Literature analysis and development of a metadata model for human capability description in production

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Abstract: This research article addresses the critical gap in describing human capabilities for assembly, disassembly and reassembly processes in production systems at a granular level. As circular economy principles become essential in manufacturing, understanding production-centered capability requirements is increasingly vital. While most metadata models focus on technical resources, existing human capability models either focus narrowly on human-robot collaboration or lack integration across diverse capability dimensions. This study conducts a systematic literature review following the PRISMA scheme, examining different scientific databases to develop a comprehensive, production-centered metadata model. The resulting model formalizes three fundamental classes as well as two supplemental classes for describing human resources while incorporating knowledge and possible legal requirements essential for production environments. The present article proposes a holistic integration of capabilities from a human factor perspective, with the objective of facilitating data science and artificial intelligence approaches to inform decisions in the product creation process. The developed metadata model provides the foundation for decision support systems that match human capabilities to specific production tasks and requirements, advancing circular manufacturing practices and sustainable production system design.

Keywords:
Human capability, Capability description, Metadata model, Systematic literature review

1 Motivation

In today's production environments, it is becoming increasingly important to anticipate products and their creation at an early stage [1]. Due to dynamic markets, stricter regulations, and intensified competition, companies are faced with the challenge of operating in an economically and ecologically sustainable manner [2,3]. One approach to face these issues lies in the establishment of circular cycles [4,5]. Circular economy (CE) is a model of production and consumption, which involves reusing, repairing, refurbishing and recycling of existing materials and products as long as possible [6,7]. It is particularly important to consider the resources required for manufacturing products in advance to enable material circularity. Despite global efforts to promote a CE, global circularity rate has fallen from 7.2% to 6.9%, as overall material use and primary raw material extraction are increasing faster than the use of secondary materials [8]. According to the Circularity Gap Report 2025, almost one-fifth of global material input ends up in landfill [8]. The European Union can be seen as a pioneer in this regard: In a study conducted in 2022 by the Statistical Office of the EU (Eurostat), 40.8% of the total waste volume in the EU was recycled, and 6.4% was used for energy recovery [9]. There are different strategies to enhance circularity, often referred to as the 9R framework based on POTTING et al. [10]. While there are some low-barrier strategies like the energetic recovery or recycling of material, the higher objective of CE is to extend the lifespan of products for their intended use (e.g., through repair or reuse) or directly influence usage, for example by rethinking usage [7,10]. To reduce the share of linearly used materials

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right from the start, measures can be taken into account early on in the product creation process [11]. The potential for increasing the reusability of products or their components is an important aspect of product design. However, achieving this higher goal requires more than just design; implementation in production must also be taken into account.

The reuse of components or products usually requires disassembly with subsequent reassembly. The whole process of assembly, disassembly and reassembly (ADR) needs thorough planning in advance [11]. For example, special design guidelines must be followed and manufacturing techniques must meet certain requirements [1,11]. These requirements correspond to necessary capabilities of a production system. To exemplify, the required capabilities must be described prior to assembly, but this consideration must also be made throughout the entire process of ADR. For instance, to assemble a newly developed module, there is a need for new manufacturing technologies. At the same time, consideration must also be given to the return of the module: Do new processes also need to be implemented or further technologies developed for this purpose? For this reason, digital methods are particularly necessary, which enable early-stage simulation and suggest alternative strategies for ensuring manufacturability and subsequent disassembly [12]. A first approach is to formalize available possibilities for capability description in a digital model so that they can be processed using data science/artificial intelligence (DS/AI) methods [11].

The assessment of ADR capabilities can be related both to the technical level, with machines and manufacturing technologies, and to human capabilities with different skills and characteristics. As a result of ongoing digitalization, the representation of such models in the form of metadata models (MDMs) is beneficial. Thanks to their digital representation, these models can be modified with little effort and can be expanded at a later date. In recent years, the focus of the required capability description has been on the technical level. Examples are the Manufacturing Resource Capability Ontology (MaRCO) [13] or a Semantic Web model for automated robots [14]. Both of them primarily deal with the description of machine capabilities on shopfloor level. In the encroachment on the human domain, research has already been conducted for integrating so-called human factors into assembly systems [15]. However, most of these models only describe the capabilities required of employees to collaborate with robots [16]. There is also a research gap in models that specifically include all ADR processes. The modeling of competencies for all processes of the ADR is still in its early stages. MDMs for describing human resources and capabilities usually target specific areas of application that are not related to production. It is easier to record known parameters such as constitutional characteristics or model them in classes. The main issue stems from the lack of integration of the various approaches into a holistic description of all human capabilities. This leads to the following research question (RQ):

RQ: What does a production-centered MDM look like that makes
human resources holistically describable for ADR processes?

This paper aims to provide a comprehensive description of human capabilities in circular production systems. To do this, the paper follows the principles of a systematic literature review (SLR) according to the PRISMA scheme [17]. The following structure of the paper was chosen: Section 2 introduces the concept of human competencies in a general way and the principles of building a MDM. Section 3 presents the methodological approach to conduct a SLR and transparently reflects the decisions that have been made. In Section 4, the MDM for human capability description is developed. The literature identified in the SLR is used for this purpose. Section 5 opens a discussion on the scientific findings and limitations of the model, while Section 6 concludes with a summary and suggestions for future research.

2 Theoretical foundation

2.1 Concept of competence

There are many terms used to describe an employee's overall knowledge and skills. Even though some terms are used interchangeably, a trend can be extracted from the majority of academic literature regarding the dependencies between these terms [18]. This section provides an overview of the general hierarchy. For this purpose, the taxonomy according to ERPENBECK et al. [19] in Figure 1 is used, which shows the relationships between the different contents in the concept of competence.

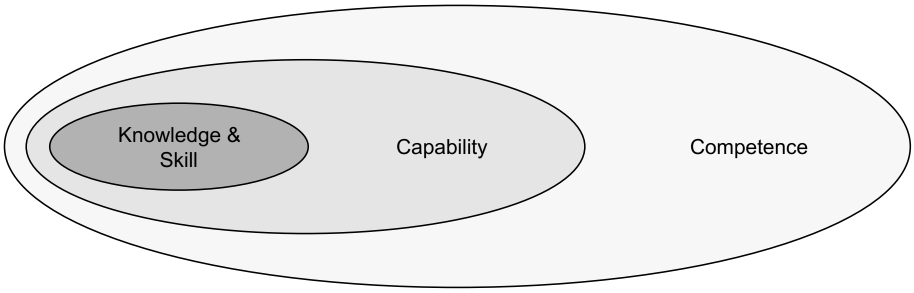

Figure 1: Relationships between knowledge, skills, capabilities and competence (based on [19])

The knowledge of an employee is core to the business. *Knowledge* is described as a stock of facts, theories, and rules available to individuals or groups, embedded in a social and contextual dimension. It is characterized by a high degree of certainty, so that its validity can be assumed [20]. Knowledge can be divided into implicit and explicit knowledge [21]. Explicit knowledge is consciously acquired and thus, it can be communicated verbally or graphically [22]. Implicit knowledge is expressed in simple terms in practical actions, without being able to explain the underlying principles [21]. It is formed in particular through the accumulation of experience in the course of work and can arise from both conscious learning or unconscious and unreflective absorption [20,22]. A s*kill* is action-oriented knowledge acquired through practice or training [19]. STANLEY and WILLIAMSON [23] state that knowledge and skill are closely interlinked. Skills relate to specific tasks and require "knowing how" in order to perform these tasks [23]. They can be composed of several sub-skills, e.g. broken down into smallest units like movements according to the Methods-Time Measurement (MTM) method [24]. Skills can usually be learned more quickly than capabilities [19]. They can usually be tested or measured. Typical examples of practical skills are welding, screwing, or inspecting. *Capability* describes a meta-level. Capabilities (or abilities) are often equated with skills. However, this broader concept corresponds to natural talents or those developed through experience [25]. These talents enable employees to cope with unforeseen task contexts, and therefore, they can be learned comparatively slower than skills. Capabilities can include coordination, creativity, learning ability, etc. In addition, a distinction must be made between the visible and invisible nature of skills and capabilities: While constitutional traits like dexterity can be measured directly, mental traits like spatial thinking can only be recorded by means of predictors and thus provide a classification of how the employee performs in comparison to other people. The broadest concept of *competence* includes all previously mentioned categories. VITELLO et al. state in their Cambridge report that "competence is the ability to integrate and apply contextually-appropriate knowledge, skills and […] [capabilities] to consistently perform successfully within a specified domain." [26]. Competence can therefore be viewed as the overarching concept. As pictured in Figure 1, there are several inclusions between the aforementioned concepts. Competencies include skills, but cannot be reduced or limited to them. This also applies to knowledge and capabilities and vice versa.

2.2 Introduction to metadata models

A MDM describes the relationships between data elements and metadata artifacts at a conceptual and logical level [27]. Metadata represents structured information about entities such as data, processes or systems. The model itself consists mainly of four components [28]: (1) Resources or the data itself; (2) Attributes to describe the datasets further and give them specific features; (3) Relationships to describe how the resources interact with each other; (4) Categories to classify the different types of metadata. Metadata can be divided into three categories: descriptive, structural, and administrative. Descriptive metadata provides information about the content of a digital object, e.g., title, author, subject. Structural metadata documents how component pieces of complex information resources fit together. For example, it might describe the relationships between different entities. Typical are parent-child-relationships where properties are passed on and specialized. Administrative metadata is used to support the management of resources, including details about creation, file type, access conditions, rights management, and preservation [29].

To develop a MDM, the purpose of the model must be defined initially [30]. After that, the user group has to be specified. For easier, automated processing, the model implementation should use a standardized modeling language like Web Ontology Language (OWL).

3 Research methodology

In order to answer the RQ, a SLR was conducted. The SLR follows the PRISMA scheme from Page et al. [17]. The objective of the search is to identify existing models or parts that deal with the description of human capabilities. An emphasis hereby is placed on the production area, i.e., all processes of the ADR. The inclusion and exclusion criteria were the following:

1. The paper has no relation to human capabilities.
2. The paper has no production context.

Due to the RQ and the focus on human resources, the first exclusion criterion was stated. The second one was intentionally formulated to be more general, covering the entire production process. This meant that results for individual ADR processes, e.g., only assembly processes, were also taken into account. The further development of an MDM for a holistic description in the ADR is therefore the aim of this work.

The SLR was initiated on December 7, 2025, on which the exports of the widely recognized databases Scopus, Web of Science and IEEE Xplore were downloaded. The search period has been set until the end of 2024, with only papers published in English or German language and accessibility as open access. All search strings consist of a combination of the terms “capability”, and “model” or “metadata model”. The search was conducted based on the author keywords. Therefore, the following strings were used:

Table 1: Search strings within the databases

Database	Search string
Scopus	KEY(capability) AND (KEY(model) OR KEY(metadata model)) AND PUBYEAR < 2025 AND (LIMIT-TO (OA,"all")) AND (LIMIT-TO (LANGUAGE,"English") OR LIMIT-TO (LANGUAGE,"German"))
Web of Science	(AK=capability AND (AK=model OR AK=metadata model))
IEEE Xplore	("Author Keywords": capability) AND (("Author Keywords": model) OR ("Author Keywords": metadata model))

As can be seen from the strings provided in Table 1, the search was initially as broad as possible. There was no initial focus on the production context and all possible capability description models should be found. By applying the exclusion criteria, the results were gradually narrowed down to human capability description in production environments. In addition, the SLR within the searched databases was supplemented by a manual search to include sources that have introduced specific submodels of human capability description that were needed for the subsequent model development in Section 4. A screening was then carried out to pinpoint the pertinent articles from the entire collection. To maintain the study's rigor and objectivity, working papers, preprints, and other non-peer-reviewed publications were omitted from the analysis. A summary of the complete process is provided in Figure 2.

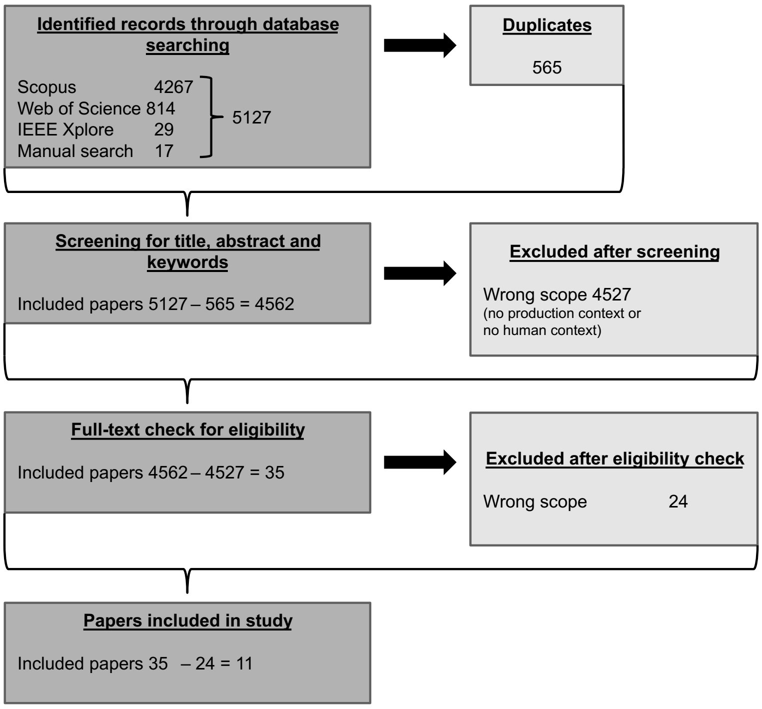

Figure 2: Flow chart of the SLR according to the PRISMA method (based on [17])

The search yielded a total of 5127 entries. Of these, 565 papers were disregarded as duplicates of existing entries. The remaining 4562 papers were meticulously evaluated based on their titles, abstracts, and keywords. By applying the previously defined exclusion criteria, 4527 papers were discarded as irrelevant. The subsequent full-text check for eligibility excluded another 24 papers due to incorrect scopes, resulting in a total of eleven included papers. Analysis of the identified papers revealed that both internal thought processes and externally observable characteristics are essential for describing human capabilities. In addition to internal processes, knowledge about the application context is also relevant, as explained in the following section.

4 Capability description model

The previous findings lead to the development of the MDM for human capabilities in production. With a concentration on the human component in accordance with the RQ, classes describing technical resources were omitted. In order to describe human capabilities at an operational level, the category of competence will be not included in the model. Necessary competencies are often used in a generalized manner in job descriptions, resulting in a lack of clarity regarding the capabilities required for ADR. The narrower concepts of knowledge, skill, and capability still apply. The analysis of the papers led the development and resulted in the formalization of the MDM. At the highest level, five aggregated classes are introduced. Each class will be explained in detail and stated in the respective figures below.

Knowledge of ADR processes and production are essential elements for a worker. Therefore, all concepts of knowledge are summarized in the class *domain knowledge*. In a production context, employees must be able to direct themselves toward completing a task and perform both physical and mental processes. Beyond that, each person has senses that enable them to perceive their environment and react accordingly. So, to describe a human worker fundamentally in his mental and physical attributes, the three classes *sensory capability*, *mental capability* and *physical capability* are introduced. Apart from normal activities carried out in everyday production, there are also special requirements for training or proof that the employee is capable of carrying out a specific ADR process. This leads to the introduction of the class *certification*. In order to describe human capabilities in the production environment holistically, subclasses were introduced for each class. The concept of classes and subclasses was originally derived from JÄRVENPÄÄ [31], who divided capabilities further into simple and combined ones. The aggregation of classes and subclasses for this MDM is based on production requirements. This means that specific skills are referred to as explicit subclasses in certain places, whereas (mostly in the mental area) entire capabilities are more often named. On top, the semantic structuring was introduced based on BAUERNHANSL et al. [32].

The following Figure 3 explains the further composition of the cognitive processes in production. First, domain knowledge contains specific knowledge about the sequence of *product/process*. The worker needs to know for example different product variants or how to (dis-)assemble a product. *Material knowledge* consists mainly of knowing how certain materials behave, as well as what makes them hazardous. To exemplify, a worker knows the probability of breaking between a plastic clip or a metal screw when disassembling a returned product. At least, the human needs *tool knowledge* about the deployed ones in ADR processes – things that are indispensable for achieving a good process quality.

The class certification has no specific subclasses. The justification for its existence is of a regulatory nature. Many companies use certifications to explicitly authorize workers to perform tasks that they would otherwise not be allowed to perform.

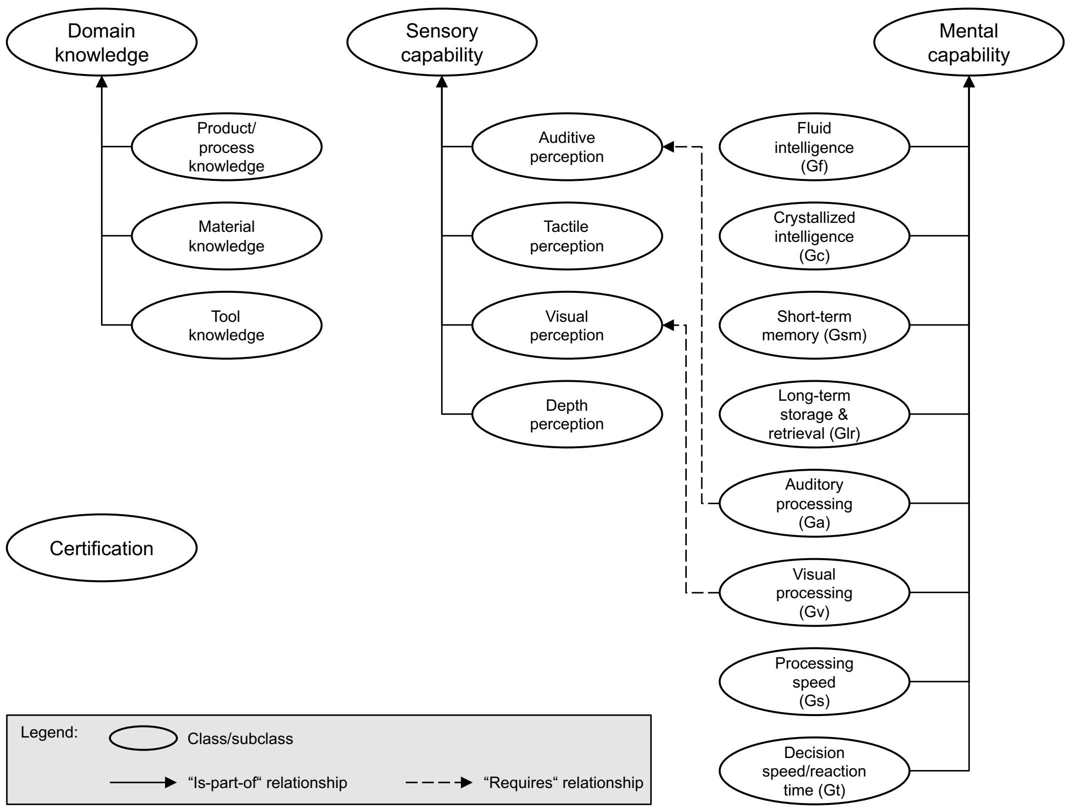

Figure 3: Classes domain knowledge, certification, sensory capability and mental capability

In terms of sensory capabilities, the senses that are regularly required in a production context were identified as particularly relevant for performing an ADR task. *Auditive*, *tactile* and *visual perception* are the most important subclasses here, supported by *depth perception* as an extension of vision [33]. Most ADR processes can already be covered by the first three sensory subclasses mentioned above. The addition of depth perception for spatial imagination is necessary because complex products or disassembly processes in particular often involve difficult or restricted access.

Regarding cognitive processing, a basic approach is required: Different types of mental processes are used to solve ADR tasks. For example, loosening a corroded joint requires a mental problem-solving process that must be remembered and then continuously checked and adjusted during execution. The extraction of mental capability subclasses was carried out based on the Cattell-Horn-Carroll (CHC) theory [34,35]. It is one of the leading psychological models for structuring cognitive capabilities, developed in the mid-1990s and constantly refined since then [36]. The core of the model is the hypothesis that human intelligence consists of different factors, called G-factors. At the bottom of the CHC theory are specific factors or rather capabilities, which are tied to a specific task or test [37]. Originally, there were two factors, Gf and Gc. The *fluid intelligence (Gf)* is used to for inductive and deductive reasoning and enables employees to adapt to new environments and develop solving strategies for novel problems [34]. In a production environment, Gf is crucial for unexpected events, defects or new product variants during ADR processes. In contrast, *crystallized intelligence (Gc)* describes the worker's capability of problem solving with automatisms and established strategies. Areas such as general knowledge and vocabulary fall within the scope of Gc. For example, understanding (dis-)assembly instructions, technical terms, or apply learned procedures requires Gc. The CHC theory was then divided further, with two subclasses describing intelligence factors concerning the human memory. *Short-term memory (Gsm)* is used for temporarily storing and remembering information in working memory. For example, it is important for tracking process steps and managing parts. *Long-term storage & retrieval (Glr)* is the counterpart and can be used, for instance, to retrieve and compare defects with previous signs of wear on a product. The subclasses *auditory processing (Ga)* and *visual processing (Gv)* exist based on the worker's senses. Ga is the capability for analyzing and distinguishing auditory stimuli (excluding language); it is relevant for noise localization (e.g., error sources) and the recognition of patterns or deviations such as rattling noise from a broken component. Gv can be defined as "the ability to make use of simulated mental imagery (often in conjunction with currently perceived images)" [36]. In production environments, Gv first requires visual perception in order to generate, analyze, and mentally manipulate visual patterns. It is essential for spatial understanding of components and connections in products. The last two subclasses are more concerned with the time needed to take an action. The *processing speed (Gs)* can be described as the capability to perform simple, repetitive cognitive tasks quickly and fluently [36]. *Decision speed/reaction time (Gt)* refers, in comparison, to the worker's capability to react quickly to situations and making simple decisions. Gt capabilities reflect the immediacy with which a human can react to stimuli (e.g., number of seconds before moving a hand towards a dropping part), whereas Gs capabilities reflect the ability to work quickly over a longer period of time (e.g., loosening ten screw connections).

Alongside the mental aspects of human individuals, there are also their physical capabilities. As a rough preliminary classification for the production context, there are specific *body characteristics* that constitute a worker and different *movements* that can be executed with the body. The detailed classification can be seen below in Figure 4. To distinguish between the different characteristics and their movements, a partition of the body was made. The anatomy from the waist upward was assigned to the upper musculoskeletal system (UMS), for example, the torso and arms. Complementary, all areas below the waist were assigned the lower musculoskeletal system (LMS). Adapted from GRÄßLER et al. [38], different parameters can be assigned to each body characteristic and movement. The number of parameters can be expanded as needed. Parameters were assigned according to the principle that unchangeable or quasi-static characteristics were attributed to body characteristics, while attributes equivalent to a momentary state were attributed to movements. For example, reach distance and arm length are unchangeable characteristics of a worker. When specific ADR tasks require a given arm span, then it is possible to match technical requirement profiles with the given worker’s capability profiles.

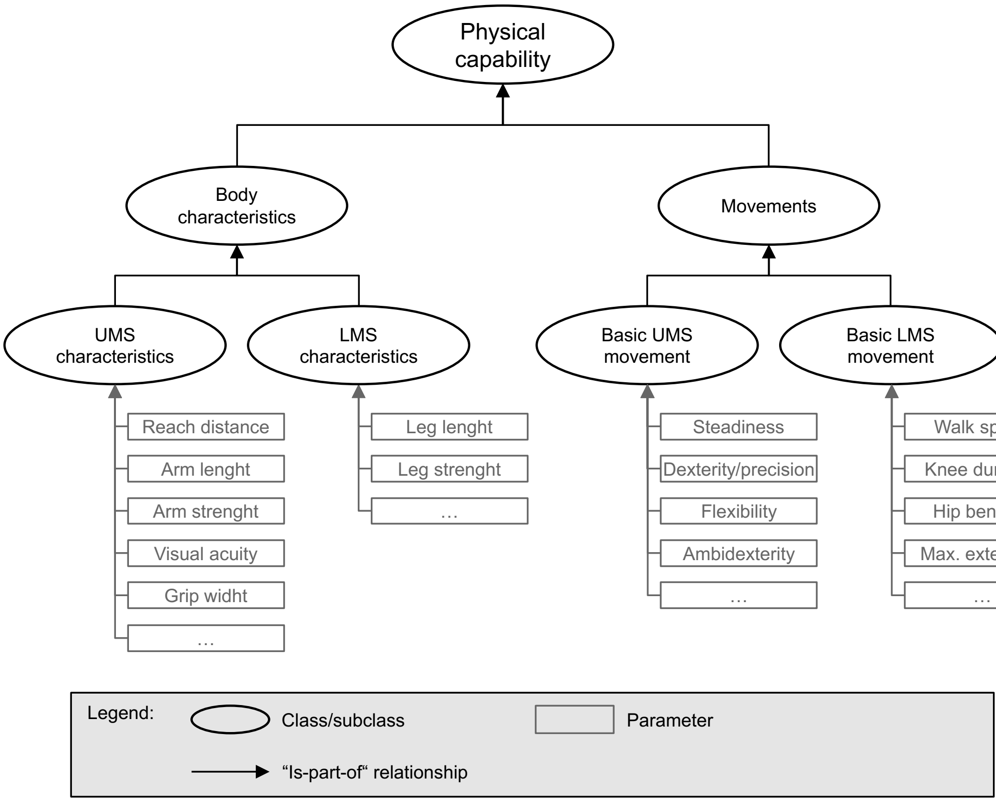

Figure 4: Class physical capability

5 Limitations

The scientific findings presented above are subject to certain limitations that should be taken into account when interpreting the results. An open search was enabled by the broad formulation of the search strings within the scope of the methodological approach selected, without excessive restriction of the results. However, this approach also necessitated greater effort during the review. Because a significant number of papers were outside the field of production, more than 4500 entries were already excluded during the initial screening. Notably, several seminal works were not identified through the SLR and had to be included manually. One reason for this could be that their application context is not limited to production and that they did not originate from a MDM. In addition, the search was limited to open accessible literature in the databases Scopus, Web of Science, and IEEE Xplore. Thus, papers that were not open access or listed in the aforementioned databases could not be screened. The search was also limited to keywords; hence, contributions that list human capabilities only in their title, abstract or full text were not found.

Besides that, the MDM is designed to be expandable if needed. Most classes describe human workers holistically in production environments. However, emotional capabilities such as empathy or conflict resolution capability were not considered. Hence, the focus of this MDM lies in the human-task interaction and not between several workers in production. In addition, human learning and forgetting effects were not part of this study. Employees who are initially unsuitable for certain tasks may later become qualified by undergoing targeted training.

6 Conclusion and outlook

For enabling circular production systems, a holistic understanding of the production process including disassembly and reassembly is important. The paper at hand addresses this critical research gap and offers an initial approach for describing human resources. Existing models often neglect the human influence on task completion and emphasize the technical aspect of production systems. A SLR based on the PRISMA scheme identified eleven relevant publications which formed the basis for the development of a production-centered MDM. The developed MDM formalizes five aggregated classes for the holistic description of human resources: domain knowledge, certifications, sensory abilities, mental abilities (based on CHC theory), and physical abilities (differentiated according to movements and physical characteristics of the upper and lower musculoskeletal system).

The significance of this model lies in its application as a foundation for data-driven decision-making systems that match human capabilities with specific production tasks. This is particularly essential for the circular economy, as repair, overhaul, and recycling processes require specialized human resources.

Future developments should expand the MDM to include technical skills and product specifications in order to create a complete knowledge graph for hybrid decision support systems. To model product requirements and the corresponding capabilities, it is necessary to establish a connection between these two elements. In addition, the MDM should be validated using actual data, and the interfaces to data systems must be specified. At the same time, learning effects, emotional capabilities and collaborative aspects could be taken into account to make the model operationalizable for more complex scenarios.

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