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A Multi-Model Ontological System for Intelligent Assistance in Laser Additive Processes

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Abstract: This study examines the key obstacles that hinder the mass adoption of additive manufacturing (AM) processes for fabrication and processing of metal parts. To address these challenges, the necessity of integrating an intelligent decision support system (DSS) into the workflow of AM process engineers is demonstrated. The advantages of applying a two-level ontological approach to the creation of semantic information to develop an ontology-based DSS are pointed out. A key feature of this approach is that the ontological models are clearly separated from data and knowledge bases formed on this basis. An ensemble of ontological models is presented, which is the basis for the intelligent DSS being developed. The ensemble includes ontologies for equipment and materials reference databases, a library of laser processing technological operation protocols, knowledge base of settings used for laser processing and for mathematical model database. The ensemble of ontological models is implemented via the IACPaaS cloud platform. Ontologies, databases and knowledge base, as well as DSS, are part of the laser-based AM knowledge portal, which was created and is being developed on the platform. Knowledge and experience obtained by various technologists and accumulated within the portal will allow one to lessen a number of extensive trial-and-error experiments to find suitable processing settings. In the long term, the deployment of this portal is expected to reduce the qualification requirements for AM process engineers.

Keywords: decision support system; ontologies; ontological design; laser additive manufacturing; graph model; cloud platform



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1. Introduction

Additive manufacturing (AM) technologies for metal parts offer several key advantages, including the ability to produce parts with complex geometries, significantly reduce component weight, accelerate prototype development, and improve material efficiency. In customized and small-scale production, AM techniques serve as a viable alternative to conventional methods of material processing (casting, forging, cutting, etc.) [1]. Their application in production processes opens up the possibility of creating, repairing, and modifying complex structures with improved properties that previously could not be obtained due to technological limitations [2]. The trend of steady growth of the global market of additive technologies is stated today and forecasted in the future by leading consulting companies (Frost & Sullivan, Precedence Research, Zion Market Research, etc.) [3].

Laser-based directed energy deposition (DED-LB) [4] (both powder-based [5] and wire-based [6]), an additive manufacturing process involving simultaneous material deposition and laser energy application, is one of the most technologically complex but promising AM techniques [7]. This technology can be used not only for the fabrication of large-sized metal objects, but also for the restoration of damaged or worn-out parts, as well as for structural modification and functional enhancement of existing parts [8].

Along with the significant advantages of introducing AM technologies, there are also barriers that hinder widespread adoption of AM for metal part fabrication [9]. The main challenge is the need to take into account the influence of numerous laser processing factors and technological parameters on the elemental composition, microstructure of the part material, defect formation (cracks, pores, delaminations, etc., acting on the way to post-processing), as well as the physical and mechanical characteristics of the final product [10]. Currently, the settings for laser processing of metallic materials are often identified by “trial and error” method [11]. This approach to the design of AM processes is resource- and time-consuming [12]. Taking into account the interdependence between the process parameters requires interdisciplinary knowledge and professional cooperation of specialists. These requirements contribute to a significant personnel problem, often referred to as the “high entry threshold” for laser AM (LAM).

Against this background, there is an insufficient level of intellectual support for the process engineers designing AM processes [9,13]. It is closely associated with the difficulty of scaling technological solutions in the manufacture of metal products by directed energy deposition (DED). There is an acute shortage of long-lived intelligent advisory systems (intelligent assistants) to help designers, technologists and other specialists in determining the proper technological parameters (processing regimes). The fundamental issue lies in the fact that the labor intensity, time and cost of such systems maintenance, which become necessary whenever changes occur in additive manufacturing equipment operating conditions (e.g., range of processed materials) or customer requirements, often make this process unprofitable [14,15].

Despite significant achievements in the research and development of software systems and platforms [16] to support decision-making in LAM [9,17], the “industrial adoption of such systems remains notably limited. Central concepts such as automated knowledge acquisition and inference mechanisms are still in nascent stages, demanding further research efforts”. The latter also applies to “creating user-friendly software tools that make” various AI techniques “accessible to a broader range of AM designers and process engineers” [13].

These problems determine the relevance of creating a viable intelligent decision support system (DSS) for LAM process engineers [18]. At the design stage of the technological operation [19], the DSS should generate recommendations on suitable operating regimes for laser robotic equipment when developing control programs. We consider a “suitable operating regime” as a set of such technological parameter values which make it possible to ensure that the resulting metal components meet the required quality criteria, including target elemental composition, required geometric dimensions, acceptable defect thresholds, and the desired microstructure (specified in the requirements for the result of the technological operation).

One of the widespread approaches used in the creation of software systems is the design and development of software based on ontologies (ontology-based (-driven) software engineering, OBSE/ODSE) [20–22]. This study presents an ontological model (OM) ensemble, which is designed to serve as the foundation for an intelligent DSS for process engineers in the field of LAM of metal parts using DED technology.

The rest of the paper is organized as follows. Section 2 describes the main features of the approach used to develop an ensemble of OMs, and analyzes the key requirements and

factors influencing the composition of this ensemble; Section 3 comprehensively delineates the architecture of the OM ensemble and its development on a cloud platform; Section 4 outlines the key advantages of the applied development approach and discusses the directions of further research; and Section 5 provides the conclusion of the study.

2. Materials and Methods

The development of a set of semantic information resources follows an ontological two-level approach to the representation and formation of data and knowledge [23,24]. This methodology maintains a strict separation between ontological models and their instantiations in databases (DBs) and knowledge bases (KBs). Here, the ontology is the set of rules for the structured formation of subject information and its interpretation, but not the information itself [23]. At the same time, databases and knowledge bases (containing the domain-specific knowledge) are clearly separated from software components that implement methods of their processing (knowledge about methods of problem solving). The integration, consistency and reusability of these components are ensured at the ontology level (Figure 1).

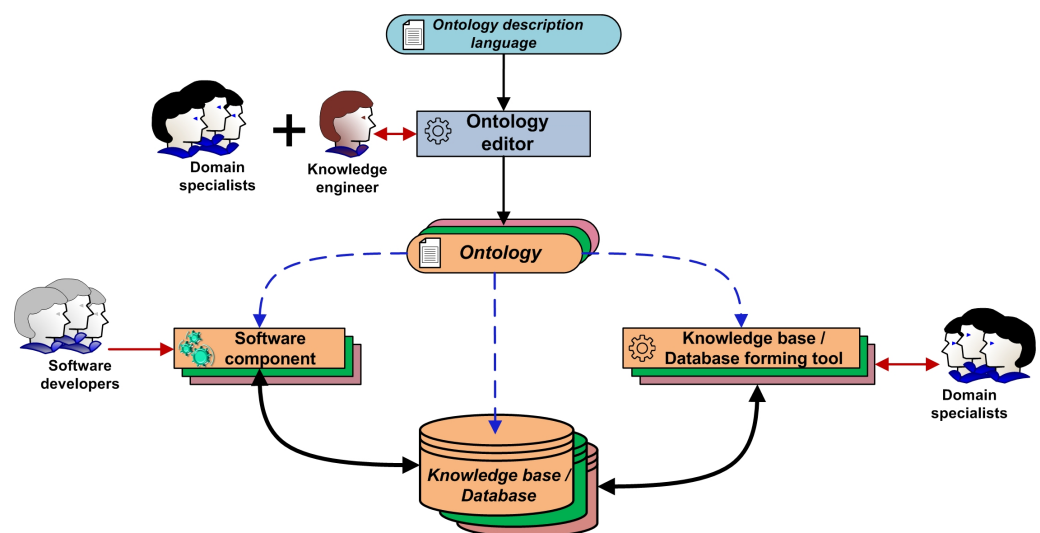


Figure 1. An ontological two-level approach to the knowledge bases and databases creation: separation of domain-specific knowledge from problem-solving methods knowledge.

This approach enables the development and further maintenance of domain-specific knowledge and software components independently by different groups of specialists. The separation of software components from the database/knowledge base allows one to modify the latter without making changes to the program code (in most cases).

The ontologies, DBs/KBs created on their basis, as well as software components for their processing share a common declarative semantic representation in the form of concept digraphs [25]. For the formal representation of ontologies, we use the ontology description language for a digraph connected two-level model of information units [23]. The language provides a means of specifying ontology models in the form of labeled root hierarchical binary digraphs. Semantic information generated on the basis of ontology models is represented by the same type of digraph, except that these digraphs do not contain markup defining the rules for the formation of target (subject) information digraphs.

The composition of the ensemble of related OMs is determined by the following requirements and factors. First of all, it must enable comprehensive structuring and formalization of all necessary information about the technological operations (TO) of the LAM, as well as about the characteristics of the materials and equipment used. It should be possible to form interconnected databases and reference books containing information on the characteristics materials processed in LAM, the equipment used, and on the protocols of TOs carried out. The LAM technological equipment includes industrial technological lasers equipped with laser optical heads; devices that facilitate the movement of the heads relative to the surface to be processed and the positioning of parts (e.g., multi-axis industrial robots and positioners); powder feeders; material supply units for the melting/processing area, etc. Processed and consumable materials include metal powders and wires made of various alloys and process gases used as carrier, shielding and auxiliary (shaping) agents. Thus, the OM ensemble should include ontologies of relevant databases and reference books, as well as the ontology of the archive (library) of laser processing protocols.

The next factor is the techniques that are proposed for the generation of recommendations for process engineers responsible for setting up TO regimes. These include deductive logical inference based on formalized knowledge and facts; reasoning by analogy (case-based reasoning) using an accumulated database of cases (which are formalized protocols of performed TOs) and numerical modeling of physical and chemical thermodynamic processes occurring in the field of interaction of a focused laser beam with the processed material. Numerical modeling represents a reliable and cost-effective approach for predicting the quality characteristics of parts synthesized via DED-LB technology [26]. Consequently, the OM ensemble should also include the ontology of the KB on the settings of laser processing modes; the ontology of the case database; and the ontology of the database of mathematical models of thermodynamic processes accompanying the DED-LB technology. The database of mathematical models is designed to store software implementations (source code) of numerical calculations of parameter values of simulated processes. When forming knowledge and the library of laser processing protocols, the terms and contents of a set of interconnected reference databases are used.

Finally, an important requirement is to ensure greater modularity and reusability of databases and reference books, as well as the possibility of their independent formation by different domain specialists (in laser physics, materials science, optics, etc.).

A set of such ontologies was created by the authors [27]. Their testing and evaluation by domain specialists allowed us to identify potential improvements in the developed ontologies. Thus, the validation process revealed several enhancement pathways: refinement and extension of ontology model content, expansion of the ontology model spectrum, and modularization-based transformation of individual models.

3. Results

We conducted a systematic analysis and formalization of the LAM process engineers' workflow related to designing regimes for performing TOs. This study specifically examined key characteristics of laser robotic equipment (as AM machine), as well as of processed and consumable materials. The key characteristics are those that can influence the progress of the laser technological process and determine its result. Consequently, the OM ensemble has been substantially restructured and expanded to provide intellectual support for decision-making by process engineers when designing technological regimes (modes). The set of ontology models included in the ensemble is shown in Figure 2.

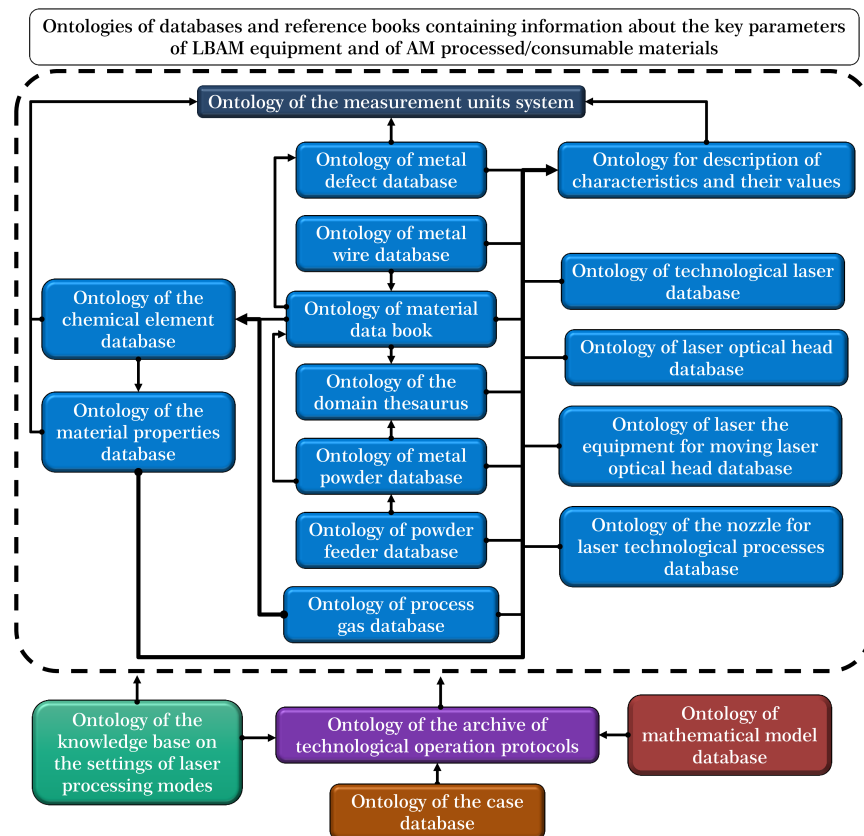


Figure 2. A composition of the ontology model ensemble.

The arrows in Figure 2 represent directed connections (relations) between ontologies. These connections (see Figure 3) can be of two types. The markup of the digraph arcs is not shown in the figure, in order not to complicate it with insignificant details in this case.

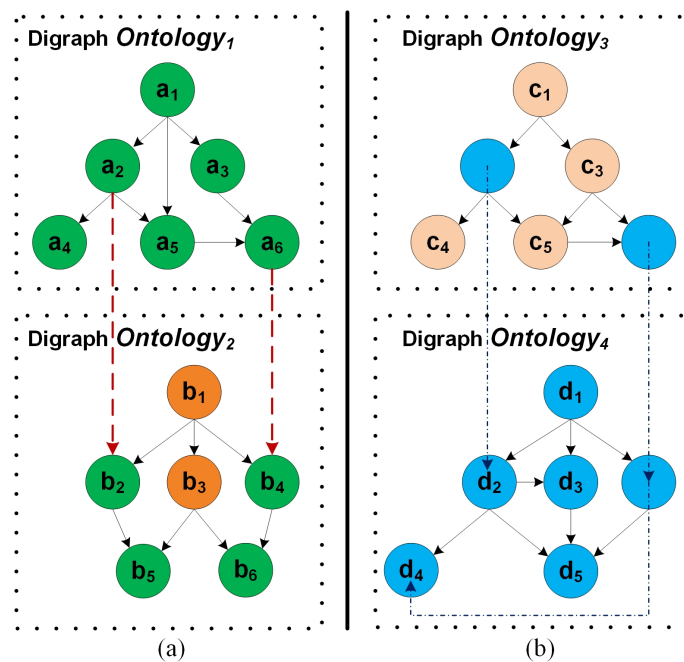


Figure 3. Schematic representation of two types of coherences between ontology digraphs: structural coherence (a) and terminological coherence (b).

1. Structural coherence. The directed connections between the concepts of ontologies (arcs between vertices of corresponding ontology digraphs) determine the reuse of subgraphs from one ontology's digraph within another. Such subgraphs may consist of either a single terminal vertex or represent an entire digraph. In Figure 3a, connections of this type are represented by dotted arcs $a_2 \rightarrow b_2$ and $a_6 \rightarrow b_4$. Vertices b_2, b_4, b_5, b_6 belong to the digraph of the *Ontology₂*, but they become attainable and thus logically included in the *Ontology₁* digraph.
2. Terminological coherence. Such directed connections are established between the labels of ontology concepts and determine the fact that labels are “borrowed” by some vertices of the digraph (which in this case do not have their own labels) from other vertices whose labels are their own. In Figure 3b, connections of this type are represented by dash-and-dot arrows coming out of vertices that do not have their own labels and entering vertices with their own labels— d_2 and d_4 , respectively.

The terminological coherence (Figure 3b) has the following features.

- These are one-to-many relationships: the label of one vertex can be borrowed by many other vertices.
- Cross-digraph applicability: A vertex with its own label and vertices with borrowed labels can belong to different digraphs or to the same digraph. At the same time, there may or may not be a path in the digraph between a vertex with its own label and a vertex that borrows this label.
- Label-borrowing mechanism: The borrowing of a label can be both direct and indirect. In the first case, for a pair of vertices, one of them necessarily has its own label, and the other borrows it. This case is represented by a vertex with its own label d_2 and a vertex that is a direct descendant of vertex c_1 . In the second case, the vertex whose label is being borrowed may also have not its own label, but may borrow the label of another vertex. This creates an iterative chain that terminates when reaching a vertex with its own label. The second case is represented by a two-step iteration, which terminates in a situation where one of the vertices in the pair becomes a vertex labeled d_4 . The limitation here is that the sequence of such connections should not form a cycle (to prevent infinite loops).

Connections of the second type allow us to ensure the terminological consistency of ontologies. Two or more OMs may have both types of connections between them. The ensemble of digraphs of target (subject) information formed on the basis of ontologies has the same type of connection, and their creation is regulated by marking the arcs of ontology digraphs [23].

3.1. Ontologies of Reference Databases on Equipment and Materials

Let us refer to the set of interconnected ontologies of reference databases containing information about key characteristics of LAM equipment and materials, as shown in Figure 2. Further, regarding the equipment, we will consider such an important component of LAM machines as a technological (industrial) laser. A fragment of the ontology of technological laser database and a fragment of the database (Technological laser database) formed on this basis are shown in Figure 4. This figure, as well as Figures 5–10, show the user interface of the IACPaaS cloud platform tool (see Section 3.4) Digraph editor, which is used to create both ontologies and databases/knowledge bases in the platform's storage.

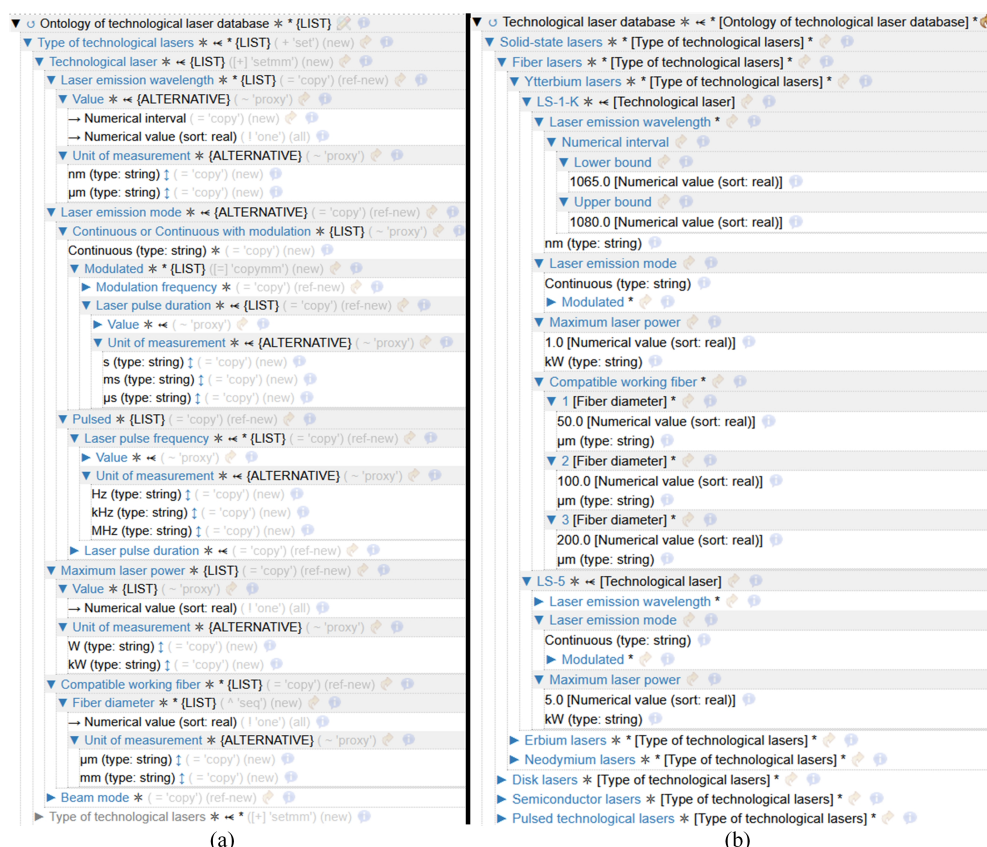


Figure 4. A fragment of the technological laser database ontology (a) and a fragment of the database of technological lasers (b) formed on this basis.

In this figure and similar figures below, the symbol $\rightarrow$ indicates the structural coherence between the digraphs of ontology models. The symbol $\updownarrow$ indicates the terminological coherence between the vertices of the digraphs of ontology models, as well as between the vertices of the digraphs of target information. The symbol $*$ standing next to the vertex label denotes that this label is borrowed by some sets of vertices. The symbol $\Leftarrow$ indicates that more than one arc enters the vertex next to the label of which this symbol is displayed. The symbol $*$ standing next to the vertex label indicates that a comment has been specified for this vertex. Comments become visible in a pop-up tooltips when hovered over $*$. The beginning vertex of such an arc can belong to either the same or another digraph. The ontology model digraphs incorporate the following markup elements that control target graph database construction: LIST, ALTERNATIVE, (= 'copy'), ([=] 'copymm'), (! 'one'), ([!] 'onemm'), (+ 'set'), ([=] 'setmm'), (~'proxy'), (new), (ref), (clone), (all), etc. The formal semantics of these markup elements, as well as the rules of formation based on it, are described in [23].

The key characteristics of the technological equipment and the materials of the LAM are the characteristics that are essential for their usage in technological processes. As shown in Figure 4, the essential characteristics of an industrial laser as an energy source include the laser emission wavelength; the laser emission mode (continuous wave—CW, continuous with the possibility of modulation—quasi-continuous wave (QCW), pulsed); the maximum laser power; compatible working fiber, the key characteristic of which is the diameter. The key characteristics of pulsed and QCW emission, in turn, are the pulse repetition rate (modulation frequency, respectively) and the pulse duration.

A fragment of the ontology of the materials reference book and a fragment of the reference book (Materials reference book) formed on this basis are shown in Figure 5.



Figure 5. A fragment of the materials reference book ontology (a) and a fragment of the materials references book (b) formed on its basis.

The material (alloy) is characterized by its elemental (chemical) composition, which specifies the chemical elements present and their percentage. The percentage can be specified not for one, but for a combination of chemical elements. The properties of the material (physical, thermal, mechanical, etc.), as well as its microstructure, are also of great importance. The property is characterized by its name and a range of possible values, which may have synonymous names and a list of units of measurement. The value of a property can be numeric or qualitative, a set of discrete values, or a numeric interval. A property can be simple or have many characteristics. Structurally, the characteristic is similar to a property and is recursive, i.e., it contains a set of similar (but possibly empty) nested characteristics (Figure 6).

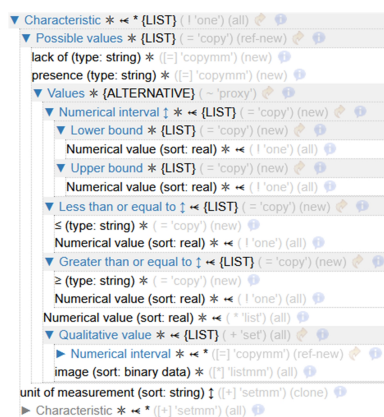


Figure 6. A fragment of the ontology for describing characteristics and their values: Characteristic section structure.

The microstructure is characterized by the size of grains, their shape (polygonal, dendritic, polyhedral, spheroidal, etc.) and predominant orientation. It is also characterized by the presence or absence of second phases, as well as the presence or absence of typical defects. In case of the second phases' presence, their percentage, shape, and grain size are specified. In the case of defects' presence, their total quantity is indicated as a percentage, and the structure of the description of each defect completely coincides with the structure of the description of the material property. For the microstructure, it is possible to store its images. Important information about the material is a list of its analogues, if such analogues are known.

3.2. The Ontology of the Case Database

Based on initial testing results, we substantially revised and expanded the ontology of the archive (library) of laser processing TO protocols (previously called ontology of technological operations) [27]. The enhanced ontology uses fragments of equipment and materials reference database ontologies (Figure 7).



Figure 7. A fragment of the ontology for the archive of laser processing technological operation protocols.

The TO protocol includes the following sections: general information about the TO; environmental conditions when performing the TO; terms of reference for the TO; the specification of equipment for performing the TO; information about preliminary preparation of the substrate or the part; the working gas environment created; key process parameters for performing the TO; possible controlled cooling of the part or the workpiece; and the result of the TO.

General information about the TO includes the TO designation, the protocol number, the deadline, the purpose and the location in which the TO is performed. Environmental conditions include the ambient temperature, relative humidity, and atmospheric pressure of the environment in which the TO has been performed. This information is significant because the technological equipment must operate under conditions where its working temperature will be higher than the dew point of technological (process) gases.

The terms of reference for the TO include the following sections: requirements for the result of the TO; the object to be processed which is a substrate or a part; the feedstock material used to perform the TO which is a metal powder (there may be more than one) or metal wire; process gases used to perform the TO.

The Section containing the requirements for the result consists of the following sub-sections: geometric characteristics, defects, elemental composition, microstructure and properties of the deposited material.

These sections may be completed selectively, depending on the task being performed. In accordance with ASTM F3413-19, there are four types: the manufacture of a new part/workpiece, the repair of a worn or damaged part, the application of a functional coating on the part/workpiece (surface modification), and the build-up of functional or structural elements on the part/workpiece. A separate type of task to perform may involve conducting research studies to identify regimes of the TO that are suitable for a specific practical application.

In the geometric characteristics section, a file describing the digital model of the part is placed (usually, in either the *.stl or *.amf format). Alternatively, depending on geometrical shape, one can specify a set of dimensions of the geometrical characteristics of the target result, by which it needs to be evaluated. The defects section lists which defects (and their characteristics) are acceptable (and within which limits), and which must be entirely absent. Porosity is a typical example of a defect that is permitted within certain thresholds. In the elemental composition section, one can specify the elemental (chemical) composition that is necessary/desirable to obtain as a result. In the microstructure section, the preferred microstructure of the deposited material can be specified. The properties section can list the requirements for the characteristics (properties) of the deposited material that must be obtained as a result of performing the TO.

It is very important that the markup specified in the ontology regulates that the names of chemical elements, defects, properties (and their values), etc., as well as their units of measurement, should be selected from the appropriate reference databases while forming the protocol. Additional ontological agreements consist in the fact that the specified values for defects, properties, etc., should belong to the range of possible values that are defined for them in the relevant reference databases. These ontological agreements ensure data consistency and interoperability across the knowledge system.

The essential characteristics of the substrate are the material (alloy) from which it is made, its geometric characteristics and its mass. The same characteristics are essential for the part being processed, but with the additional consideration that its functional surface material (if any) may differ from the bulk material. The process gas can be either a monogas or a multicomponent gas mixture.

In the equipment for performing the TO section, the technological equipment used for carrying out the operation is specified by selecting it from the appropriate reference databases.

The preliminary preparation of the substrate section is completed if the substrate (rather than a part) is the object of processing (e.g., in certain research applications). Substrate specifications are not duplicated here if already defined in the terms of reference. However, mandatory pre-processing conditions (such as controlled heating of the substrate to specified temperatures at a certain heating rate before starting the process) must be documented here if applicable. If the substrate has not been specified in the terms of reference, then the characteristics listed in the terms of reference for performing the TO should be specified here. Controlled heating is characterized by the temperature to which the substrate should be heated, as well as by the heating rate. The temperature value is usually the numerical range that needs to be maintained during processing. If a part (not a substrate) was specified as the processing object in the terms of reference, then information about controlled heating of the part can be documented in the preliminary preparation of the part section. Controlled heating is required, first of all, for massive parts with high thermal conductivity, in order to bring the crystal structure of the material to a certain energy state prior to focused radiation processing.

The gas environment in the working chamber section must be completed when a “global” protective gas environment is created in a working chamber during the TO—in addition to the shielding gas/gas mixture. The latter is delivered through the gas-powder mixture supply unit and forms a “local” protection of the melt pool and of solidification zone. The working chamber gas environment specification includes information about which filling process gas—monogas or a gas mixture—was used to create the environment, as well as parameters such as the volume flow rate, the pressure and the temperature of the gas. In the case of using a gas mixture, the percentage is indicated (i.e., the volume fraction of each monogas in it).

The key parameters of the TO section consist of four subsections: laser emission parameters; process gas supply parameters; material feeding parameters and parameters of positioning and movement of the laser optical head (relative to the processed surface). The key parameters of laser emission include the mode of radiation generation (continuous, modulated, pulsed), its power, and the beam spot diameter on the processed surface. For modulated and pulsed modes, the pulse duration and, accordingly, the modulation frequency of the output power/pulse frequency are also important characteristics.

The process gas supply parameters section consists of three subsections: parameters of the shielding gas environment (providing “local” protection of the melt pool and of solidification zone), parameters of the carrier gas and parameters of the auxiliary (shaping) gas. The structure of the information for describing the shielding gas environment coincides with the structure of the information for describing the gas environment created in the working chamber. The carrier and auxiliary gases are monogases; their key parameters are the volume flow rate, the pressure and the temperature.

The material feeding parameters section comprises two mutually exclusive options: metal powder material and metal wire material. Specification of metal powder material includes information about which metal powder or composition of metal powders was used as a material for performing the TO, as well as parameters such as mass flow rate and, optionally, the rotation speed of the powder feeder dosing disk. When using a metal powder composition, these parameters are specified for each component. Note that in this case, the metal powders are not mixed in one hopper of the powder feeder but are fed separately. The specification of metal wire material includes information about which wire was used as a material for performing the TO, as well as parameters such as the feed

rate and the feed technique—central or lateral. In the second case, the feed angle is also specified in degrees.

The parameters of positioning and movement of the laser optical head include the linear velocity of the laser beam movement over the surface; the angular velocity of the positioning device rotation; the distance from the focus point of the laser emission to the surface being processed; the focused beam center offset step size (relative to the center of the pre-created bead); the tool path strategy, and other relevant process parameters of the TO.

The controlled cooling section is filled if, after completion of the TO, the cooling of the part (workpiece) should be controlled, i.e., carried out to a certain temperature at a certain cooling rate. Controlled delayed cooling can be used to prevent or reduce the possibility of forming various types of cladding (or welding) defects. The structure of this section coincides with the structure of the controlled heating section.

The result of the TO section includes a description of the result obtained and its evaluation. The description of the result contains the same subsections as the section with the requirements for the result—geometric characteristics, defects, elemental composition and microstructure of the deposited material. The evaluation assesses both the overall TO result and the result for each of the listed sections (subsections) against the terms of reference. For each result it is indicated whether it meets the requirements specified in the terms of reference and, if it does not, it is indicated whether to consider this result positive or negative. The conformity assessment of the properties is carried out after completion of the result post-processing. The latter has a positive effect on the microstructure, as well as excluding or significantly reducing the possibility of defects formation in the deposited material. Post-processing includes various types of thermal, mechanical, or chemical treatment. This section also contains subsections in which files with images of the TO result and files of control programs for laser robotic equipment can be placed.

Figure 8 shows a representative sample from the Archive of laser processing TO protocols; in particular, a fragment of the protocol for “Growing an implant from MPF-4 magnesium powder on a substrate made of MA20 alloy” TO. Argon monogas was used as the filling process gas in the working chamber. Helium monogas was used as a shielding gas environment, providing protection for the melt pool area, and as a carrier gas. No auxiliary (shaping) gas was required, since a powder feed module 4W (four-stream with a circle of 2 mm diameter) was used to supply metal powder to the processing area (the powder mass flow rate was maintained at 1.75 g/min).

In accordance with the revised ontology of the archive of laser processing protocols, the ontology of the case database was also modified [27]. This ontology determines the organization of the case database which comprise protocols of performed TO. The protocols hierarchically grouped by types of processed materials, types of tasks performed, as well as classified based on three key factors. These factors are the parameters proposed by the DSS for performing the TO, the parameters actually selected by the technologist (operator) for performing the TO and the result of performing the TO. The derived classes are shown in Figure 9.

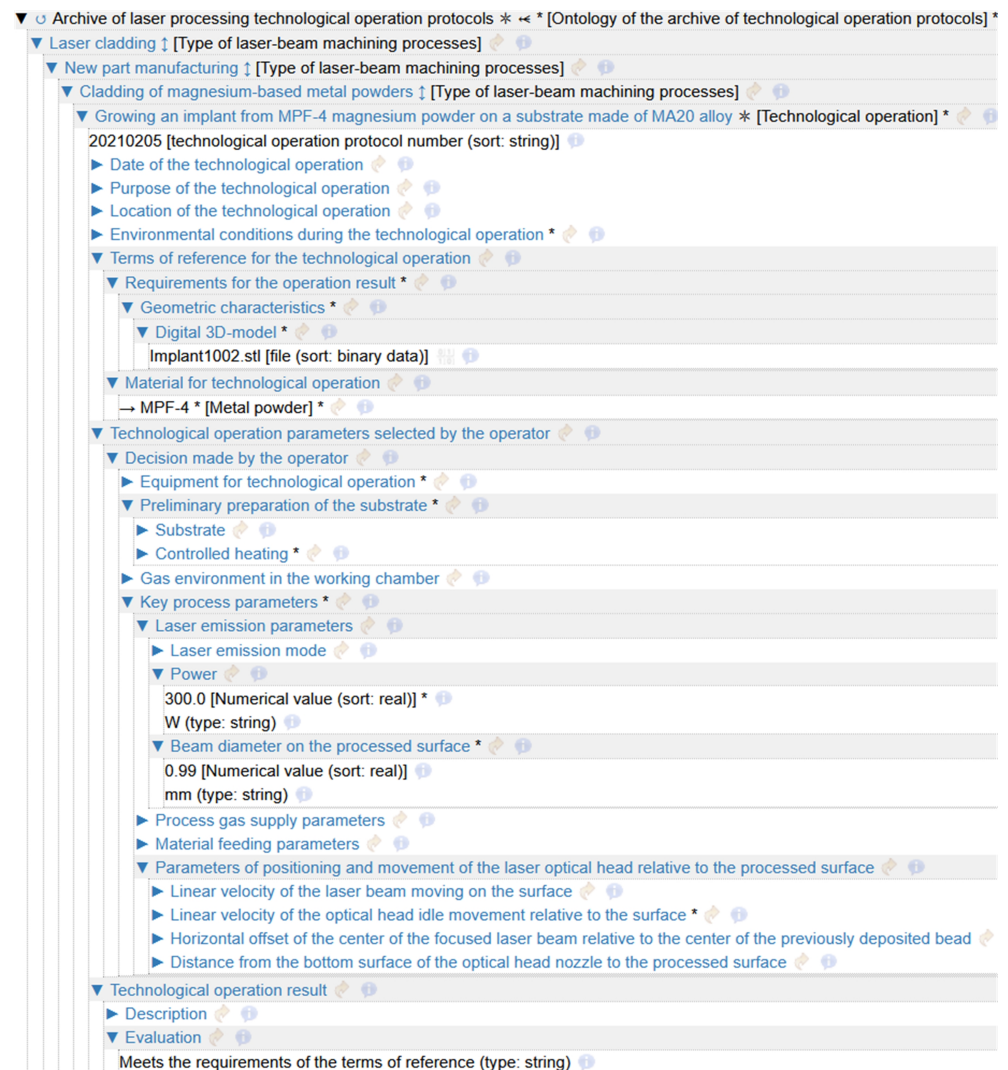


Figure 8. A fragment of the archive of laser processing TO protocols (a fragment of the “Growing an implant from MPF-4 magnesium powder on a substrate made of MA20 alloy” TO protocol).

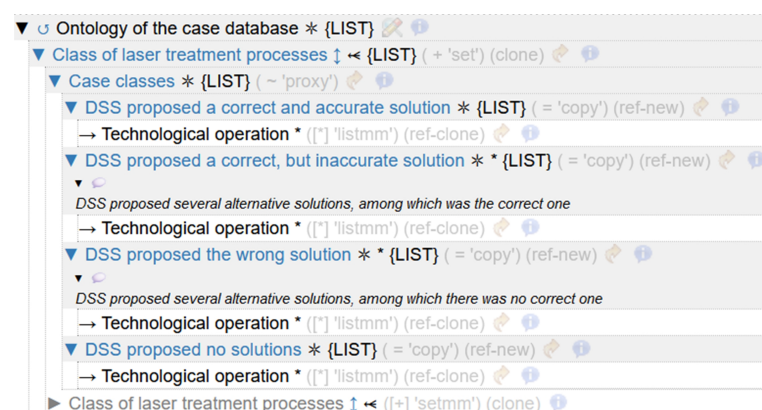


Figure 9. An ontology of the structured case database.

3.3. Ontology of the Knowledge Base

To form the knowledge (which is a basis for making decisions about practically suitable laser processing settings), the OM ensemble includes ontology of the knowledge base on the settings of laser processing modes. Figure 10 shows a fragment of this ontology, as well as a fragment of the knowledge base formed on its basis. The KB ontology reuses fragments of ontologies of reference databases on equipment and materials, as well as fragments of

the ontology of the archive of laser processing protocols. This structured approach enables consistency of knowledge representation.

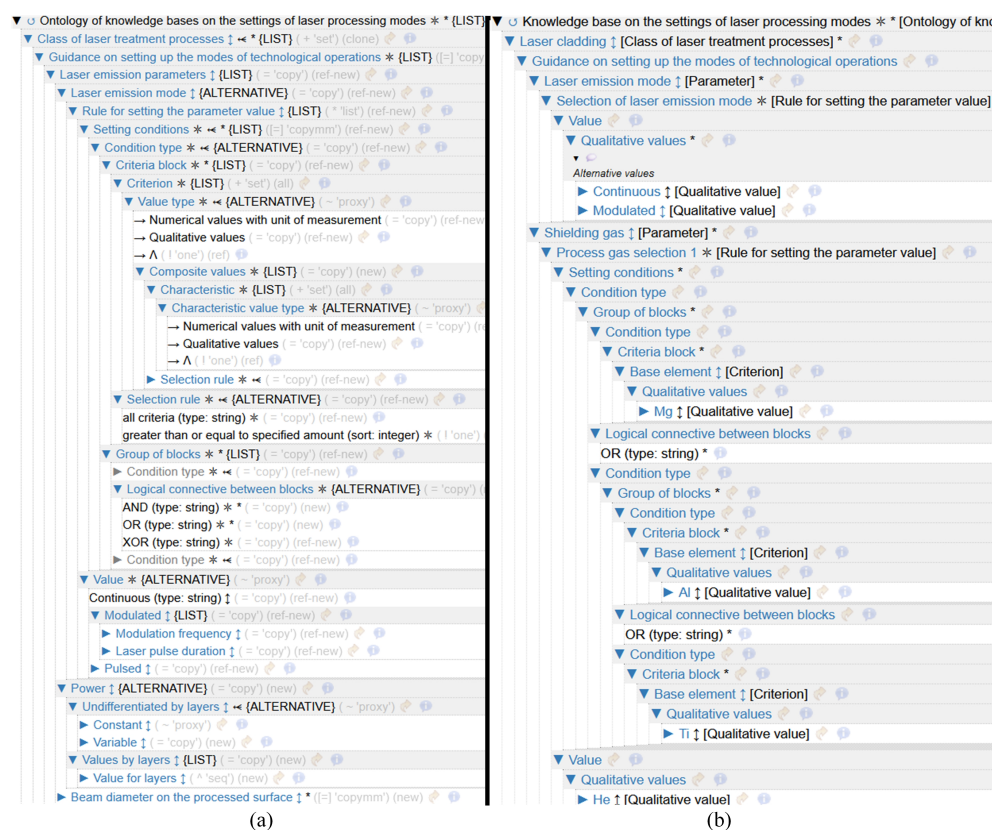


Figure 10. A fragment of the ontology of knowledge base on the settings of laser processing modes (a) and a fragment of the knowledge base (b) formed on its basis.

Analogously with the principle of the structural organization of the library (archive) of protocols, the knowledge (guidance) on setting up TO modes is hierarchically structured according to the types of materials processed and the types of tasks performed (part manufacturing, part restoration, and application of functional coating). Next, a hierarchical parameter set determining the mode of the TO is established. This hierarchical set strictly adheres to the hierarchical set of parameters specified in the ontology of the archive of laser processing protocols. The names of the parameters in the KB ontology are entirely consistent with that of the ontology of the archive of laser processing protocols, due to the establishment of terminological coherence (the second type of connection) between them.

Furthermore, for each key parameter of the laser processing, there are many rules which must be followed when setting its possible values. The antecedent of the production rules specifies the conditions that influence the setting of parameter values. Each condition is a list of criteria (factors) to be checked for matching with a certain selection rule. Either “all criteria” must match (i.e., strict conjunction) or “greater than or equal to specified amount” (meaning some threshold satisfaction). The criterion refers to any element from the laser processing TO protocol or from the reference databases of equipment and materials that influences the setting of the parameter value. The criterion values can be quantitative or qualitative, including those representing elements of reference databases on equipment and materials. Also, the value of the criterion may be composite: it may represent some characteristic or a set of characteristics (see subsection 3.1). Lists of criteria (criteria block) may be combined into groups of blocks, which are sets of blocks of criteria that can be logically combined using “AND”, “OR”, or “EXCLUSIVE OR” logical operators, thus forming hierarchical decision structures.

The consequence of production rules specifies the permissible values for the corresponding parameters. The parameter value belongs to the range of possible values of this parameter, defined in the ontology of the archive of laser processing protocols.

To clarify and validate solutions (obtained using AI methods), a methodology for integration with software systems for numerical modeling of thermodynamic processes has been developed and tested. The Wolfram Mathematica system is used as a representative implementation. The ontology of the mathematical model database, which is designed to store software implementations (as well as some meta-information about them) of numerical calculations of the parameter values of the modeled processes is presented in [28].

3.4. Implementation of the OM Ensemble

The IACPaaS (Intelligent Applications, Control and Platform as a Service) cloud platform (<https://iacpaas.dvo.ru>) is used to implement the OM ensemble. It is developed for the creation, control and remote use of intelligent cloud services and thematic knowledge portals [29]. The platform's technologies and tools provide support for full cycle developing graph knowledge bases, databases and data repositories, as well as DSS based on them as cloud services to which shared remote access can be organized. The toolkit takes into account the specifics of systems comprising KB (in particular, it is aimed at specialists of different types—domain experts, knowledge engineers, and software developers), so it allows us to simplify and automate the process of their development, as well as to reduce maintenance labor costs.

A portal of knowledge about LAM has been created and is constantly being enhanced on the platform. The portal is intended to identify and investigate technological modes suitable for practical application [28]. The developed OM ensemble as well as the databases and knowledge bases formed on its basis are part of the information content of this portal.

To construct the OM ensemble in the knowledge portal, the Digraph Editor platform tool is used. This tool serves as an interpreter of the specialized ontology (metainformation) description language. The specification of this language is stored in the fund (structured repository) of the IACPaaS platform. This editor streamlines the development of ontology models, providing their interactive construction and saving developers from having to study the syntax of the ontology description language.

The creation and maintenance of all databases and knowledge bases within the portal are carried out by domain experts using appropriate specialized ontology-driven editors. Each of these editors is derived from the Digraph Editor by connecting to it the appropriate ontology model (Figure 11).

All ontology-driven editors used for the creation and maintenance of the database and knowledge base of the knowledge portal have the following key features:

- The editing process is controlled by the underlying ontology model, and the user interface is generated basing on the ontology model;
- Any modifications to the ontology model trigger automatic adjustments to both the user interface and editing process (if required, all corresponding data and knowledge bases are also adjusted to ensure consistency with the modified ontology automatically).

Furthermore, along with the construction of databases, knowledge bases and ontologies in interactive mode, they can also be exported and imported in JSON format with the use of platform tools and API.

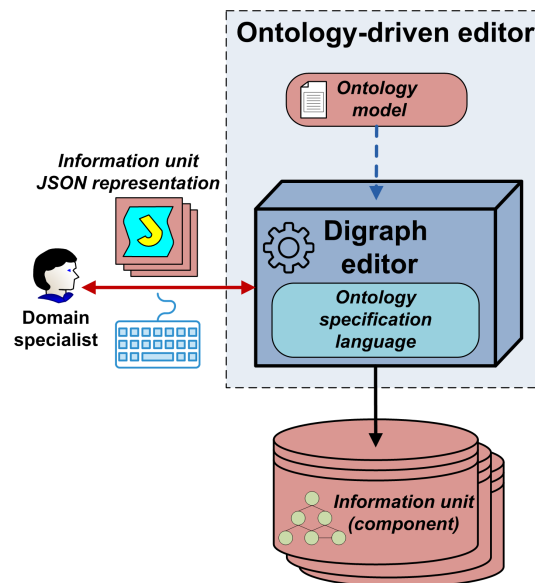


Figure 11. A scheme of construction of the information unit based on its ontology.

To support the internationalization of ontologies, databases and knowledge bases, special type information resources created within the knowledge portal are attached to them. These resources contain translations of ontology terms, as well as of terms of subject databases and knowledge bases. Currently, English translations are available. When viewing or editing an information component of the knowledge portal, its contents as well as the user interface of the corresponding ontology-driven editor are displayed in the language selected by the user on the IACPaaS platform website, in Russian or English.

4. Discussion and Future Work

The design and development of a DSS for LAM process engineers based on ontologies with a uniform declarative semantic representation allows us to achieve the following principal goals. Firstly, it is used to establish a conceptual framework (foundation) that creates the possibility of structuring, unifying, and standardizing specifications in the development of LAM models that can be seamlessly integrated with each other [30,31]. Secondly, it is used to facilitate cross-disciplinary collaboration by enabling the direct (without requiring any intermediaries) coordinated participation of various domain specialists in the development process [19], and not only software developers. Finally, applying an ontological two-level approach to the formation of semantic information is aimed at ensuring the following:

- The possibilities of creating databases and knowledge bases using conceptual representation and terminology native to domain specialists;
- The scalability and operational extensibility of the DSS without the involvement of software developers. The emergence of new types of materials (alloys), lasers, and other technological equipment, the expansion of the range of processed parts, and the expansion/modification of knowledge bases should not (in most cases) require modifications to the ontology-oriented algorithms (being developed for interpreting subject databases) that perform reasoning based on concepts and relations specified in ontologies (which remain consistent under such changes).

Thus, one of the principal requirements for DSS being developed will be fulfilled—its viability.

We have designed and implemented (as a software component of the portal of knowledge about LAM and, at the same time, it serves as a part of the intelligent DSS for process

engineers) an ontology-oriented case-based reasoning algorithm. A key feature of this algorithm is the use of a hybrid approach to case retrieval. Exactly, the similarity measure of cases (global similarity measure) is evaluated using domain-specific expert knowledge on similarity measure of terms of reference elements (local similarity measures), combined with the classical k-nearest neighbors (k-NN) method. Also, the algorithm uses information from the reference databases on equipment and materials.

At the same time, one of the key challenges within the proposed approach is the continued reliance on manual construction of the library of protocols, databases and knowledge bases, which remains a rather time-consuming process. Currently, they are developed only using the appropriate ontology-driven editors. To address this limitation, future work will explore natural language processing (NLP) techniques to automate text-to-knowledge graph transformations. Specifically, we aim to extract relevant information from poorly structured and unstructured texts and replenish appropriate information resources of the LAM knowledge portal. Here, we are going to consider and compare two main approaches: a rule-based approach and one based on large language models (LLM-based). In both cases, the result of the text analysis should be a JSON representation, the structure of which should correspond to the given ontology. For instance, when parsing texts of TO protocols, this is the ontology of the archive of laser processing protocols. Further, the obtained JSON representation can be imported, using the IACPaaS platform tools, into the corresponding information resource (e.g., Archive of laser processing TO protocols) of the LAM knowledge portal.

Another direction for further research is the creation of an OM for generating explanations for the recommendations issued by the DSS. This model should be seamlessly integrated into the set of existing ontological models. Furthermore, we need to develop a method for generating explanations based on this ontological model and the set of reference databases. The generated explanations must adhere to the four principles of explainable AI defined by the National Institute of Standards and Technology [32]. Together with the recommendations, these explanations can be used as a reasonable guide for helping process engineers to make decisions.

Additionally, we can consider yet another separate direction of the team's work. This work is aimed at enhancing the reusability of ontologies through refinement and generalization to other types of melting of metallic materials. In these processes, besides laser beam, other sources of concentrated flows of energy are employed, such as electric arc, plasma, and electron beam.

This study demonstrates that the developed ontologies and knowledge/data resources are sufficient for constructing various intelligent decision-support systems in LAM. The structured ontologies enable systematic data integration, while the IACPaaS platform provides a functional environment for hosting and utilizing these resources. Upon request, the authors can provide access to the knowledge portal, facilitating further research and industrial applications.

An important feature of the proposed solution is its interoperability: the ontologies and associated data can be exported in JSON format, allowing integration with external systems and services beyond the IACPaaS platform. This ensures flexibility in deployment and adaptation to different technological environments.

Beyond LAM, the developed knowledge base has broader applicability in fields requiring structured reference data on alloys, metal powders, gases, and related technical parameters. Potential use cases include materials science, metallurgy, and industrial gas applications. Moreover, the presented methodology can be replicated to create specialized knowledge portals in other domains where interconnected reference data and decision-support functionalities are needed. Future research may explore extending the ontology

framework to cover additional materials and processes or integrating AI-driven analytics for enhanced decision-making.

5. Conclusions

The paper presents the ensemble of OMs, which is the foundation for the intelligent DSS. The DSS is being developed to assist specialists engaged in setting up the modes of performing laser-based additive technological processes of the DED-LB category for manufacturing and processing of metal parts. We provide a justification and detailed description of the OM ensemble's architecture, including the roles of its components and connections between the components.

The IACPaaS cloud platform tools were used to implement the OM ensemble. All ontologies as well as databases and knowledge bases formed on their basis are part of the information content of the portal of knowledge about LAM, which was created and is being developed on this platform. The DSS is currently being developed as a part of the software ecosystem of the portal. In the long term, this portal, which allows us to accumulate and use knowledge and experience of different technologists, will make it possible to solve an important problem: namely, to reduce the number of preliminary experiments aimed at identifying practically suitable technological modes, as well as to reduce the qualification requirements for industrial users of technological equipment.

The findings confirm that the proposed ontology-based approach effectively supports the development of intelligent DSS in additive manufacturing. The modular design ensures scalability, while standardized export mechanisms (e.g., JSON) enable cross-platform compatibility. The solution's adaptability suggests promising applications in adjacent domains.

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