Ontology-Based Matchmaking for Manufacturing-as-a-Service

Joachim Lentes*. Michael Hertwig Frauke Schuseil*****

**Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany (Tel: +49 711 2285; e-mail: joachim.lentes@iao.fraunhofer.de).*

*** Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany (e-mail: michael.hertwig@iao.fraunhofer.de)*

**** Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany (e-mail: frauke.schuseil@iao.fraunhofer.de)*

Abstract: A promising approach to advance the resilience of industrial value creation is the transition of manufacturing networks and systems towards Manufacturing-as-a-Service (MaaS). In this paradigm, manufacturing services are offered and consumed to create products. To realize MaaS, platforms are needed to bring service providers and consumers based on a matchmaking together. An approach to ensure the future-proofness of suchlike platforms and the related matchmaking is to use semantic technologies, which enable the extension of models, on which platforms and matchmaking are based, over time.

Keywords: Ontology-Based Matchmaking, Manufacturing-as-a-Service, MaaS, Ontology-Based Systems, Manufacturing Network Planning, Resilient Manufacturing Systems

1 INTRODUCTION

Servitization is a phenomenon already identified 1988 by Vandermewe and Rada (1988), describing the shift from traditional production and sale of products to the additional provision of services, thereby creating added value for customers and at the same time benefits for manufacturers in financial, strategic and marketing terms (Paschou et al., 2020). An outcome of this development is the concept of Manufacturing as a Service (MaaS), which is changing the way companies access and use manufacturing capacity. Such measures can be useful, for example, in uncertain times, to avoid production breakdowns and thus maintain a resilient system or at least systems recovery. Digital technologies that enable the exchange of data and information for possible collaboration are key to a functioning Maas system, whereby ontologies can be used to model manufacturing systems (Kusiak, 2019). One of the challenges in designing a MaaS system is to find a suitable approach to align providers of manufacturing services with potential customers. This paper will present an ontology-based semantic matchmaking approach which allows for a human integration into the decision-making process by a three-step method. The prototypical realization will also be covered to show a strong emphasis on the practical application in companies willing to open their production setting to MaaS application scenarios.

2 RELATED WORK

In the context of MaaS, a systematic approach is needed to find providers of manufacturing services with excess capacity and bring them together with those seeking them. In general, such matchmaking can be roughly divided into two categories: *syntactic matchmaking*, which uses the structure or format of a task specification to match a requesting party with a providing party and decide which service providers should be recommended, and *semantic matchmaking*, which uses the meaning and information content of the request to match it with the meaning of the services offered. In case of the latter, service requesters and providers use an ontology to identify similarities between two services and determine a 'semantic distance' between services (Shu et al., 2007). An ontology represents knowledge of a specific application domain by means of a formal, explicit description (Gruber, 1995). Ontologies are useful for avoiding ambiguity and providing a widely accepted and consistent vocabulary. As a result of the agreement on terminology within a user community, this can also facilitate semantic interoperability between people and between people and computers (Yang et al., 2019).

As described above, semantic matchmaking approaches typically take semantic similarities into account when determining a match. The various approaches that can be found in literature usually differ according to the modelling language, the criteria considered when selecting matches and the type of match (exact, flexible, etc.). The majority of the identified initiatives utilise OWL (particularly OWL-DL) as the formalisation language. Other initiatives are directed towards the formalisation of a core/upper ontology, which could provide the fundamental building blocks necessary for the description of a diverse range of manufacturing services, including MSDL (Manufacturing Service Description Language) or MASON (Manufacturing's Semantics Ontology) (Landolfi et al., 2018).

Ameri and Dutta (2008) had already proposed a matchmaking algorithm in 2008 that brings together suppliers and customers based on their semantic similarities in terms of their production capabilities. Cai et al. (2011) is further advancing this approach to model distributed manufacturing services. Järvenpää et al. (2017) study capability matchmaking to support rapid configuration and re-configuration of production systems. Key components of the matchmaking system are the rules used to compute the combined capabilities of multiple cooperating resources and the matchmaking rules used to compare the product requirement description with the resource capabilities to find possible matches. Vennesland et al. (2019) present a semantic matching algorithm designed to enable an exchange of capacities.

The approach presented here introduces a semantic comparison of requirements for manufacturing services to be performed externally and the characteristics of services offered based on quantifiable or non-quantifiable values to facilitate matchmaking. It builds upon the works of Schuseil et al. (2024), who propose a three-step matchmaking approach intended for use in a MaaS scenario. A key consideration in the design was to involve the user in the decision-making process and also to give them the opportunity to specify preferences for the search. Many approaches aim at automated inferences, whereas this approach embraces human decision making by transparently rendering each step of the matchmaking process, thus enabling the user to retrace them. Hertwig et al. (Hertwig et al.) also base their work on this three-stage approach and show how a combination of matchmaking and scheduling can be successfully used in the entire value chain and to support further services. Furthermore, there are more conceptual solutions than practical implementations of service matchmaking in literature (Järvenpää et al., 2023), and the approach presented here in detail was particularly designed for successful practical application in companies.

3 MATCHMAKING METHOD

The challenge in the application of MaaS approaches is the identification and selection of suitable offers for the queries made. This requires a suitable approach to bring together a wide range of service offers with the service requests (Cheng et al., 2017). The market volume of the manufacturing industry in the European Union alone comprises 21 million enterprises (EuroStats, 2024). When transforming from a conventional manufacturing business to a service-orientated manufacturing business, a large number of potential services may have to be considered. This will pose a challenge for those responsible in the companies in their search for adequate *Manufacturing Services* (MS). A fit of the required function and offered service is necessary, whereby it is a multi-dimensional problem, because various elements have to be taken into account (Chen et al., 2024).

To achieve a match, the requirements from the request must match the characteristics of the offers. Since both sides do not naturally use the same words and phrases, both must be understood semantically and thus an agreement must be found (Cheng et al., 2018). Nevertheless, the decision should ultimately be made by humans. Central to a human-centered decision-making approach, this also supports transparency and understanding of the reasoning (Günther & Kasirzadeh, 2022). Consequently, the number of relevant services has to be reduced to a level that can be processed by humans (Oliveira et al., 2019).

Due to the objective to reduce the effective choices to be considered by the human, the matchmaking approach developed attempts to meet these requirements using a three-

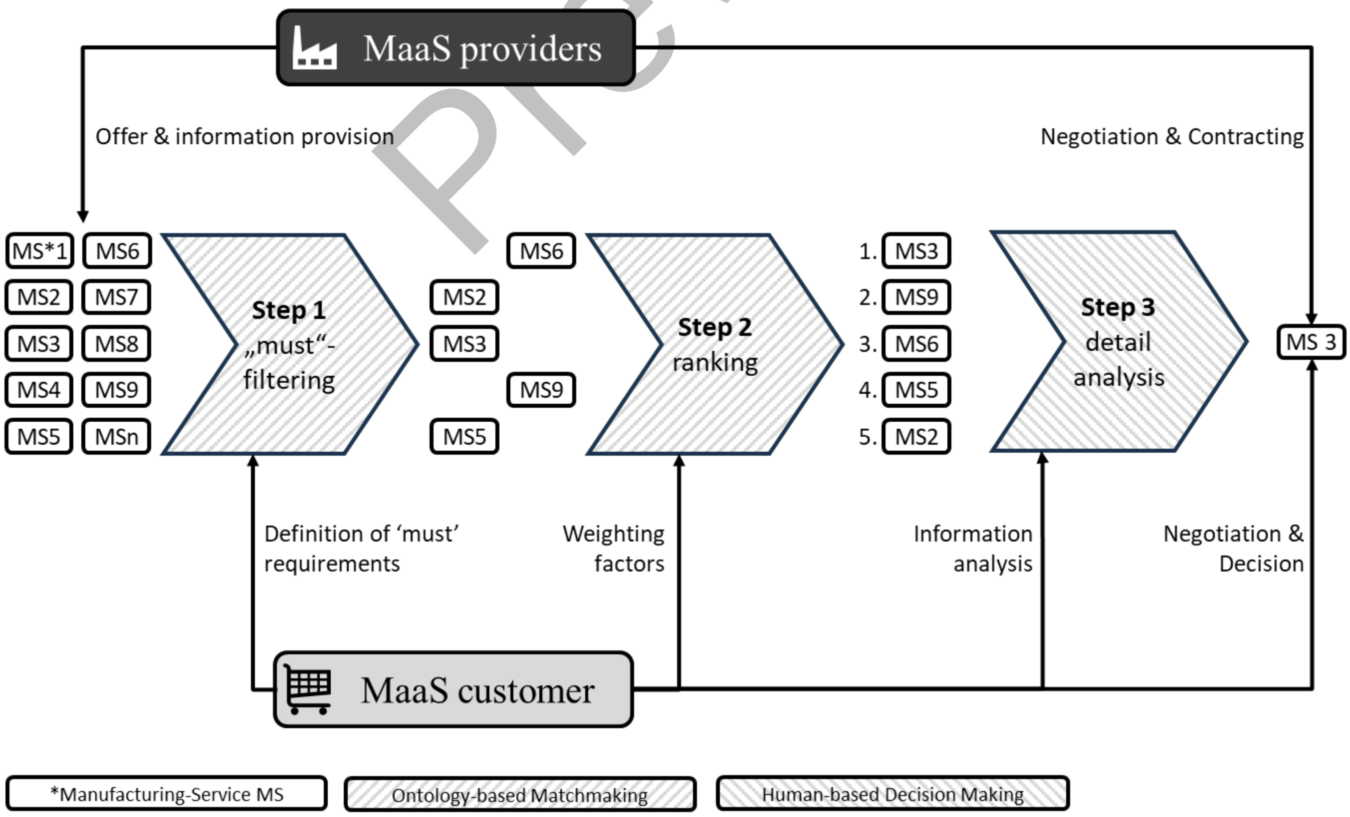

Figure 1: Three-step procedure for matchmaking

step evaluation process (Figure 1) (Schuseil et al., 2024). In the first step, the number of options is narrowed by assessing the degree of fulfillment. Only considering mandatory criteria, the examination will be binary, either passing or failing on the criteria.

The approach can take into account various possibilities. For status values, an existence test would be carried out (i.e. binary). The analysis of a range or tolerance field is a comparison of the given value with minimum and maximum parameters that represent the positive range. Failure to fulfill the conditions will result in the exclusion of the MS.

Based on the reduction achieved in the relevant manufacturing services, a second step is carried out. The objective of this step is to have a deeper analysis of the remaining MS. Since only compatible MS remain, further criteria are analyzed to create a ranking. The aim is to sort the MS based on their fit of further criteria. The criteria can thus be weighted by the searching user. Prioritization of some evaluation criteria results in a high degree of fulfillment being rated higher in this field than in others. A sorted list of MS is provided based on the individual preferences. The prioritized MS can now be manually reviewed and validated by the decision maker. Exploring specific details can help in advancing the decision (Sele & Chugunova, 2022).

Derived from the matchmaking approach proposed by Jävenpaa et. al (2018; 2017; 2023) the client-side request must be matched with the available capabilities. As described by Schuseil et. al (2024) the customer has requirements, since the supplier’s offer can be described by characteristics.

4 SEMANTIC SOLUTION APPROACH

In the following, our semantic solution approach to realize the presented matchmaking approach is introduced. After general considerations, the presentation follows the three steps of the matchmaking.

4.1 General Approach

To realize the matchmaking method, so to match consumer demands with service offerings, the concept of ‘requirement’ is introduced, whereby service demands, e.g. products to be produced, have a related set of requirements which bundle the requirements described on the service which is sought. These requirements may be quantified or unquantified, whereby quantified requirements may be minimum, maximum, or equality conditions with minimum and maximum may be inclusive or exclusive. On the other side, services are described by means of characteristics, which may be quantified or not, too. Consequently, for the matchmaking, services have to be evaluated concerning the requirements on the consumer side based on their characteristics. For this, requirement fulfilments for all requirements of a product-service-matching are determined, whereby the product-service-matching may be a possible matching, i.e. the requirements are fulfilled, or not. The resulting scheme of ontology classes is simplified illustrated in Figure 2.

The mapping of requirements to service characteristics, which is needed for the assessment of the fulfillments of the requirements, is done based on their relation to instances of the same ontology class, like greenhouse gas emissions as an example. Consequently, explicit relations of requirements to characteristics are unnecessary.

4.2 Step 1: Must filtering

The procedure for the must filtering as first step of the matchmaking is to loop over all available services and inside this to loop over all requirements, which are marked as must requirement, of the requirement set of the service consuming entity, e.g. of the product to be produced. For these mandatory requirements, a related requirement fulfillment is calculated, stored and assigned to an instance of “ProductServiceMatching” of a product-service-matching for the respective combination of the product to be produced and the service which is currently under consideration. The same approach is feasible for other consuming entities and reasons, respectively. After completion of the loop over the requirements set for a service, the product-service-matching is marked as “possible”, if all requirements are fulfilled and as “not possible” if at least one requirement is not fulfilled. Consequently, result of the first step of the matchmaking are product-service-matchings for all available services, marked based on the applicability of the related service for the consuming product.

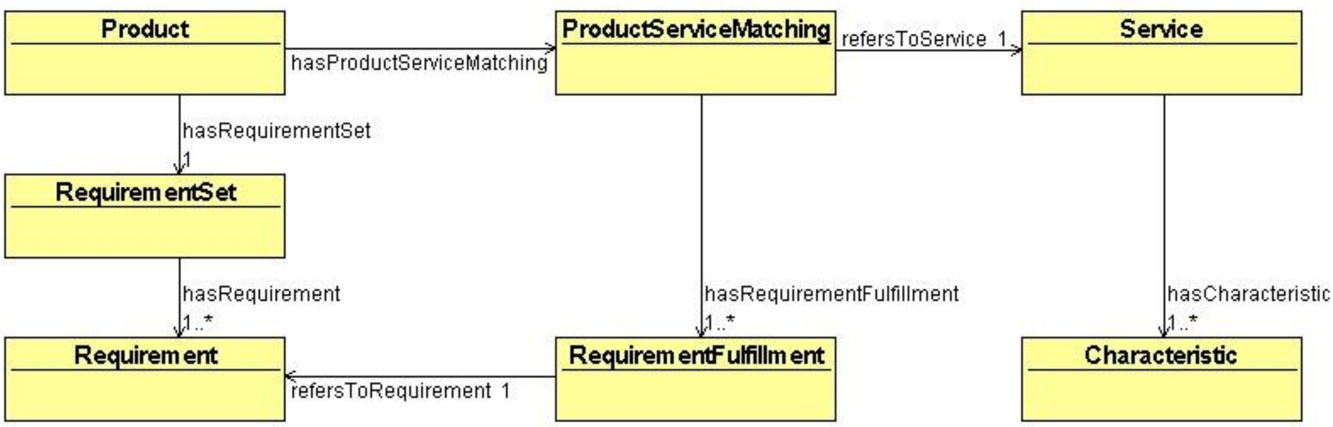

Figure 2: Product-Service-Matching Ontology Classes

4.3 Step 2: Ranking

In the second step of the matchmaking, numerical values for the product-service-matchings which are marked as possible are calculated. Based on these fulfillment degrees, a ranking of possible services can be provided to human decision makers.

For this, for each requirement fulfillment, its fulfillment proximity is multiplied with the weighting of the respective requirement. For unquantified requirements and equality-related quantified requirements, the fulfillment proximity is set to 1 as for the service filtering as part of the matchmaking, the requirements are fulfilled by the services. For quantified requirements, which are not equality-related, the fulfilment proximity corresponds to the absolute value of the difference between the values of the quantities of the requirement and of the characteristic under consideration of the unit of measurement. To take account of deviating orders of magnitude, two measures are taken. Firstly, the weightings w_j of the j requirements are defined on identical scales and normalized subsequently. Secondly, the normalized weightings $w_{j,n}$ are scaled to compensate the order of magnitude of the quantity of the characteristic $w_{j,n,s}$. Possible product-service-matchings are then provided in a ranking based on their matching degree m_i as the sum of the weighted fulfillment degrees $f_{i,j}$ of the requirements fulfillments of the product-service-matching to the users as human decision makers.

4.4 Step 3: Selection of the most appropriate service

The third step of the matchmaking process, the selection of the most appropriate service based on a detailed analysis, is not supported methodically by semantics, but human decision-makers may analyze the services with their characteristics and product-service-matchings with the related fulfillment degrees. For this, the semantic relations between the ontology classes of the respective instances for the considered services and their characteristics may be investigated.

In future, this selection process may be supported by an according decision support system.

5 PROTOTYPICAL REALISATION

The realization was done based on the principal design decision, to be able to build software to process ontologies in the Web Ontology Language (OWL) but to publish the ontology as semantic data model to the used software platform in LinkML. This decision resulted in the requirement for ontology development to use the intersection of modelling possibilities of both languages, OWL and LinkML. To manage the complexity of ontology development, we propose a modular design approach, allowing for incremental updates and integration of new domain-specific ontologies. Automated tools for ontology evolution will be explored to ensure the system remains adaptable to changing manufacturing landscapes.

Some further, more detailed design decisions for ontology development, partly resulting from the above basic design decision were:

- The overall ontology contains definitions for the semantic data model, i.e. ontology classes with properties, including relations, as well as instances for the actual data about services and requirements for their selection.
- The usage of standard ontologies as the ones of the Industrial Ontology Foundry (IOF) (OAGi, 2024) and Quantities, Units, dimensions, and Datatypes (QUDT) (*FAIRsharing | QUDT*, 2024) by the National Aeronautics and Space Administration (NASA) as far as possible, or appropriate, respectively, to support interoperability, and re-usage.
- Sub-classes of ontology classes are disjunct but not necessarily complete – since we are aiming for a model that is as detailed as necessary to solve our use case, but as small as possible to reduce complexity in the resulting model and efforts for its development.
- The ontology and the accompanying software modules are as loosely coupled as possible but will be semantically linked to some extend were absolutely needed (see below).

The prototypical realization of the matchmaking is based on the assumption that the people working with the matchmaking systems need not be directly familiar with semantic technologies. Staff entering services and their characteristics into the matchmaking system require just as little knowledge of such technologies as staff searching for suitable services to manufacture their products. So, semantic approaches and technologies are hidden for the users, as highlighted by Lentes (2022) for the case of assembly system design. Based on this basic design decision, the matchmaking system is designed to be a software system, which is in practice operated in containers. The software system is divided in three essential components: (1) a user interface for the work with services and their characteristics, i.e. to insert and modify related data, (2) a matchmaking component, which performs the first two matchmaking steps, and (3) a user interface for service consumers which enables them to insert data about requirements and to select the most appropriate service for their demand. The user interfaces are implemented as web interfaces for usage with internet browsers.

To make the user interfaces usable despite advancements of the ontology classes as well as of their attributes and relations, for the requirements and services for the matchmaking, the interfaces are written to configure themselves based on the respective state of the ontology. So, user interfaces for the work with instances of ontology classes and for tables (lists) of instances of ontology classes are provided in an ontology class-agnostic way. This can be realized as the ontology not only contains the data for the matchmaking, but the descriptions of the data, i.e. the ontology definition, too. An example realization of an instance editor in front of a table editor implemented with the software frameworks Apache Jena (*Apache Jena - Home*, 2024) and Vaadin (*Vaadin: Build Modern Web Apps Using Java Full-Stack Platform*, 2024) is shown in Figure 3.

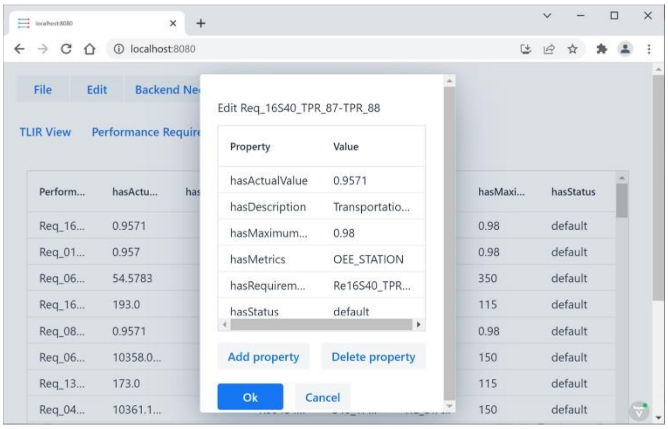

Figure 3: Screenshot of ontology agnostic editors

With the universal user interface components for ontology instances and tables of ontology instances, the needed user interfaces for the management of data about services as well as for working with requirements are realized.

For the matchmaking, a dedicated containerized software component is used. The component is realized by using Apache Jena for the ontology processing and models the matchmaking proceeding as described in chapter 4 of this contribution. Therefore, despite of the instance and table editor, which work with instances of all ontology classes if they're defined in OWL, the matchmaking component is semantically coupled to the ontology to be able to process requirements in accordance with the conditions they represent, e.g. a minimum or maximum condition, inclusive or exclusive the defined boundary condition etc.

User feedback from initial deployments will be gathered to refine the user interface and ensure the system aligns with the decision-making processes of industry professionals. Case studies will be conducted to validate the system's usability and effectiveness in real-world scenarios.

6 CONCLUSIONS

In conclusion, the ontology-based matchmaking approach for Manufacturing-as-a-Service (MaaS) presented in this paper offers a significant advancement in aligning manufacturing service providers with potential consumers. By leveraging semantic technologies, this approach not only enhances the resilience and adaptability of manufacturing networks but also facilitates human-centered decision-making processes. The prototypical realization demonstrates the practical applicability of the proposed method, paving the way for its integration into real-world manufacturing scenarios. Future work could explore the development of decision support systems to further assist human decision-makers in selecting the most appropriate services. Additionally, expanding the ontology to include more diverse manufacturing domains could enhance the versatility and robustness of the matchmaking process. This research contributes to the ongoing evolution of MaaS, promising a more resilient and efficient manufacturing ecosystem.

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