rating scale distinguishes between four maturity levels. The results given by the InAsPro maturity model for an entire company are presented, along with those for each product lifecycle phase. Extensive descriptions for each specific maturity level are also provided.

Keywords Maturity model · Digitalization · Development · Production · Assembly · Aftersales

1 Motivation and aim

This paper presents the maturity model [1] established as part of the InAsPro project [2], which was developed to determine the digitalization level of a manufacturing company and thereby considers the requirements and properties of manufacturing companies. The basic maturity model was already partly published in german [1] and is here extended by an extensive literature review, detailed identification of the research gap as well as a real-world application example in a small and medium-sized enterprise (SME). Additionally, the paper provides the "InAsPro maturity model guide", which contains all indicators as well as an extensive description of each stage.

In general, digitalization has been proclaimed as the strongest driver of industrial change and business advancement in the twenty-first century, leading to the Fourth Industrial Revolution [3]. However, a closer look at the organizational and process structures of manufacturing companies reveals that reality is less simple, because digitalization is implemented within all departments of a company and, therefore, corresponding interrelations exist. On the one hand, manufacturing comapnies in Germany have barely established a full coverage of the technologies and processes targeted by the Third Industrial Revolution; therefore, they have not yet founded bases for digitalization introduction [4]. On the other hand, recognition of a need for digitalization is always accompanied by the challenging task of determining the most suitable digital technologies to satisfy a

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given company's needs; these technologies must be chosen from among a large selection of often investment-intensive options [5]. Addressing these challenges is crucial, as only a focused and needs-based implementation of digital technologies can ensure a company's future business success; this should be accompanied by both transformation of the existing organizational structures and processes [6] and employee participation [7, 8].

Before starting the digitalization of a manufacturing company, it is necessary to understand the current digital state of the company [9, 10]. A maturity model can be used to determine the digitalization level. The presented maturity model was developed for manufacturing companies and therefore, contemplates companywide aspects as well as certain criteria typical for the *Development*, *Manufacturing*, *Assembly*, and *Aftersales* areas. Moreover, the area of tension *Technology*, *Organization*, and *Social* as well as *Corporate Strategy* are featured. Not only the whole company can be assessed, also the digitalization level of different sizes of work systems can be determined. To improve the understanding of the maturity model, the procedure how it was created as well as the final maturity model are explained in detail. The maturity model results serve as a starting point for optimization and digitalization projects. Additionally, the maturity model is implemented in a software demonstrator, where the results can be stored and afterwards used as a benchmark both within the manufacturing company and across sectors.

2 State of the art

2.1 Digitalization of manufacturing companies

Digitization is the process of converting analog information into a digital format. In this format, the information consists of discrete data units that can be addressed, stored, processed, and managed separately with computing devices [11, 12]. The term "digitization" is also applied to refer to the digital revolution, along with "digitalization" or "digital transformation". Thus, digitalization indicates a process of continuous change triggered by the growing usage of digital technologies [13] within the economy; this term is used throughout the present paper. Digital technologies are causing significant change along the value chain and creating strategic potential for companies and organizations. However, companies must attempt to manage the structural changes and organizational barriers that influence the positive and negative outcomes of this process [14].

Digitalization of manufacturing companies is implemented with the aim of horizontal integration through value networks, as well as vertical integration of all corporate levels [15]. This yields connected and integrated systems (information systems within and outside companies),

objects (including products, devices, and machines), and people (workers, vendors, and users) within a company [16, 17]. Digitalization enables manufacturing companies to manage complex industrial processes [18] and introduces new possibilities, regarding e.g. efficiency, adaptivity and automation, thereby ensuring competitiveness and growth [19]. To achieve these goals, digital technologies must be implemented within all areas of a company [14]. Digital technologies are technologies that capture, process, transfer, and integrate analog information, e.g., data, documents, and procedures, into digital (virtual) values, which are then used in the work systems of manufacturing companies [20, 21]. Examples are augmented reality [22], radio frequency identification [23], and data management systems [24]. However, as noted above, only implementation of digital technologies with consideration of the associated transformation of existing organizational structures and processes, as well as employee participation (so-called "digitalization solutions"), yields successful digitalization of manufacturing companies and their work systems.

2.2 Product lifecycle phases

To avoid isolated digitalization solutions, a valid, end-to-end approach for all corresponding work systems is needed. Therefore, all lifecycle phases of a product must be considered. A product lifecycle consists of consecutive and interlinked steps [25] and begins with the product idea, followed by the design, process planning, product manufacturing, product usage and, finally, end of life (Fig. 1) [26]. To simplify matters, the product lifecycle is condensed to the four phases *Development*, *Production*, *Assembly*, and *Aftersales* phases within the project [27]. Nevertheless, it is essential to consider several phases in order to avoid isolated solutions and for a consistent digitalization.

The end-to-end approach supports exploitation of the effects of digitalization on other work systems [18]. For example, the quality assurance staff should be supported in performing test and measurement operations, as well as in responding to test results and correcting causes of incorrect measurements. This requires digital data preparation along several product lifecycle phases, such as product planning and product manufacturing.

The challenges of digitalization within the *Development* product lifecycle phase are, e.g., prospective determination of the production and the assembly work contents. Another challenge is engineering of smart products, i.e., cyber-physical systems (CPSs) that use and integrate Internet-based services to perform a required functionality [28].

Discrete parts are produced within the *Production* product lifecycle phase. The aim of (part) production is to produce individual parts for assembly or for delivery to customers [29]. The *Assembly* product lifecycle phase involves
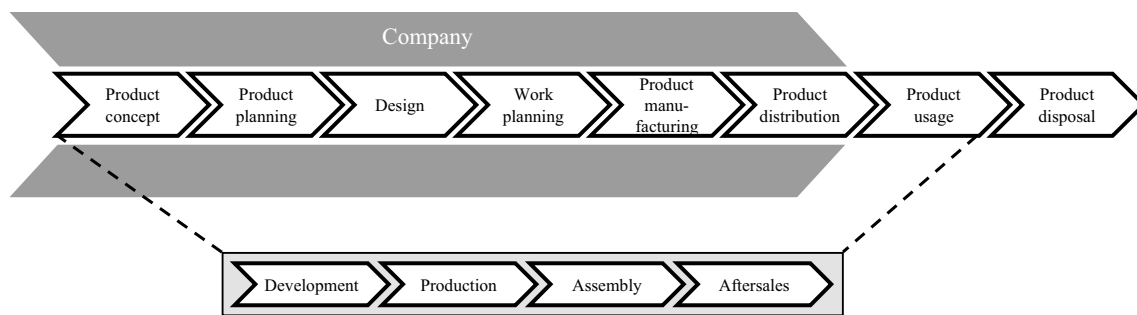
Fig. 1 Product lifecycle phases considered within InAsPro (own representation)

mounting of the individual parts to form modules or products [30]. As the tasks in the *Production* and *Assembly* phases differ, the material and information flow also differ. Therefore, it is necessary to analyze the process conditions in the first step before digitizing these product lifecycle phases [31]. Nevertheless, digitalization of the *Production* and *Assembly* product lifecycle phases can be achieved using CPSs, which are embedded systems connecting the physical environment and the virtual world [20]. Autonomous and cooperative elements and subsystems (e.g., CPSs), interconnected with each other and across the *Production* and *Assembly* phases form so-called "cyber-physical production systems (CPPSs)" [3].

The *Aftersales* product lifecycle phase contains services for manufactured goods and activities to support customers with goods usage, e.g., provision of predictive maintenance [32] and repair services as well as operating personnel training [33]. Digitalization expands the number and variety of aftersales activities and, also, customer contact [34]. Companies tend to offer not only a particular product, but also integrated solutions associated with the product [33], i.e., so-called "product–service systems (PSSs)" [35, 36]. They consist of technical product, complemented by different services of the product lifecycle [37]. PSSs are customer-oriented solutions that yield increased product value and, therefore, increased customer value [38].

Based on the knowledge that implementation of specific digital technologies can also influence processes within all other product lifecycle phases, tools to assess a company's individual status with regard to digitalization must also consider all these phases to provide a comprehensive assessment. With the help of maturity models, a company's digitalization level can be determined and described.

2.3 Maturity models

Maturity models have a wide range of applications [39], but all models are structured similarly. In general, a maturity model is an instrument to measure the current status of an object of investigation, e.g., a person, a company, or a behavior within a specific area [40]. It consists of four basic elements: a predefined number of maturity levels with accompanying descriptions, indicators and its characteristics, and linkages between each maturity level and the corresponding characteristics and recommended activities based on the resulting maturity level. To apply the instrument, the user must select the characteristics of each indicator that best fit his or her company. By consolidating these aspects, a maturity level can be calculated and corresponding activities can be recommended [41].

In this study, a selection of existing maturity models were identified (Table 1) and subsequently analyzed regarding their suitability in terms of set requirements (see Sect. 3.2).

3 Development of InAsPro maturity model

The InAsPro maturity model was developed based on the existing maturity models (see Table 1) and through consolidation of the practical experiences of InAsPro project partners. The basic maturity model is explained and is extended by an extensive literature review, detailed identification of the research gap as well as a real application example by means of a small and medium-sized enterprise (SME). In the first developmental step, the goals and requirements were defined.

3.1 Goals and requirements

The maturity model was designed to measure the current state of a company's digital readiness on two levels: the company level and the level of the *Development*, *Production*, *Assembly*, and *Aftersales* product lifecycle phases. Differentiation of the phases is important as the digitalization of each single phase differs from those of the others. Furthermore, the maturity model aims to create results that can be used for companies of all sizes and as a benchmark across businesses [63]. Additionally, the InAsPro maturity model is intended to be compatible with other concepts developed through the

Table 1 Existing maturity models

No	Maturity model name	Research context	Focus area	Maturity levels	Dimensions
1 [19]	DREAMY	Assessment of digital readiness of manufacturing companies	Manufacturing companies	5 levels (Initial, Managed, Defined, Integrated and Interoperable, Digital oriented)	5 main areas (Design and Engineering, Production Management, Quality Management, Maintenance Management, Logistics Management)
2 [42]	Readiness-Check Digitalisierung	Provision of basic status information regarding digitalization for midsized companies	Small-to-medium enterprises (SMEs)	5 levels (Explorer, Beginner, Intermediate, Expert, Pioneer)	5 dimensions (Strategy, Technology, Products and Services, Organization and Processes, Employees)
3 [43]	Industry 4.0 Maturity Index	Transformation into a learning, agile company	Manufacturing companies	6 levels (Computerization, Connectivity, Visibility, Transparency, Predictive capacity, Adaptability)	4 dimensions (Resources, Information Systems, Organizational structure, Culture)
4 [44]	Industrie 4.0-Readiness	Assessment of company willingness and ability to implement Industry 4.0 concepts	Mechanical engineering industry	6 levels (Outsider, Beginner, Intermediate, Experienced, Expert, Top Performer)	6 dimensions (Strategy and organization, Smart factory, Smart operations, Smart products, Data-driven services, Employees)
5 [45]	Digital Maturity Check	Assessment of company digital maturity to reflect on the effects of digital transformation	Companies	5 levels	9 dimensions (Customer Experience, Product innovation, Strategy, Organization, Process digitalization, Cooperation, Information technology, Culture & Expertise, Transformation management)
6 [46]	Model for assessing Industry 4.0 readiness	Determination of Industry 4.0 grade of industrial companies in discrete manufacturing systems	Manufacturing systems	5 levels (Likert-scale: not distinct–very distinct)	9 dimensions (Strategy, Leadership, Customers, Products, Operations, Culture, People, Governance, Technology)
7 [47]	Industrie 4.0-Audit	Support for transformation of manufacturing systems into CPPS	Manufacturing systems	Up to 7 characteristics per criterion	3 dimensions (Technology, Organization, Personnel)
8 [48, 49]	Quick-Check	Digital transformation of manufacturing systems	Manufacturing systems	4 levels	6 activity fields (Organization and Administration, Production planning and control, Quality and fault management, Station, Product)
9 [50]	Produktionsassessment 4.0	Collection of lean management principles and presentation of migration paths for Industry 4.0 implementation	Manufacturing systems	4 described levels	5 dimensions (Strategy, Processes and value stream, Organization, Methods and Tools, Personnel)
10 [51]	Werkzeugkasten Industrie 4.0	Development of procedures for digital transformation	SMEs in mechanical engineering industry	5 described levels	6 different dimensions for products and manufacturing

Table 1 (continued)

No	Maturity model name	Research context	Focus area	Maturity levels	Dimensions
11 [52]	Smart Manufacturing System Readiness Assessment	Assessment of smart manufacturing system readiness	Manufacturing systems	6 levels (Not performed, Initial, Managed, Defined, Qualitative, Optimizing)	4 dimensions (Organizational maturity, IT maturity, performance management maturity, Information connectivity maturity)
12 [53]	Manufacturing Operations Management (MOM) Capability Maturity Model (CMM)	Evaluation of organization capability to improve its operational processes	Operational processes	5 described levels	4 operational areas (Production, Quality, Inventory, Maintenance)
13 [54]	Industrie 4.0 Reifegradmodell	Determination of information processing maturity level	Information processing	11 levels	3 dimensions (Data, Intelligence, Digital Transformation)
14 [55, 56]	System Integration Maturity Model Industry (SIMMI) 4.0	Classification of application system infrastructures in Industry 4.0 context	Application systems	5 stages (Basic digitalization, Cross-departmental digitization, Horizontal and vertical digitization, Full digitization, Optimized full digitization)	3 dimensions (Vertical integration, Horizontal integration, Digital continuity)
15 [57]	ManuTech Maturity Model	Maturity level of manufacturing technologies and their characteristics regarding Industry 4.0	Manufacturing technologies	4 levels	8 dimensions (Core technologies, People & culture, Knowledge Management, Real-time Integration, Infrastructure, Strategic awareness & alignment, Process excellence, Cybersecurity)
16 [58]	IoT Technological Maturity Assessment Scorecard	Support for manufacturing companies in adopting Internet-of-Things (IoT)-technologies within manufacturing	Manufacturing systems	8 levels (3.0 maturity, Initial to 4.0 maturity, Connected, Enhanced, Innovating, Integrated, Extensive, 4.0 Maturity)	n/a
17 [59]	–	Digitalization of manufacturing industry's supply chain	Supply chain	5 levels (Digitalization awareness, Smart networked products, The service-oriented enterprise, Thinking in service systems, The data-driven enterprise)	4 dimensions (Conventional production, Smart production, Product-oriented, Service-oriented)
18 [60]	Industry 4.0-MM	Creation of common base for assessment of Industry 4.0 technology establishment	Manufacturing industry	6 levels (Incomplete, Performed, Managed, Established, Predictable, Optimizing)	2 dimensions with attributes (Capability, Aspect)
19 [61]	Maturity Model for Servitization	Development of a Maturity Model for digital Servitization in Manufacturing Firms	Manufacturing Firms	3 levels (Beginner, Experienced, Leader)	4 dimensions (Strategy, Customer experience, Business Processes, Organization & Culture)
20 [62]	Industry 4.0 maturity model	Roadmapping towards industrial digitalization based on a maturity model	Manufacturing Enterprises	3 realitation phases (Enable, Implement, Formalize)	8 dimensions (Technology, Products, Customers and Partners, Value Creation Pricesses, Data & Information, Corporate Standards, Employees, Strategy and Leadership)

InAsPro project, such as the technology map [21, 64] and the transformation concept [27].

Besides the already mentioned objectives, the content goals were also considered. The developed maturity model equally considers criteria associated with the *Social*, *Technology*, and *Organization* dimensions based on the Men-Technology-Organization (MTO) Model [65]. Therefore, besides technological criteria, organizational (especially "Data Management" and "Cooperation and Collaboration") and social criteria (such as "Leadership," "Corporate Culture," and "Employee Development") must be considered. Additionally, it is necessary to consider the corporate strategy, as decisions on creation or maintenance of competitive advantages [66] are made on the company level.

As the maturity model considers the company level as well as the four product lifecycle phases, companywide aspects must be incorporated in the model, as well as aspects specific to each product lifecycle phase. However, the specific aspects that can be considered in the product lifecycle phase do not apply to all companies equally. For some companies, it is only necessary to evaluate small work systems, e.g., a machine or a manufacturing line, whereas for other companies, it is appropriate to equate the work system with a product lifecycle phase. Therefore, the maturity model must consider scalable work systems.

Furthermore, from the user perspective, the InAsPro maturity model must be easy to understand and use, and yield a comprehensible result that can be generated with minimal effort. For easier assessment of existing maturity models with regard to their attainment of the named goals, the above goals were translated into model requirements and specifications for the model architecture, as shown in Fig. 2.

3.2 Identified research gap

The reviewed maturity models (Table 1) were evaluated with regard to their fulfillment of the defined requirements (Fig. 2). The results are shown in Table 2.

Fig. 2 Maturity model requirements [1]

- **Companywide**: Many of the considered maturity models focus on companywide aspects. These models aim to digitalize manufacturing or small and midsized companies (SME) and provide guidance during the transformation (e.g., [19, 42, 47, 49, 55, 60, 61]).
- **Development**: The *Development* product lifecycle phase is only considered by the maturity models presented in [42] and [43]. However, those models handle the product lifecycle phase in a general manner, e.g., if data transfer occurs between the *Development* phase and subsequent processes in the company [42].
- **Production and Assembly**: Digitalization of manufacturing systems is the main focus of maturity models (e.g., [46] [50–52, 58, 61, 62]). However, none of the existing models divide the manufacturing system into *Production* and *Assembly* phases; therefore, they do not consider potential differences between these two product lifecycle phases (see also Sect. 2.2).
- **Aftersales**: Only the models of [42, 43], and [44] consider the *Aftersales* product lifecycle phase. Those models contemplate, e.g., data-driven services [44], communicating or smart products [42, 44], or marketing channels [44].
- **Technology**: The *Technology* requirement is considered to different extents by almost all the maturity models. An exception is that of [54], which considers the Digital Transformation and Data and Intelligence dimensions but neglects technological aspects.
- **Organization**: Apart from the models of [53] and [54], all other maturity models take the *Organization* requirement into account.
- **Social**: Only a few maturity models include *Social* aspects (e.g., [45, 50, 62]).
- **Corporate Strategy**: Corporate Strategy is incorporated into most of the maturity models (e.g., [42],, [45, 46, 49, 50, 57, 59, 61, 62]). However, the priority varies in terms of focus and level of detail. The maturity models consider the company's specific digitalization strategy for development of marketing channels, but also for creation of new business models.
- **Scalable work system**: The only maturity model suitable for a scalable work system is that of [43]. All other approaches neglect this requirement.

To summarize, the majority of the existing maturity models consider digitalization and focus on companywide aspects, especially technological, organizational, and social ones. Furthermore, the approaches employed by these models concentrate on digitalization of manufacturing systems. Only a few models also consider the corporate strategy and further product lifecycle phases, e.g., *Development* or *Aftersales*. Additionally, none of the identified models divide the

Table 2 Evaluated existing maturity models

No.	Name of the model	Requirements										
		Company wide	Development	Production	Assembly	Aftersales	Technology	Organization	Social	Corporate Strategy	Scalable work system	Digitization
1 [19]	DREAMY	4	0	4	4	0	4	4	0	0	0	4
2 [42]	Readiness-Check Digitalisierung	4	4	2	0	4	0	4	4	4	0	4
3 [43]	Industry 4.0 Maturity Index	4	4	2	2	4	4	4	4	0	4	4
4 [44]	Industrie 4.0-Readiness	4	0	4	4	4	2	4	4	4	0	4
5 [45]	Digital Maturity Check	4	2	2	2	2	2	4	4	4	0	4
6 [46]	Model for assessing Industry 4.0 readiness	4	0	4	0	0	4	4	4	4	0	4
7 [47]	Industrie 4.0-Audit	4	0	2	0	0	4	4	4	2	0	4
8 [48, 49]	Quick-Check	4	0	2	0	0	4	4	4	4	0	4
9 [50]	Produktionsassessment 4.0	0	0	4	0	0	4	0	4	4	0	4
10 [51]	Werkzeugkasten Industrie 4.0	0	0	4	4	0	4	4	2	0	0	4
11 [52]	Smart Manufacturing System Readiness Assessment	0	0	0	4	0	4	4	2	0	0	4
12 [53]	Manufacturing Operations Management (MOM) Capability Maturity Model (CMM)	0	0	2	2	0	4	4	0	2	0	4
13 [54]	Industrie 4.0 Reifegradmodell	4	0	2	2	0	0	0	4	0	2	4
14 [55, 56]	SIMMI 4.0	4	2	0	0	0	2	4	0	0	2	4
15 [57]	ManuTech Maturity Model	0	0	2	2	0	4	2	0	0	0	4
16 [58]	IoT Technological Maturity Assessment Scorecard	4	0	2	2	0	4	2	0	0	0	4
17 [59]	-	4	2	2	2	0	2	4	4	4	0	4
18 [60]	Industry 4.0-MM	4	2	2	2	2	4	4	0	4	0	4
19 [61]	Maturity Model for Servitization	4	0	2	2	4	0	4	4	4	0	4
20 [62]	Industry 4.0 maturity model	4	0	2	2	0	4	4	4	4	0	4

4 Requirements fulfilled 2 Requirements partially fulfilled 0 Requirements not fulfilled

manufacturing area into production and assembly (see also, Sect. 2.2). As mentioned previously, a scalable work system must be taken as an object of investigation; however, this aspect is also neglected by the existing approaches. According to the above evaluation, none of the existing maturity models can fulfill all requirements to a satisfying extent. Consequently, a new maturity model must be developed.

3.3 Development procedure

For the structural design and development of the InAsPro maturity model, the methodological studies of de Briun [67], Becker [68], Akkasoglu [69], and Kübel [70] were considered. Those authors attempted to structure and simplify development of maturity models. By combining those guidelines, the development procedure for the InAsPro maturity model was defined. Figure 3 presents this procedure. First, preparation for development of the maturity model was conducted (Sects. 3.1 and 3.2). This was followed by the development (Sects. 3.4, 3.5) and application (Sect. 4) phases.

3.4 Description of maturity levels

The InAsPro maturity model consists of four maturity levels: Explorer, Beginner, Intermediate, and Expert. These levels and their value ranges are shown in Fig. 4. Here, ML_{total} describes the total maturity level as regards digitalization of the company and is calculated by obtaining the arithmetic mean of the achieved maturity level of the four product lifecycle phases and the *Corporate Level* (see also Sect. 3.5). Additionally, for the *Corporate Level* as well as for each product lifecycle phase, every maturity level is defined with their characterizing aspects. These are, e.g., IT system design, development and manufacturing of smart products, as well as real-time data collection. This allows a detailed description of each product lifecycle phase and its individual maturity level. Hence, the user receives a comprehensive explanation of the calculated maturity level as well as the individual product lifecycle phases in which the user

is interested. The four maturity levels are defined in Fig. 4 and the ML_{total} values allocated to each level are shown. Additionally, for each product lifecycle phase, exemplary characteristics for each maturity level are presented.

The calculation of the digitization maturity level follows the structure of the model. Not only for each product lifecycle phase and for the corporate level an individual maturity level is calculated, also for each dimension and criterion. This enables companies to compare the digitalization degree of different dimensions as well as product lifecycle phases in more detail.

Starting with the value of each criterion (e.g. IT-system design or Data management), each criterion digitization degree ($DD_{criterion}$) can be calculated through the mean of the belonging indicator values (iv_n) depending on the total number of rated indicators $N \in \{1, 2, 3, \dots\}$

$$DD_{criterion} = (1/N) \sum_{n=1}^{N} iv_n. \tag{1}$$

If the user does not evaluate an indicator (e.g. networking along the value chain or data evaluation), this missing value is not considered within the calculation and therefore it does not change the resulting dimension maturity level ($ML_{Dimension}$). The maturity level of the dimensions Technology, Organization, Social and Strategy can be calculated through the mean of the belonging criterion digitization degree ($DD_{criterionk}$) depending on the total number of rated criteria $K \in \{1, 2, 3, \dots\}$:

$$ML_{Dimension} = (1/K) \sum_{k=1}^{K} DD_{criterionk}. \tag{2}$$

For each of the product lifecycle phases Development, Production, Assembly and Aftersales as well as the corporate level, the digitization maturity levels for all dimensions are calculated. To receive the maturity level for each product lifecycle phase (ML_{plp}) and the Corporate level (ML_{cl}), the mean of the calculated dimension maturity
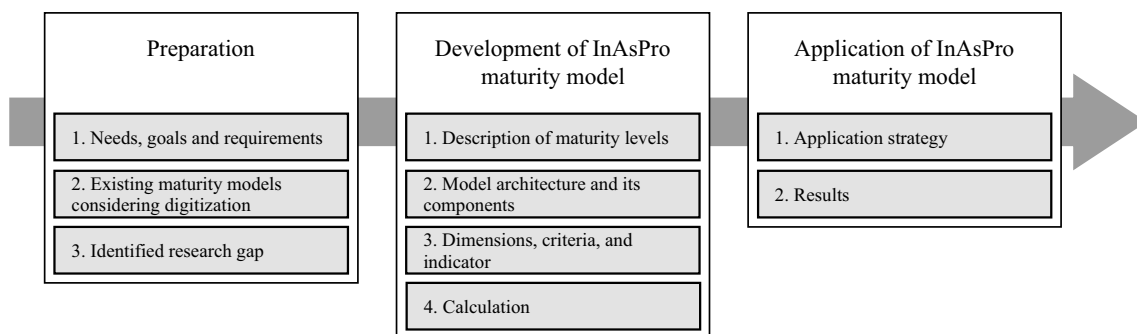

Fig. 3 Developmental procedure for digitalization maturity model

⟵——————————— Increasing maturity level ———————————⟶

	Explorer	Beginner	Intermediate	Expert
Overall description of maturity levels	The company has limited digitalization.	Digitalization is the focus of only some company divisions and their linkage is rare.	Digitalization is the focus of most company divisions, which are mostly horizontally and vertically linked. The digitalization mindset is enshrined within the corporate culture.	Digitalization is fully implemented within the company. The divisions are all horizontally and vertically linked. Furthermore, digitalization is actively implemented and fully enshrined within the corporate culture and strategy.
ML_{total} value	$1{,}0 < ML_{total} < 1{,}4$	$1{,}5 < ML_{total} < 2{,}4$	$2{,}5 < ML_{total} < 3{,}4$	$3{,}5 < ML_{total} < 4{,}0$

	Explorer	Beginner	Intermediate	Expert
Corporate level	▪ Rarely interlinked IT systems ▪ Data are stored in individual formats ▪ A digitalization mindset is not embedded ▪ No digitalization-oriented strategy is available ▪ …	▪ Some IT systems are interlinked ▪ Data can be converted into standard formats ▪ A digitalization mindset is to some extent embedded ▪ A digitalization strategy is planned ▪ …	▪ Most IT systems are interlinked ▪ Data are stored in standardized formats ▪ A digitalization mindset is mainly embedded ▪ A digitalization strategy is under development ▪ …	▪ Rarely interlinked IT systems ▪ Data are stored format-independant ▪ A digitalization mindset is fully embedded ▪ A digitalization strategy is implemented ▪ …
Development	▪ Product and system requirements are not recorded digitally ▪ The product design is not digital and simulation-based ▪ …	▪ Product and system requirements are derived and stored on a document-based basis ▪ The product design is partially digital and simulation-based ▪ …	▪ Product and system requirements are mapped on a discipline-specific basis ▪ The product design is mostly simulation-based ▪ …	▪ Product and system requirements are modeled along all disciplines ▪ Continuous computer-aided modeling and simulation has been implemented ▪ …
Production	▪ Machinery and equipment in the manufacturing process are incapable of communication ▪ The production planning and control are performed exclusively manually ▪ …	▪ Machinery and equipment in the production process are capable of communication but this facility is not used ▪ Production planning and control is software-based ▪ …	▪ Machinery and equipment in the production process are capable of communication but this facility is only partially used ▪ The production planning and control are performed by integrated systems, e.g., ERP systems	▪ Machinery and equipment in the production process are capable of communication, are fully networked, and this facility is used ▪ The production planning and control is implemented through digital planning (digital twinning)
Assembly	▪ Manufactured components are not communicable ▪ Data are not collected in real time ▪ …	▪ Individual manufactured components are capable of communication ▪ Data are sometimes collected in real time ▪ …	▪ A large portion of the manufactured components are capable of communication ▪ Data are mostly collected in real time ▪ …	▪ All manufactured components are communicable (smart products) ▪ Data are collected completely in real time ▪ …
Aftersales	▪ Product maintenance is performed at customer locations ▪ Product and customer data are not collected and therefore not evaluated ▪ …	▪ Occasionally, the company digitally performs production maintenance, e.g., through remote access ▪ Product and customer data are collected partly and analyzed as needed ▪ …	▪ The company predominantly performs product maintenance digitally ▪ Product and customer data are collected at intervals and subjected to an automatic analysis ▪ …	▪ The product maintenance is performed completely digitally ▪ Product and customer data are collected automatically and evaluated by means of algorithms ▪ …

Fig. 4 Description of company maturity levels and exemplary characteristics of each product lifecycle phase [1]

levels is taken depending on the total number of rated dimensions $M \in \{1, 2, 3, 4\}$:

$$ML_{cl} = ML_{plp} = \left(\frac{1}{M}\right) \sum_{m=1}^{M} ML_{Dimension m}. \tag{3}$$

Finally, the total maturity level (ML_{total}) over all product lifecycle phases and the companywide aspects can be determined. ML_{total} is calculated as shown below, where $Q \in \{1, 2, 3, 4\}$ is the total number of rated product lifecycle phase.

$$ML_{total} = \left(\frac{1}{Q+1}\right)\left(ML_{cl} + \sum_{q=1}^{Q} ML_{plpq}\right). \tag{4}$$

According to the structure of the InAsPro-maturity model, ML_{sca} has to be always determined. Depending on the product lifecycle phase the user is looking at, only those phases are considered within the calculation. An application example is described in Sect. 4. Adding additional weighting factors to the calculation is possible, but it is not recommended, as this might shift the results and will therefore hide the less digitalized areas. All product lifecycle phases should be treated equally, and the prioritization of the digitalization process depends on the company's internal decisions.

3.5 Model architecture and its components

The InAsPro maturity model is structured according to different levels of consideration: the *Corporate Level* and levels corresponding to the product lifecycle phases (*Development*, *Production*, *Assembly*, and *Aftersales*) (Fig. 5). The *Corporate Level* focuses on companywide aspects such as digital strategy, business models, and IT security, to gain an overall impression of the digitalization level of the company.

For each level of consideration, the model analyzes the *Technology*, *Organization*, and *Social* dimensions. On the *Corporate Level*, the *Strategy* dimension is added as a fourth dimension. Note that strategy can only be investigated on the *Corporate Level* because strategy (according to its definition) refers to decisions on how the company will create or maintain competitive advantages [66]. This decision can only be made at a *Corporate Level*. Actions performed within individual product lifecycle phases can implicitly support the strategy [71, 72] but cannot define a unique strategy [73].

Each dimension is described by criteria such as "IT-System Design" or "Customer Service" within the *Technology* dimension and "Corporate Culture" or "Leadership" within the Social dimension. Furthermore, the criteria depend on the level of consideration. Within the *Organization* and *Social* dimensions, all criteria for the *Corporate Level* are
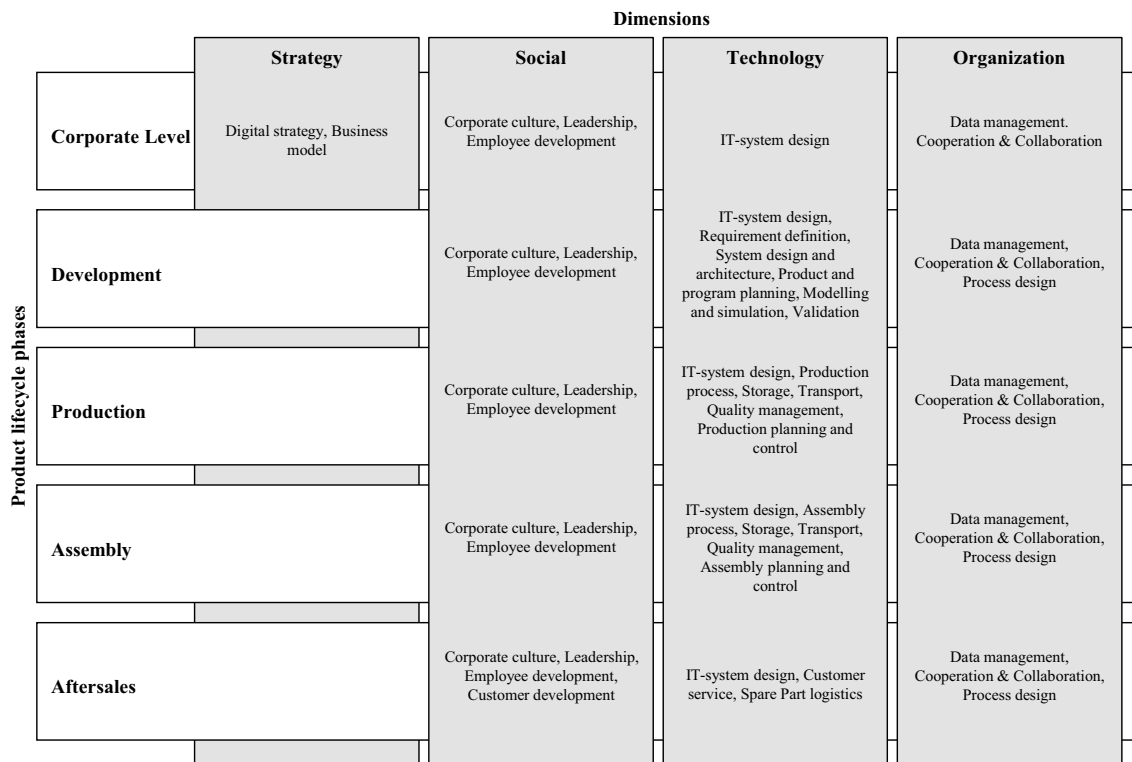
Fig. 5 Structure of InAsPro maturity model, with its product lifecycle phases, dimensions, and criteria [1]

the same as those for the product lifecycle phases. Only within the *Technology* dimension do the criteria vary. This is because of the specific use of digital technologies with certain purposes in a given product lifecycle phase. The criteria associated with both the dimensions and the levels of consideration are shown in Fig. 5.

Indicators describe the abovementioned criteria. For example, an indicator for the Transport criterion within the *Technology* dimension is identification of components in a manufacturing process (Table 3). The indicators are developed iteratively within the InAsPro project and are formulated as questions. Each indicator contains four stages representing the digitalization progress of the associated criterion. They are described textually (see also supplementary material). The first stage starts with an indicator having no or low digitalization whereas the fourth stage describes a fully digitalized indicator (Fig. 6).

Within the *Organization* and *Social* dimensions, the majority of the criteria have the same name, but the indicators vary in accordance with their associated product lifecycle phase. Therefore, the indicators must be evaluated considering their context within their individual product lifecycle phases. As an example, the Leadership criterion contains the "Communication of digitalization projects" indicator, which may vary between the product lifecycle phases in response to different executives with different management styles. Furthermore, the presence of the same criteria across the product lifecycle phases and the *Corporate Level* allows easier comparison of the degree to which a given criterion is digitized. A selection of criteria, indicators, and stages of the InAsPro maturity model are presented in Table 3. An example of the Corporate level (IT-System Design) points out the detailed description of the maturity stage definitions and is given in Table 4. A detailed description of the full set including the stage definitions and their detailed descriptions, are presented in the attached "InAsPro maturity model guide" as well as in the software demonstrator [74].

As the InAsPro maturity model is implemented within a software demonstrator, it begins with introductory questions consisting of general questions, e.g., questions regarding the company branch that is presently active or the number of employees employed by the company (Fig. 7). The introductory questions enable categorization of the data sets regarding different sectors, countries and regions, company size, etc. Consequently, setting a benchmark between these categories is possible.

4 Application of InAsPro maturity model

The InAsPro maturity model includes a comprehensive examination of the degree of digitization. Based on the results, individual measures are derived in the subsequent step with the help of the digitization strategies which were developed in the InAsPro project. This enables an individual digital transformation of manufacturing companies [75]. The application of the InAsPro maturity model is supported by the software demonstrator, which guides users step by step through the maturity model. Prior knowledge for the application of the maturity model is required on the content level, so it is recommended that the evaluation of the indicators is carried out by experts from the specific business units [76].

4.1 Application strategy

In the initial application stages of the InAsPro maturity model, the user chooses the product lifecycle phases they wish to assess. The user can choose one or all four product lifecycle phases depending on the individual objectives of the maturity assessment. Answers to the Introductory Questions and those concerning the *Corporate Level* are obligatory because of the structure of the maturity model (Sect. 3.5).

To perform the assessment, it is recommended that different persons evaluate the indicators on the basis of their stages in the maturity model. For example, the *Corporate Level* evaluation should be performed by a group of employees familiar with the strategic orientation of the company, who can make accurate statements about the indicators at this level. For assessment of the product lifecycle phases, it is best to include the relevant divisional managers and experts in the evaluation process, especially if more than one phase is assessed. This provides a more objective view of the digitalization statuses of the considered product lifecycle phases. To summarize, assessment of the company maturity level as well as the product lifecycle phases is ideally performed by a team composed of experts in individual areas.

4.2 Application example and displayed results

As an example, the developed maturity model was applied to a small and medium-sized enterprise (SME) within the mechanical engineering sector to determine its digitalization maturity level in the *Development* and *Production* product lifecycle phases. The company develops and produces its own products with high variety due to customer-specific requirements and delivers german and international markets. After applying the maturity model to the chosen product lifecycle phases, the assessment results were displayed within tables and radar charts. The results are shown separately according to the obligatory *Corporate Level* and the chosen product lifecycle phases. First, the result of the company's digitalization maturity level is shown (Fig. 8). The SME has a total digitalization level of 2.0, which means it is still a *Beginner* in the context of digitalization. The description of this maturity level is given in Fig. 4.

Table 3 Exemplary indicators and their stages for Corporate Level and Development, Production, Assembly, and Aftersales product lifecycle phases

Product lifecycle phase	Dimension	Criterion	Indicator	Stage 1	Stage 2	Stage 3	Stage 4
Corporate Level	Strategy	Digitization Strategy	Does your company have a digitization strategy?	No digitalization strategy development planned	Digitalization strategy development not started to date	Digitalization strategy development incomplete	Digitization strategy finalized and published
	Technology	IT-System Design	Are your IT systems interlinked along the entire value chain (to customers and suppliers)?	No linkage	Some systems are interlinked, leading to a variety of media discontinuities	Most systems are interlinked but some media discontinuities remain	Systems are interlinked consistently without media discontinuities
	Organization	Data Management	How you evaluate data in your company?	No data evaluation	Manual data evaluation, no software support	Predefined software evaluations are possible	Individual evaluations by big data analytics are possible
	Social	Employee Development	How do you train your employees?	No training offered	Face-to-face training offered	Face-to-face or online training is offered	Training is integrated into the working process as smart learning
Development	Technology	Requirement Definition	How do you record your product requirements?	Not digital recordings	Requirements are captured in local files	Requirements are captured with a modeling tool	The product requirements are modelled and integrated into the product lifecycle management system
	Organization	Process Design	How do you manage your data for a digital twin representation?	No digital twin data management processes	First conceptualizations and data allocation within a data management system for digital twinning	A digital twin data model is realized for sample products. Configuration-based digital twin data are derived from development information, documents, and simulations	Digital twin representations for different products are implemented and enriched with manufacturing and usage data
	Social	Employee Development	Do you use virtual visualization possibilities to enhance work?	Basic visualizations of products on monitors	Realistic representations with digital mockup means	Virtual reality (VR) facilities	VR facilities with collaboration possibilities (users can interact in VR environment)
Production	Technology	Manufacturing Planning and Control	How do you maintain machinery and equipment?	Reactive	Proactive with manual planning	Proactive with algorithm support (predictive maintenance)	Proactive predictive maintenance with automated problem solving
	Organization	Data Management	Do you collect data in real time?	No real-time data collection	Isolated real-time data collection	Predominant real-time data collection	Full real-time data collection
	Social	Leadership	How do you communicate digitization projects?	No communication	Sporadic communication via analog media	Sporadic communication via digital media	Regular communication via digital media

Table 3 (continued)

Product lifecycle phase	Dimension	Criterion	Indicator	Stage 1	Stage 2	Stage 3	Stage 4
Assembly	Technology	Storage	How do you store and pick product components in the warehouse?	Manually	Partially automatic	Fully automatic	The warehouse controls itself (smart warehouse)
	Organization	Process design	Do you control your assembly process digitally and decentrally?	Assembly processes are controlled centrally	Assembly processes are partly controlled centrally and decentrally	The assembly processes are predominantly decentralized	All assembly processes are completely digitally and decentrally controlled
	Social	Corporarte Culture	Do your employees support digitization projects?	The necessity of digitization projects is fundamentally questioned by employees	The necessity of digitization projects is principally recognized, but only a few projects are supported by employees	The necessity of digitalization projects is principally recognized, so that projects are usually supported by employees	The necessity of digitization projects is recognized by all employees and therfore these projects are supported
Aftersales	Technology	Customer Service	Do you offer your customers individual technical products and belonging services (product-service systems)?	No	These services are planned	Limited offering	Completely offered
	Organization	Process design	How do you plan service planning and scheduling?	Manually	Supported by standalone software	Through integrated IT systems	Through complete digital planning and disposition
	Social	Customer Development	Do you offer your customers product-accompanying training?	No	Yes, by presence events	Yes, through online courses	Yes, training can be done virtually
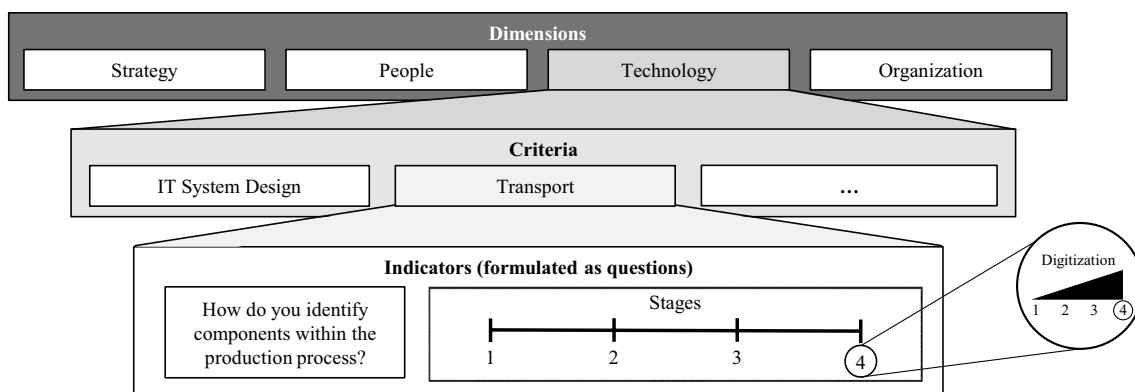
Fig. 6 Description of dimensions, criteria, indicators, and stages [1]

For a more detailed insight, the total result was decomposed into the considered dimensions, i.e., *Technology*, *Organization*, *Social*, and *Strategy* (Fig. 9). The SME ranked on the *Beginner* level for all dimensions, but performed strongest in the *Social* dimension. For each dimension, the calculated results were presented in a radar chart containing the dimension's criteria, e.g., IT-System Design as well as Requirement Definition, to provide more detailed identification of the strengths and weaknesses. As an example, the SME digitalization was found to be *Advanced* regarding the System Design & Architecture and Modeling & Simulation criteria, but the company was rated as an *Explorer* in the Quality Management and Production Planning & Control criteria. Therefore, there is potential for improvement in these areas. As only *Development* and *Production* were assessed for the SME, no values were given for the Customer Service and Spare Parts Logistics criteria.

In addition, the assessed digitalization maturity level was presented in terms of the processed individual product lifecycle phases, i.e., *Development*, *Production*, *Assembly*, and *Aftersales*, as well as the *Corporate Level* (Fig. 10). Therefore, the SME received individual digitalization maturity values for *Development* and *Production*. The assessments for all product lifecycle phases could also be examined in more detail by displaying their specific criteria. In this paper, the result for *Production* is used as an example (Fig. 10(2)).

The displayed graphs show well-digitized areas (values above 2.5) and areas with potential for improvement (values below 2.5). Therefore, the SME decisionmakers are provided with a basis on how to proceed. For instance, the already well-digitized areas (the pioneering strategy) of the SME can be taken as his strength the company could follow the pioneering strategies and advance his capabilities in these fields. Moreover, the less digitized areas (successor strategy)

can be improved indicating a successor strategy to maintain competitiveness. Consequently, the maturity assessment results provided by the InAsPro maturity model serve as a starting point for the development of a digitalization strategy, or for questioning and adjusting an already existing digitalization strategy within a company.

5 Results and discussion

The successful digitalization of a manufacturing company requires knowledge of its status quo regarding digitalization of established technical systems, organizational structures, and processes, as well as social factors. Based on this knowledge, the company can set an individual digitalization goal in all the considered areas.

The InAsPro maturity model presented in this study enables manufacturing companies to gain an initial insight into their current digitalization level by not only considering the whole company, but also differentiating between the *Corporate Level* of a company and the *Development*, *Production*, *Assembly*, and *Aftersales* product lifecycle phases. The maturity model also equally contemplates the *Technology*, *Organization*, and *Social* dimensions. Additionally, a *Strategy* dimension is incorporated into the *Corporate Level* (Sect. 3.5) of the model. The total assessment result given by the proposed maturity model allocates one of four maturity levels to the company, which contain a detailed description of the individual digitalization degree (Sect. 3.4). Furthermore, the calculated results are displayed in several graphs, showing the total result for the company as well as detailed results for all product lifecycle phases and dimensions (Sect. 4.2).

Table 4 Example of a detailed description of the maturity stage definitions

Criterion	Indicator	Stage 1	Stage 2	Stage 3	Stage 4
IT-System Design	Are your IT systems interlinked along the entire value chain (to customers and suppliers)?	No linkage	Some systems are interlinked, leading to a variety of media discontinuities	Most systems are interlinked but some media discontinuities remain	Systems are interlinked consistently without media discontinuities
		Your systems are not connected to the higher-level enterprise systems and cannot exchange information. Data is exchanged exclusively manually, for example, by printing Excel lists or by passing on information verbally	Your systems are only occasionally connected to the higher-level enterprise systems, so that information cannot be exchanged automatically. Information is passed on manually due to media discontinuity	A large part of your systems are connected to the higher-level enterprise systems and can exchange information automatically. There are only a few media breaks, i.e. missing interfaces between systems where manual information transfer is required	Your systems are networked with the higher-level enterprise systems and enable end-to-end collaboration. Relevant information is automatically forwarded. Product-related data from aftersales, for example, is also automatically transferred to development

5.1 Conclusion

Compared to existing digitalization maturity models, the developed InAsPro maturity model implements a holistic approach by considering multiple aspects of a company. That is, consideration of the *Corporate Level* as well as the *Development*, *Production*, *Assembly*, and *Aftersales* product lifecycle phases provides an integrated view of digitalization within the company. In particular, the crucial differentiation between the *Production* and *Assembly* heterogenous phases separates the proposed model from earlier approaches. Furthermore, the maturity model incorporates the *Technology*, *Organization*, and *Social* dimensions and adds *Corporate Strategy* to the overview. The maturity model has been developed so that work systems of different sizes can be evaluated. Thus, for example, a company can assess a workstation and, simultaneously, an entire department, in terms of digitalization.

Additionally, the maturity model facilitates comparisons between the product lifecycle phases; the acquired results can be used as a benchmark between manufacturing companies and across sectors. This aspect is ensured because the maturity model is intended to be implemented within a software demonstrator; thus, manufacturing companies can perform the assessment online. Therefore, anonymous results from different users can be compared objectively. Furthermore, differences in perception between the top management and divisional managers can be revealed, if repeatedly applied questions are answered differently on the *Corporate Level* and on the level of the product lifecycle phases (Sects. 3.5 and 4.1).

As technology evolves rapidly, different technologies are not explicitly considered in the maturity model and are not attributed to individual maturity levels. Furthermore, the maturity model reflects the current state and the target state is not presented. The target state is defined in the next step of the InAsPro research project using the developed concept of digitalization strategies [77]. Based on the digitalization strategies and the technology map previously reported by the authors [21], recommendations for specific application scenarios can be derived. By combining the InAsPro maturity model with the already developed technology map and digitalization strategies, a holistic modular transformation concept for work-system digitalization is developed. The concept supports companies in digitizing their work systems step by step and accompanies the implementation [2]. Furthermore, the concept was transferred into a software demonstrator, making it available for the use by the general public [74].

CREATE A NEW PROJECT

Project name

In which sector are you presently active?
- Automotive industry
- IT industry
- Engineering
- Metal and mechanical products sector
- Electrical and electronics industry
- Other

In which country is your company registered?

What is the postcode of your region? Please enter the first two digits of your postal code area.

Please estimate the number of company employees.
- up to 19 employees
- 20 to 99 employees
- 100 to 249 employees
- 250 to 499 employees
- 500 or more employees

Do you work nationally or internationally?
- national
- international

What is your position in the company?

Fig. 7 InAsPro maturity model: introductory questions [74]

Selection | Corporate level | Development | Production | Result

TOTAL RESULT

Company digitalization level: 2

Explorer	Beginner	Advanced	Expert
1 - 1.4	1.5 - 2.4	2.5 - 3.4	3.5 - 4
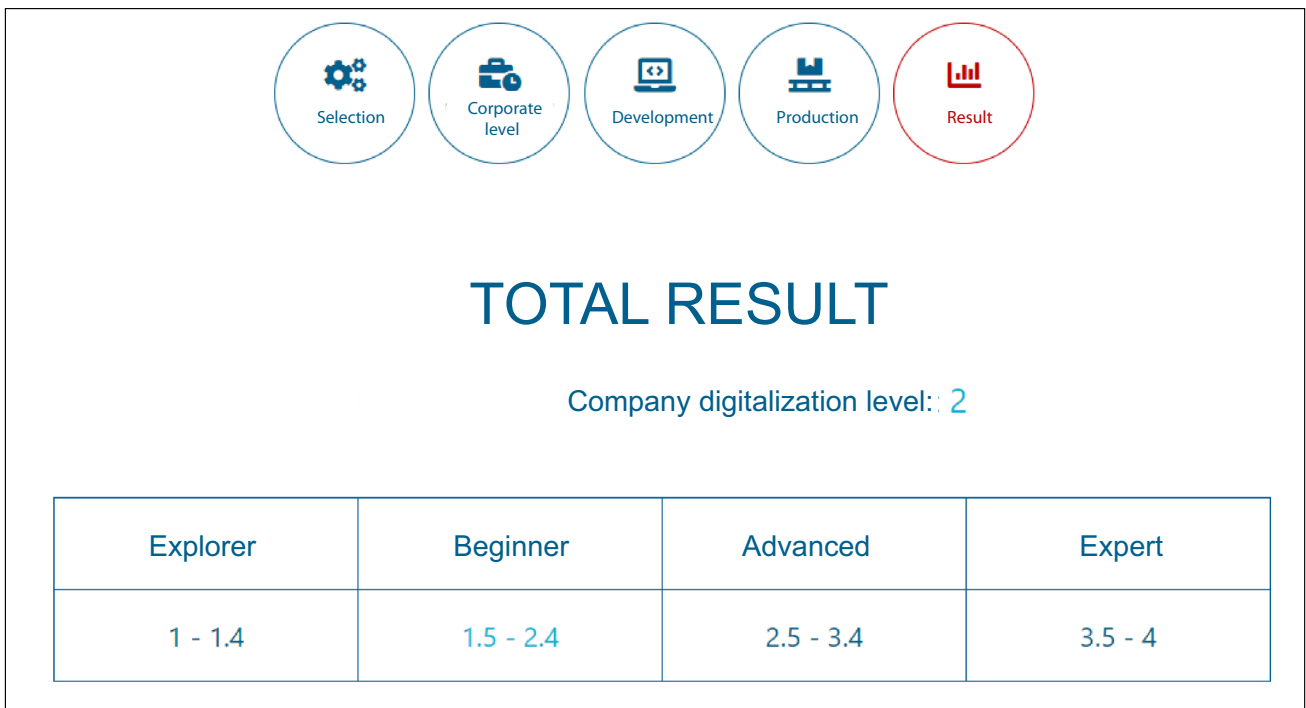
Fig. 8 Total company assessment result
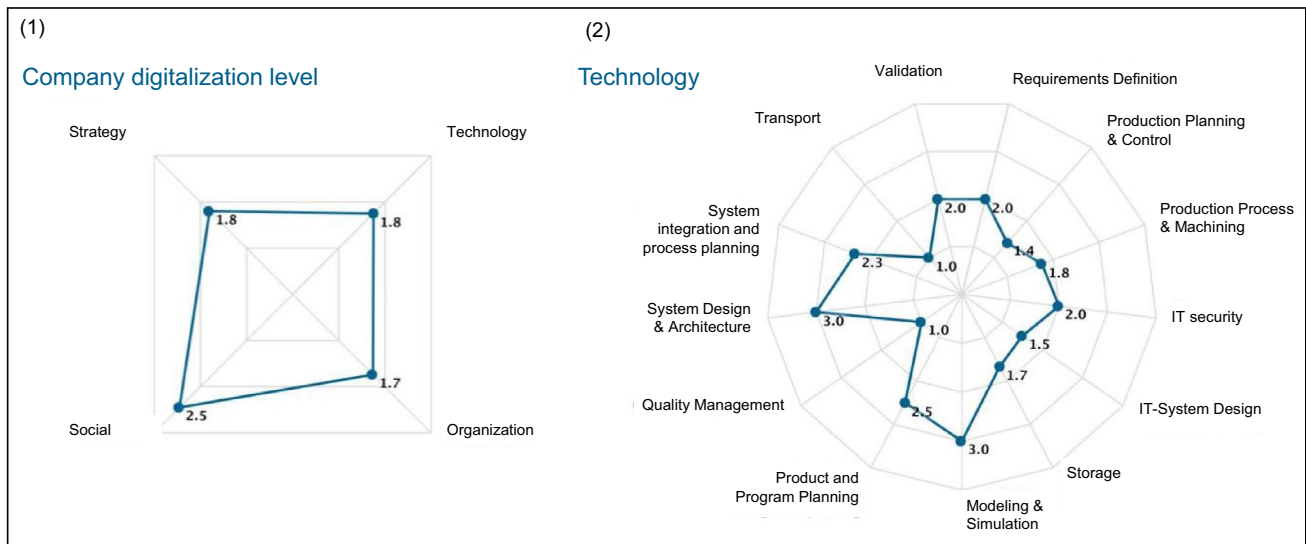
Fig. 9 (1) Overview of company digitalization levels for Technology, Organization, Social, and Strategy criteria on Corporate Level and (2) for Technology criterion only
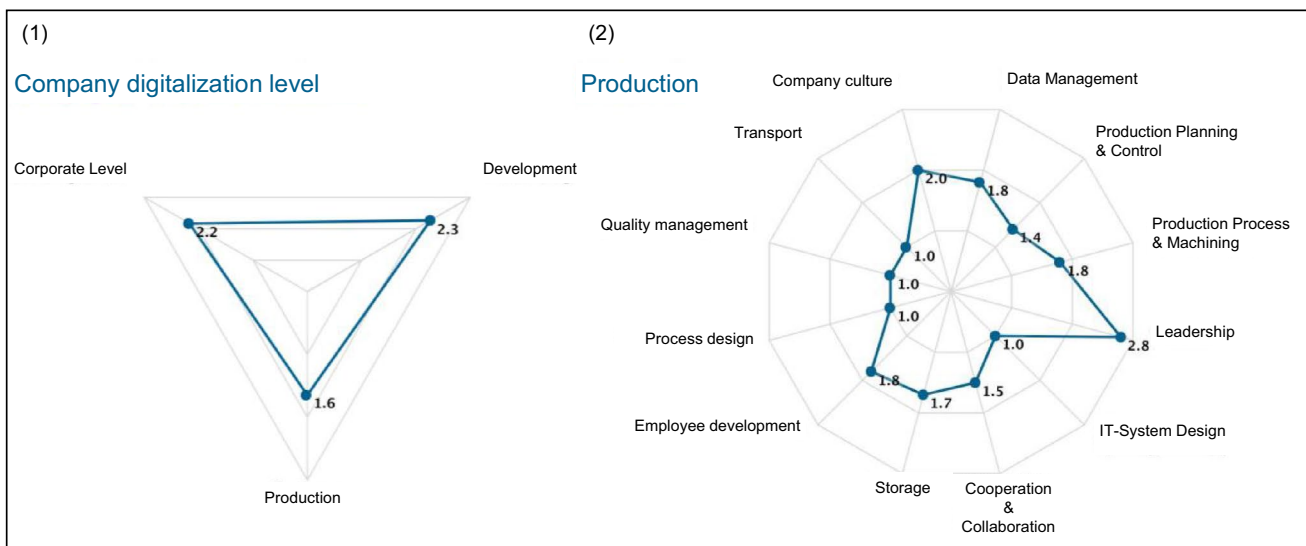
Fig. 10 Overview of company digitalization levels for (1) all product lifecycle phases and (2) Production product lifecycle phase only

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