

Title: An Approach and Decision Support Tool for Forming Industry 4.0 Supply Chain Collaborations

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An Approach and Decision Support Tool for Forming Industry 4.0 Supply Chain Collaborations

Abstract

5 Industry 4.0 technologies, process digitalisation and automation can be applied to
support the formation of supply chain collaborations in manufacturing. Underpinned
by information and communication technologies, collaborations of independent
companies can dynamically pool production capacities and capabilities to jointly react
10 to new business opportunities. These collaborations may involve a wide range of
enterprises with different sizes and scope that individually would not be able to tender
for such new business opportunities. To form these collaborative teams, assistive
processes and technologies can underpin the effort towards exploring the tender
requirements, unbundling the tender into smaller tasks and finding a suitable supplier
15 for each task. In this paper, we present an approach and a tool to support decision
making concerning forming supply chain collaborations in Industry 4.0. The approach
proposed is unique in integrating industry domain ontologies, assistive human-
computer interaction tools and multi-criteria decision support techniques to form team
compositions speeding-up the collaboration process whilst maximising the chances of
20 forming a viable team to fulfil the tender requirements. We also show evaluation
results involving stakeholders from the supply chain function pointing to the
effectiveness of the proposed solution, available as a demo online¹.

Keywords: digitalisation, supply networks, supply chain collaboration, Industry 4.0,
decision support systems.

¹ <http://130.88.97.225:4200> (username: TDMS@uniman.eu; password: uniman).

25 **1. Introduction**

There is a growing body of literature recognising the vital role of enterprise collaborations in manufacturing supply chains [1–7] where autonomous organisations combine capabilities and pool manufacturing capacities. In practice, traditional approaches for organisations to come together include face-to-face networking, peer
30 referencing, and reliance on companies known from past collaborations [8]. Traditional approaches are time and cost consuming, often lack agility, and support a collaboration model where organisations outside the mainstream networks are often excluded from tender participation [1,8,9].

Enterprise collaborations in the manufacturing supply chain can benefit from
35 Industry 4.0 technologies and application models [10–15] to increase its effectiveness [16]. The Industry 4.0 paradigm is changing the companies’ focus towards organising production processes around the principles of interoperability between physical and cyber systems, decentralisation, real-time data analytics, service orientation, and modularity — which shall enable digital integration across the entire value chain, self-
40 adaptation of production systems, and agile response to customer demand [17,18]. Yet as large companies have already embraced the concept of Industry 4.0, its adoption by small and medium-sized enterprises (SMEs) is facing several challenges, such as resource constraints and lack of awareness of advanced technologies [17,19]. Still, SMEs are highly embedded in today’s multi-tier supply chains, representing a vast
45 majority of enterprises and generating a sizeable fraction of the total value added — estimated to be, for example, as large as 56.4% in the non-financial business sector of the European Union (EU) in 2018 [17,20]. Considering that many SMEs are tied to their existing supply-chain relationships, finding and integrating suitable suppliers into highly fragmented supply chains becomes a challenge for Original Equipment
50 Manufacturers (OEMs) when the customer demand for increasingly customised products needs an agile response in line with Industry 4.0 requirements [17]. Proper tools for the dynamic formation of supply chain collaborations can help overcome this challenge and enhance the value proposition of Industry 4.0 by broadening supply opportunities for OEMs as well as market opportunities for SME suppliers. Effective

55 collaborations in the context of Industry 4.0 involve forming supply networks (teams)
faster, selecting members from a wide pool of suppliers, delivering high-quality
production outcomes, higher levels of trust between collaborating members, and the
ability to scale and adapt to highly-dynamic production requirements, product variety,
customisation, and stringent manufacturing schedules [21,22].

60 Earlier work on decision support for team formation has been developed
considering partner selection based on both objective and subjective criteria [23–25].
However, these advances lack approaches targeting agile team formation — avoiding
lengthy manual pre-processing routines such as selection of candidate partners and
exchange of offline information, which precede the invitation to join a collaboration
65 [26,27]. Our contribution to addressing this gap involves the conceptualisation,
design, implementation and evaluation of an approach that, in contrast to extant
approaches facilitating a single supplier selection only, allows for bringing together
multiple companies aiming to collaborate as a supply network. The tool automating
the proposed approach assists users in their decision process of selecting potential
70 partners for joining a collaboration by proposing compositions of suitable partners —
that may belong to different levels in the supply chain — for fulfilling the elements of
a call-for-tenders (CfT). The approach and tool currently focus on the aviation and
automotive industries, which are at the forefront of Industry 4.0 uptake [28,29].

Figure 1 overviews our team formation approach and tool for supply chain collaboration in Industry 4.0. The decision support tool requires demand-side information, comprising the CFT requirements (e.g. capabilities required, product requested, certifications needed), and supply-side information (e.g. capabilities offered, certifications possessed). The approach proposed uses ontology-based knowledge representation techniques [30] beyond the scope of vocabularies [31] in the process of conceptualising and encoding supply and demand information (e.g. ontological descriptions of products and supplier attributes). We apply ontological constructs for specifying the domain of forming Industry 4.0 supply chain collaborations, representing concepts such as teams, goals, products, decompositions, characteristics, capabilities, etc., and utilise the ontology-encoded knowledge to underpin algorithmic reasoning procedures, such as recursive search for general/specific classes in ontology hierarchies and retrieval of instances matching given criteria. The theoretical and practical gaps addressed by our work are further explored in Section 2.

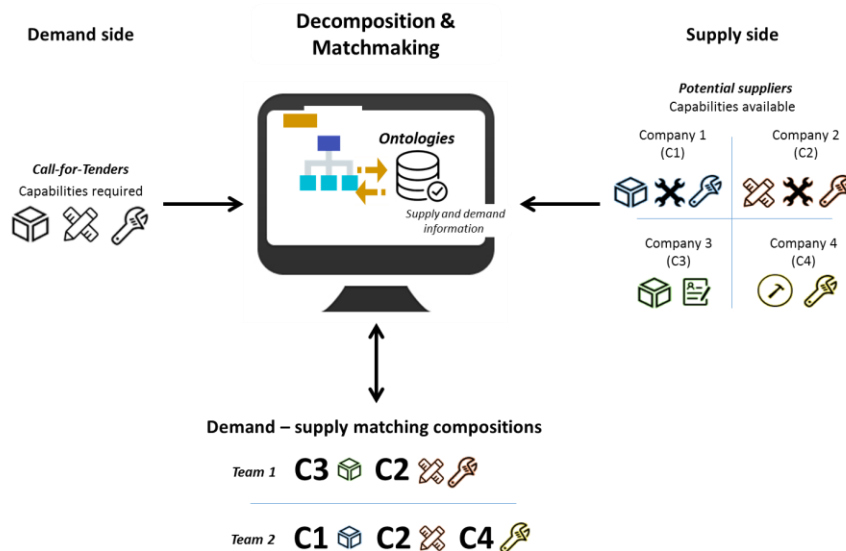


Figure 1. Tender Decomposition and Matchmaking tool and approach.

Section 2 of this paper outlines the requirements for forming collaborations in
90 Industry 4.0 and positions our work in the literature. Section 3 discusses the research
method. Section 4 presents the design and implementation of the team formation
approach and tool for supply chain collaboration in Industry 4.0. Section 5 discusses
the evaluation of the approach and tool. Section 6 presents key findings and
managerial implications. Section 7 provides a summary of the work and outlines
95 future research directions.

2. Background and Literature Review

Existing research related to Industry 4.0 technologies supporting supply chain
collaboration largely focuses on the development of models to support the
identification of suitable business partners to form a collaborative network [26,32–
100 40]. In that respect, one of the topics widely researched is the *supplier selection*
towards finding a one-to-one match (i.e. buyer–supplier), where the main body of
work aims at identifying the most suitable supplier for a given business or product and
the most effective criteria to evaluate the candidate suppliers [27,38,41–43] —
commonly ranked using different multi-criteria techniques (e.g. multi-attribute
105 decision making (MCDM), mathematical programming (MP), and Artificial
Intelligence (AI) oriented ones [38,43,44]). Table 1 presents a comparative analysis of
literature describing approaches for forming supply chain collaborations [26,27,32–
34,37,39,45].

We observe that the supplier selection body of knowledge does not fully match the
110 scope of our collaborative network problem. Although we consider multi-criteria
decisions, we propose multiple compositions of teams rather than a single-supplier
single-team composition or multiple suppliers of the same product, as the majority of
the existing solutions do; instead, our approach is designed to look for a combination
of suppliers of different parts that may belong to different levels in the supply chain
115 and, in a multi-criteria approach, we evaluate how they fit together before a
collaboration is formalised. Table 1 shows how the extant work, to the best of our
knowledge, does not fully cover the functionalities/capabilities of the approach we

propose, with a noticeable gap in algorithms and approaches to multiple team compositions based on a multi-level decomposition of tender requirements. The approach proposed in this paper is particularly suitable in the context of the Industry 4.0 collaborative network formation problem involving interoperability, decentralisation, and modularity issues [17]. It further seeks to attain agility, accuracy, and efficiency gains in the supply chain [10] by shortening the team formation time and enabling higher resource efficiency by allowing suppliers to utilise their available resources better, thus providing a solution which is both flexible to multiple players and enables integration into a dynamic value-creation network [46].

We extend the body of knowledge by proposing an agile approach for matching supply with demand, where automated decomposition of tender requirements enables widening of the team composition solution space to fulfil the demand. Further, our approach provides ontological support for collaborative network formation across industry domains. Previous research predominantly focuses on a single vertical industry domain without developing extensible collaboration ontologies [33] (Table 1). Our collaboration ontology builds on previous work on enterprise ontologies [34] proposing extensions that evolve the original ontological models from manual decomposition and single team composition [34] to support automatic decomposition and multiple team composition, as well as validating the ontological models and associated approach/tool with industrial stakeholders across two vertical domains (Section 3).

Moreover, when compared to other solutions proposed in the literature, the decision support tool underpinning our approach does not advise the user about how to bargain and induce others to collaborate; its utility is in helping the user to explore the supply market, i.e. all possible team compositions, and to re-evaluate these during the team formation process. Our work provides decision support through formalising selection criteria elicited from industry stakeholders and applying these to evaluate each prospective collaboration of suppliers as a whole.

Table 1. Comparative analysis of team formation approaches.

Approach [38]				Approach functionalities/capabilities								Validation				Tool	
Study	Multi-attribute decision making	Mathematical programming	Artificial Intelligence	Multiple team composition	Single team composition	Supplier selection	Agent-based negotiation	Manual decomposition of requirements	Multi-level decomposition of requirements	Agile selection of criteria	Automatic	Technical validation (test cases)	Numerical illustrative example	Empirical illustrative example	End-user feedback	End-user tool available	Ontology enabled
[27]	x			x		x						x					
[26]	x						x						x				
[32]	x						x										
[33]		x			x	x	x								x		x
[34]		x			x	x		x							x		x
[37]	x						x			x			x				
[39]			x		x	x						x					
[45]	x						x			x		x					
This paper	x			x				x	x		x	x			x	x	x

3. Research Methodology

Figure 2 depicts the research process adopted in this study. The study was guided
150 by the Design Science Research (DSR) methodology [47] to elicit requirements,
frame the design problem, and identify measures and constructs relevant to solution
artefact design. Table 2 summarises how we applied the DSR concepts and guidelines
[47]. We also verified and validated our results. For this, we used verification tests
using synthetic data reflecting usage scenarios, and we surveyed the view of experts
155 in the manufacturing area and validated the proposed artefact for its usage.

As part of the stage to explore the problem, we held separate sessions in the form
of semi-structured interviews and workshops where we collected insights from the
Director and Technical Director of an automotive cluster, and from five suppliers —
members of an aviation manufacturing association, concerning their vision towards
160 Industry 4.0 from the collaboration point of view. We also benefited from access to
SMEs and large OEMs involved in the EU-funded DIGICOR project, a business-to-
business (B2B) Industry 4.0 platform, from which we collected feedback and opinions
to shape the decision support tool functionalities [48]. Table 3 presents a description
of the activities executed and summarises the main outcomes.

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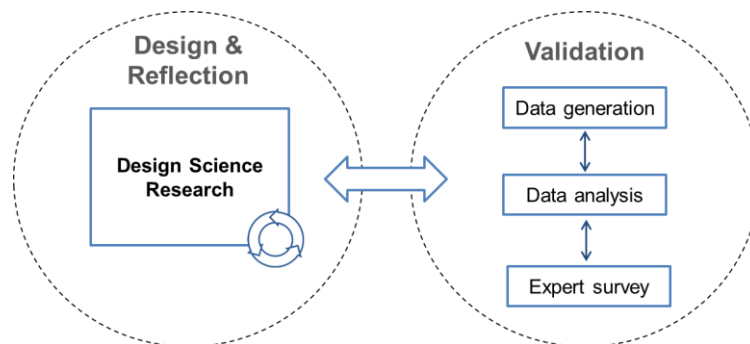


Figure 2. Research process utilised in the study.

Table 2. *Design Science guidelines [47] and their application in the study.*

<i>Guideline</i>	<i>How it was applied</i>
Design as an artefact	Research outcome is ‘a construct, a model, a method, or an instantiation’ [47]. In this stage, the artefact is a tool for selecting business partners to form a team.
Problem relevance	The artefact is to aid the team formation decision process, which is a relevant business phenomenon in the context of Industry 4.0 (Section 2).
Design evaluation	Rigorous evaluation methods shall be used when demonstrating the utility of the artefact to solve the given problem [47]. For this, quality measures were utilised when testing the usability and functionalities of the artefact (Section 5.1).
Research contributions	The research must demonstrate verifiable benefits linked to the subject area in which the designed artefacts belong. End-user testing was executed to analyse the benefits of the artefacts from their perspective (Section 5.2).
Research rigour	Rigorous methods shall be used during the whole research, from the design to implementation, as well as its evaluation and presentation of results. Standards for the design of software artefacts were utilised, such as UML, agile, and exploratory methods.
Design as a search process	Research iterations were made to reach an effective artefact with the highest quality. This includes the involvement of end-users and peer-review feedback, requirements elicitation, system development, and feedback from end-users.
Communication of research	Information Technology and managerial audiences must be involved in the presentation of the results. For this, the artefact has been presented in research and industry events [48].

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Table 3. *Overview of the activities in the exploratory stage.*

<i>Description</i>	<i>Objective</i>	<i>Method</i>	<i>Date, Stakeholders</i>	<i>Outcome/Insights</i>
Assessment of digital marketplace support for Industry 4.0 capabilities [49]	Gain a general overview of state-of-the-art	Survey and Gap Analysis	April 2017, secondary research (no stakeholders)	Team formation is not yet widely supported in the most popular B2B digital platforms.
Discussion of findings of the Survey and Gap Analysis	Gain insights and initial perspectives from end-users	Interview	June 2017, Welsh Automotive Cluster (2 respondents)	Results from the gap analysis were confirmed and aligned with the end-users’ perspective.
Presentation of the initial concept and designs	Gather feedback from stakeholders of manufacturing supply chains	Workshop	October 2017, European Aerospace corporation, EU Project members (4 respondents)	Users want to reduce time and effort for forming teams and diminish the risks involved. Users also want to maintain control over their final decisions.
Presentation and feedback collection of the initial low-fidelity design	Obtain initial comments regarding the idea of using a tool	Workshop	October 2017, German Aviation Cluster (5 respondents)	End-users value the benefits of the proposed tool; however, they have concerns about trust and information security.

3.1 Verification and Validation of Research Artefacts

We executed a technical experiment to verify the correctness of implementation based on the conceptual model proposed for the artefact. Firstly, we generated synthetic data reflecting mainstream usage scenarios elicited from end-users, where real company data is protected by privacy requirements. The created data represents five hypothetical CfTs and 14 hypothetical companies. Given that the difference between the synthetic data and real data lies only in the content, e.g. a real-world company name of an existing company, we can perform an accurate, domain-relevant and privacy-preserving verification of our proposed approach based on the specified data model. Secondly, we executed the artefact (Section 4.2) using the synthetic data and checked the team compositions for their suitability to fulfil the CfT. We sought to verify the approach's validity and confirm that the implemented solution works as designed. Section 5 shows the results of one of the test cases. [50] shows the complete data set including all test cases. Results for all five CfTs' team compositions are available at <http://130.88.97.225:4200> (username: TDMS@uniman.eu; password: uniman).

We also developed a validation study using a survey to capture experts' views and feedback on the proposed approach and to confirm that the proposed artefact provides a reasonable picture of a real-world system to these experts, i.e. to the prospective users of such a system. We collected 12 responses in September 2018 in the *Connected Smart Factories* workshop at the 9th International Conference on Intelligent Systems in Madeira, Portugal using a questionnaire (Appendix A1). Two additional responses were collected in October 2018 during a demonstration of the artefact prototype at the DIGICOR project workshop in Hamburg, Germany. Together, a total of 14 responses were collected.

Respondents were asked questions relating to what purposes the proposed artefact would serve in their company and were provided with several options. The questions in the survey focused on establishing the utility and the ability of the functionalities and purposes of the proposed artefact to produce a desired result in relation to collaborative team formation in supply chains. The study also offered an opportunity for obtaining information from experts that would help to refine the artefact.

205 The validation study constitutes primarily a formative evaluation activity in design
science research, producing (1) interpretations of expectations concerning the utility
and efficacy of the artefact; and (2) a foundation for confirming the appropriateness of
210 decisions that led to the artefact design. On both counts, the evaluation described
reached its overall objective. Further evaluation could examine the artefact deployed
in an organisational operational context (a summative evaluation as stated in [51]);
however, a summative evaluation requires a longer time frame and is beyond the
scope of this paper. Section 5 presents the results of the verification and validation
studies.

4. Team Formation Approach and Decision Support Tool

4.1 Team Formation Approach

215 Informed by the analysis of the stakeholders' requirements and feedback, and the
collaborative supply chain context about the team formation process, we propose an
approach to support team formation in Industry 4.0 collaborative supply chains in
response to a given CfT (demand-side in Figure 1). The proposed approach
encompasses the following process steps:

220 **Step 1: Retrieving CfT Requirements.** The process starts by identifying the CfT
specification of the required product or service, called the *target item* (e.g. aircraft
lavatory), and the required set of *goals* for it. Possible goals are 'Plan & Manage',
'Design & Develop', 'Integrate Design', 'Source', 'Make', 'Assemble', and 'Deliver',
(defined following the Supply Chain Operations Reference (SCOR) and Design Chain
Operations Reference (DCOR) models [52,53]). The CfT further specifies
225 characteristics required by its issuer (e.g. certifications required, minimum annual
turnover, and technological capabilities). [54] details such characteristics. We note
that the list of possible requirements may depend on the specific industry application;
the current implementation of the approach is based on a use case in the aerospace
industry [48].

230 **Step 2: Tender Decomposition.** In the next step, the process *decomposes* the CfT
by identifying the subordinate items (parts, materials and services) needed to produce
the target item (e.g. electric and water systems) and deriving the goals to be associated
with them. For example, if the target item has a ‘Make’ goal, then decomposing it into
parts assigns goals ‘Make’ and ‘Deliver’ to each part, while the target goal ‘Make’ is
235 being replaced with ‘Assemble’ and ‘Plan & Manage’. A similar rule applies to the
target goal ‘Design & Develop’. Decomposition is then being recursively executed
further — using the information about the product structure from an ontology, thus
producing a variety of different *tender decompositions* — each representing a list of
specific items and their associated goals. An item–goal pair is called a *task*.

240 **Step 3: Matchmaking.** The tasks contained in each of the tender decompositions
are then matched to the pool of available companies (supply-side in Figure 1) —
whose specific capabilities and other characteristics are stored in the ontology. [54]
provides a detailed list of the available company characteristics. This step, called
matchmaking, thus attempts to find suitable team members for each generated tender
245 decomposition and distribute tasks between them according to their capabilities.
Matchmaking potentially gives a variety of prospective teams for each tender
decomposition. It is further guided by *grouping criteria*, according to which
prospective team members need to jointly meet certain CfT requirements. From the
CfT requirements [54], the following ones have been identified by our study (Section
250 3) as representing grouping criteria: minimum annual turnover, minimum number of
employees, and required certification.

Step 4: Evaluation. All team compositions are *evaluated* towards their *fit* — or
overall suitability for the CfT. This is accomplished by applying a set of evaluation
criteria to the team members’ characteristics. From the company characteristics, the
255 following have been identified as subject to evaluation: certification, preferred
contract types, target regions, location of manufacturing departments, and capabilities
in terms of ATA, materials, technology, and specialty. Degree of coverage of the
respective CfT requirements by the team members’ characteristics is being averaged
to produce the overall team fit. Additionally, the team size and geographical
260 dispersion of its members’ manufacturing locations are taken into account in the way
that bigger teams with more dispersed manufacturing facilities have, *ceteris paribus*, a

weaker fit due to coordination challenges. The final result is a list of teams, arranged in the order of the decreasing team fit, where each team comprises one or more companies associated with the tasks that they are expected to perform.

265 The team formation approach described above can also be executed in the ‘soft constraint’ mode, in which the team compositions failing to meet grouping criteria of the Matchmaking step are still included in the result, yet with a reduced fit score. The team formation approach is fully automated by a decision support tool coined as the Tender Decomposition and Matchmaking Service (TDMS). Apart from the automated
270 mode, TDMS also offers manual execution of Tender Decomposition and Matchmaking steps to permit the user to build up the team incrementally. For reasons of space and focus, formal algorithmic specifications are provided elsewhere [55], however, we do present detailed steps of user interaction with the tool in Section 4.4.

275 *4.2 Technical Implementation of the TDMS*

The TDMS tool aids end-users’ decision process of selecting a team to jointly respond to a CFT. To design and implement TDMS, we followed a microservices architectural style [56,57], utilised the Angular 4 Java web-based framework [58], and R programming language (version 3.6) for the back-end data analysis and decision
280 support algorithms. TDMS was designed to be a secure self-contained microservice that can work on its own or integrated into third-party (e.g. B2B) platforms. TDMS also adopts technical designs based on RESTful and an event-driven architecture [59–61]. A TDMS Application Programming Interface (API) is provided to support platforms lacking event-driven capabilities. Figure 3 depicts the TDMS architecture,
285 illustrating its internal components and types of events. Appendix A2 presents a detailed account of the events and REST calls. The latter are also documented in [62].

As part of the tool’s back-end, we implemented the TDMS domain ontology [63] to support data interoperability between TDMS and integrated third-party platforms such as DIGICOR (Section 3). Figure 4 presents an overview of the TDMS ontology
290 in terms of a UML class diagram [64]; we provide further details in the remainder of this section.

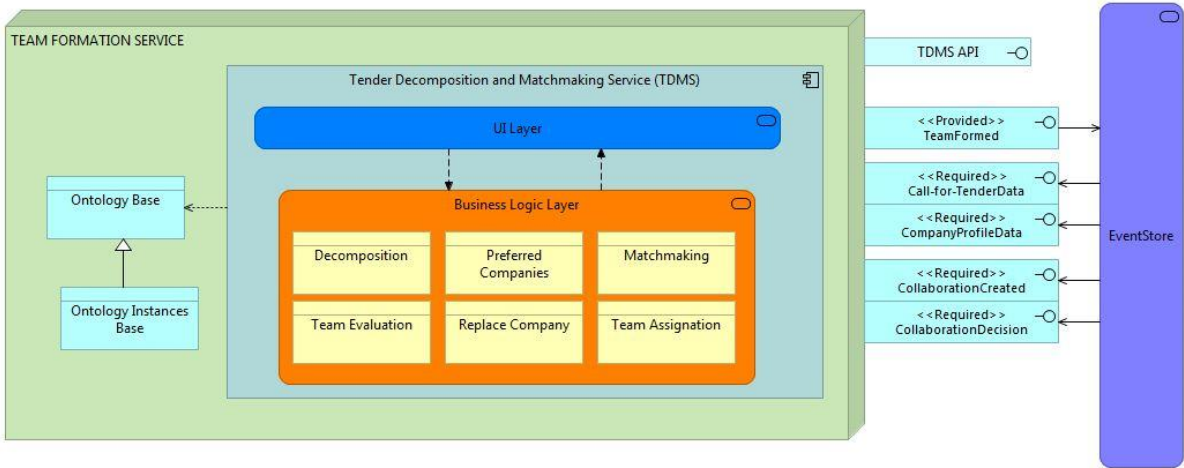


Figure 3. TDMS architecture depicting the events consumed ('required') and produced ('provided') for the communication with other services.

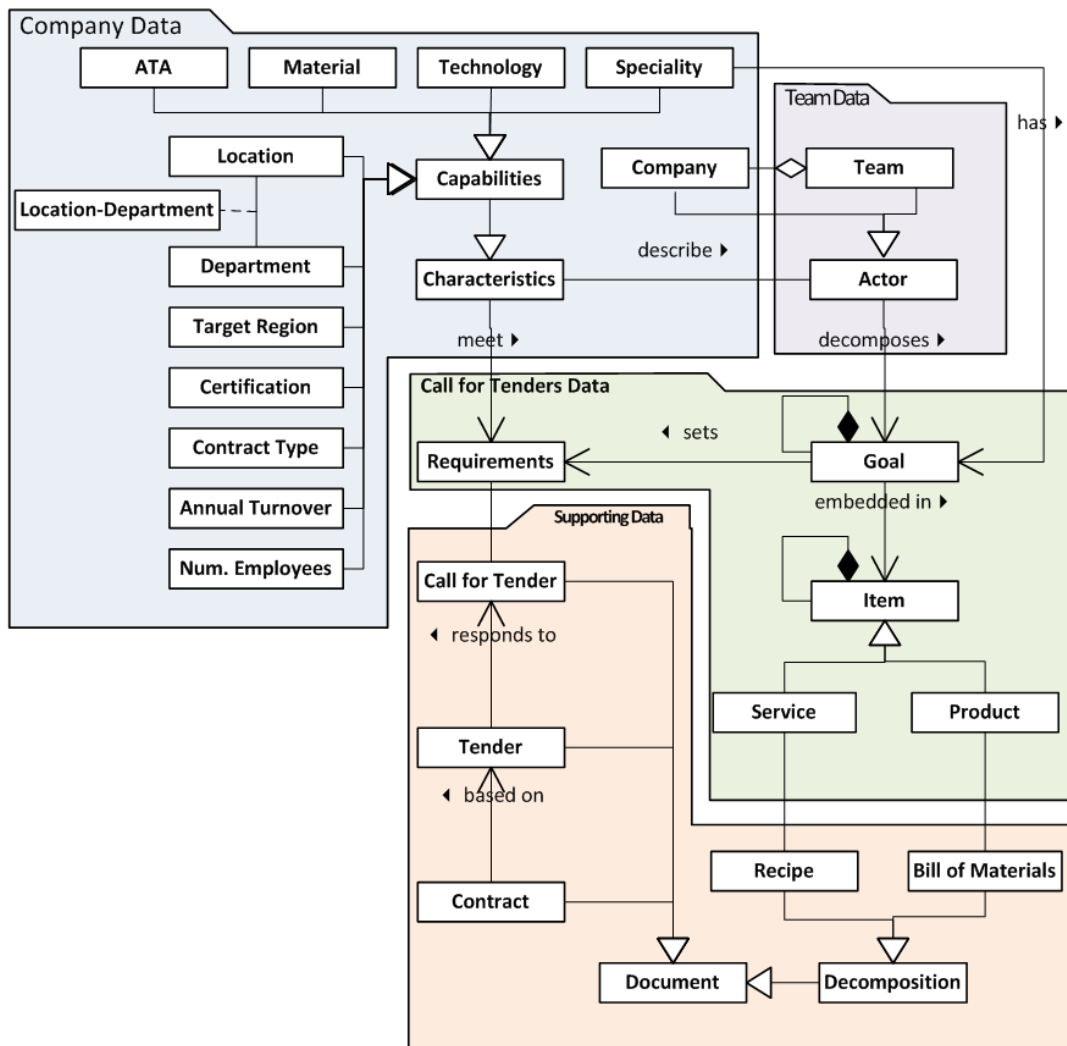


Figure 4. UML class diagram representing the TDMS ontology components and their relationships.

The TDMS ontology describes the entities participating in the team formation considering the demand and supply sides. The ontological constructs encode three main sets of data: the CfT data, the Company data, and the Team data, with three
300 types of attributes: identifiers (e.g. IDs, CfT title, company name), characteristics (e.g. company capabilities, certifications accredited) and requirements (e.g. target item, type of contract). [54] details these constructs. The TDMS utilises the internal ontological data model to store the required input data (CfT and company data) and to reduce communication costs with other services. The ontology can be manipulated
305 using Protégé² and needs to be supplied in the Web Ontology Language (OWL) format.

Using the ontology for knowledge base representation in the TDMS provides considerable advantages in terms of the flexibility in defining its main concepts, which facilitates portability of the TDMS to different application domains as well as
310 its adaptability to future changes in the same domain. Such advantages are described below in the ontological implementation of *characteristics* — a central concept for representing the supply and demand sides in the TDMS (Figure 4).

The ontological implementation of characteristics is organised hierarchically in terms of classes and instances, as shown in the ontology class diagram in Figure 5;
315 classes, as well as subclasses, may comprise specific instances of characteristics, as illustrated in Figure 6 for the *Material* subclass. As explained earlier, an instance of the *Specialty* characteristic refers to an item–goal combination (Section 4.1). *Items*, in turn, are represented by *Products* and *Services* (Figure 4). For brevity, and without loss of generality, in this paper we focus on the Products subtree.

320 Products in the ontology are organised into classes (product categories); the instances of those represent specific product variants. The classes are hierarchically structured, representing a classification of products in terms of categories, sub-categories, etc. The relationship ‘has individual’ relates a product class to a specific product it contains (Figure 7). This kind of relationship provides a core construct to
325 support matchmaking algorithms, allowing companies to specify their capabilities in terms of broader categories than just specific product variants, and enabling

² <https://protege.stanford.edu/>

approximate matching of CfT requirements to companies' capabilities. E.g., when the requested task cannot be fulfilled by any of the companies then the search for suppliers is widened using the ontological relationships as a basis for identifying
330 companies able to deal with products of the same class, or that class as a whole [62].

Furthermore, if one product is an immediate component of another then they are related to each other via the relationship 'contains'. Such relationships capture the products in terms of their structure; this is essential for identifying team compositions that would be able to fulfil the tender (e.g. by producing parts and assembling them to
335 the final product). Relationships between products and product classes are illustrated in Figure 7: the product class hierarchy originates from *Product* as the root class, which has *Fixations* as one of its subclasses ('has subclass' relationship). *Fixations* has its own subclasses, e.g. *Lateral_Fixation* and *Upper_Fixations*. The latter subclass has an individual product *upper_fixations1* ('has individual' relationship)
340 that contains other products as immediate components — which belong to their own product classes ('contains' relationship) [62].

Updating the hierarchy of product categories and adding new products to it is fairly flexible in such an ontology-based data model and does not require updating the programme code because the above relationships among products and product classes
345 are automatically respected when querying the ontology. Appendix A3 presents an extract of the OWL ontology representation of a hypothetical company.

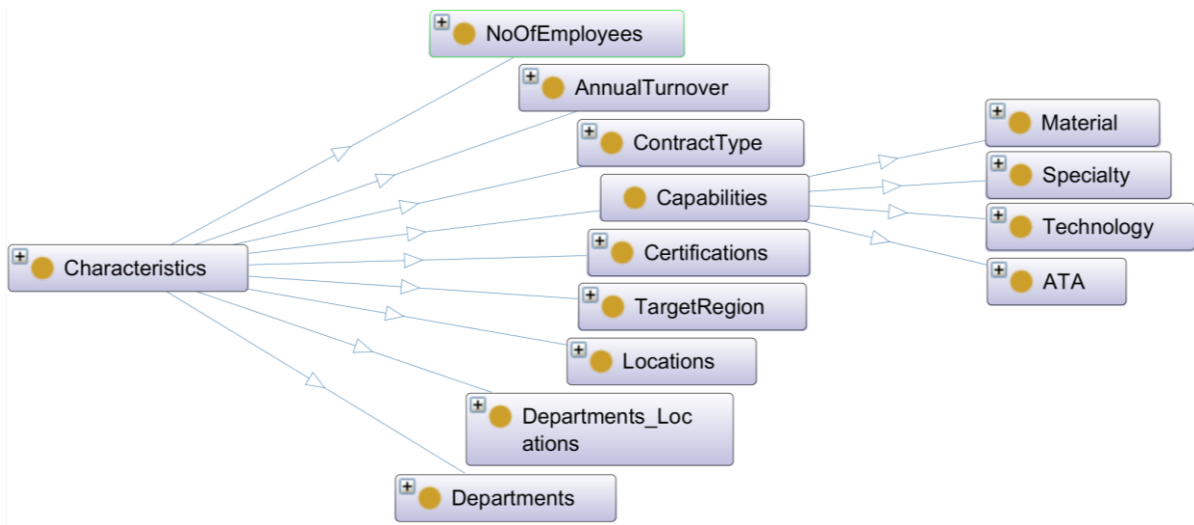


Figure 5. First and second levels of the class hierarchy of characteristics in the TDMS ontology.

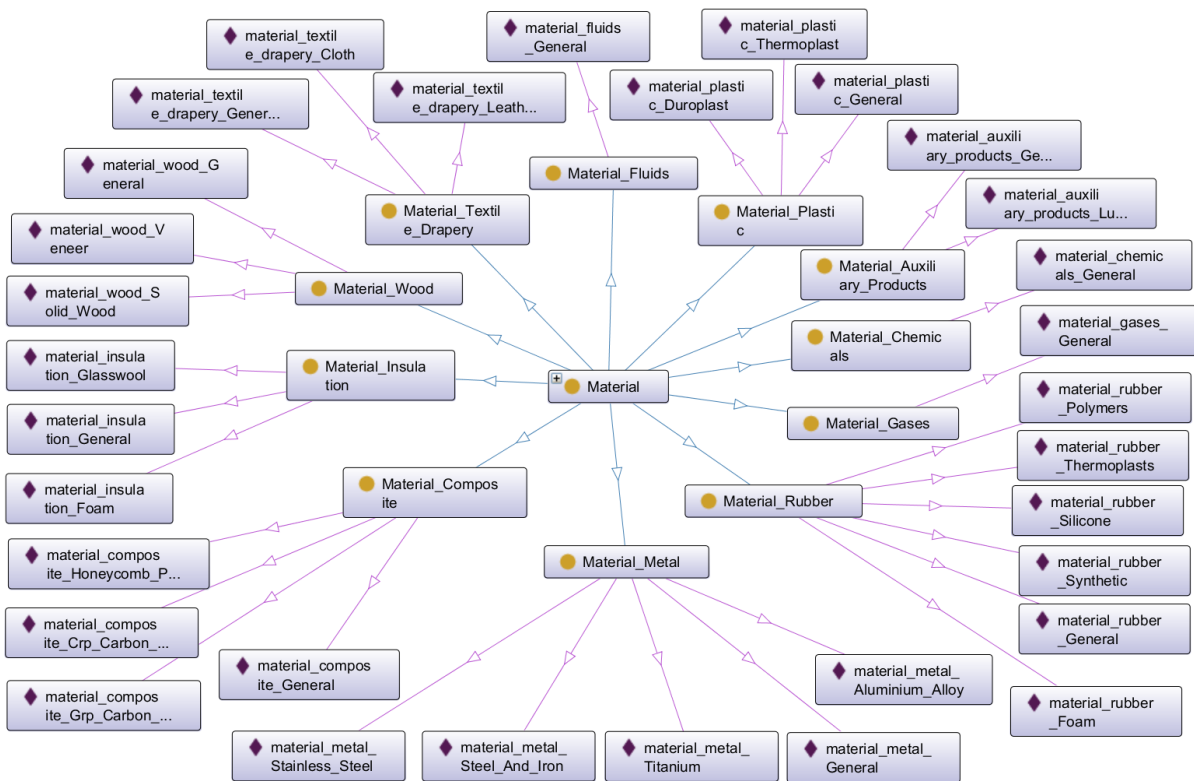


Figure 6. Subclasses of the *Material* characteristic in the TDMS ontology, and their instances.

Legend:
 — Contains
 — has individual
 — has subclass

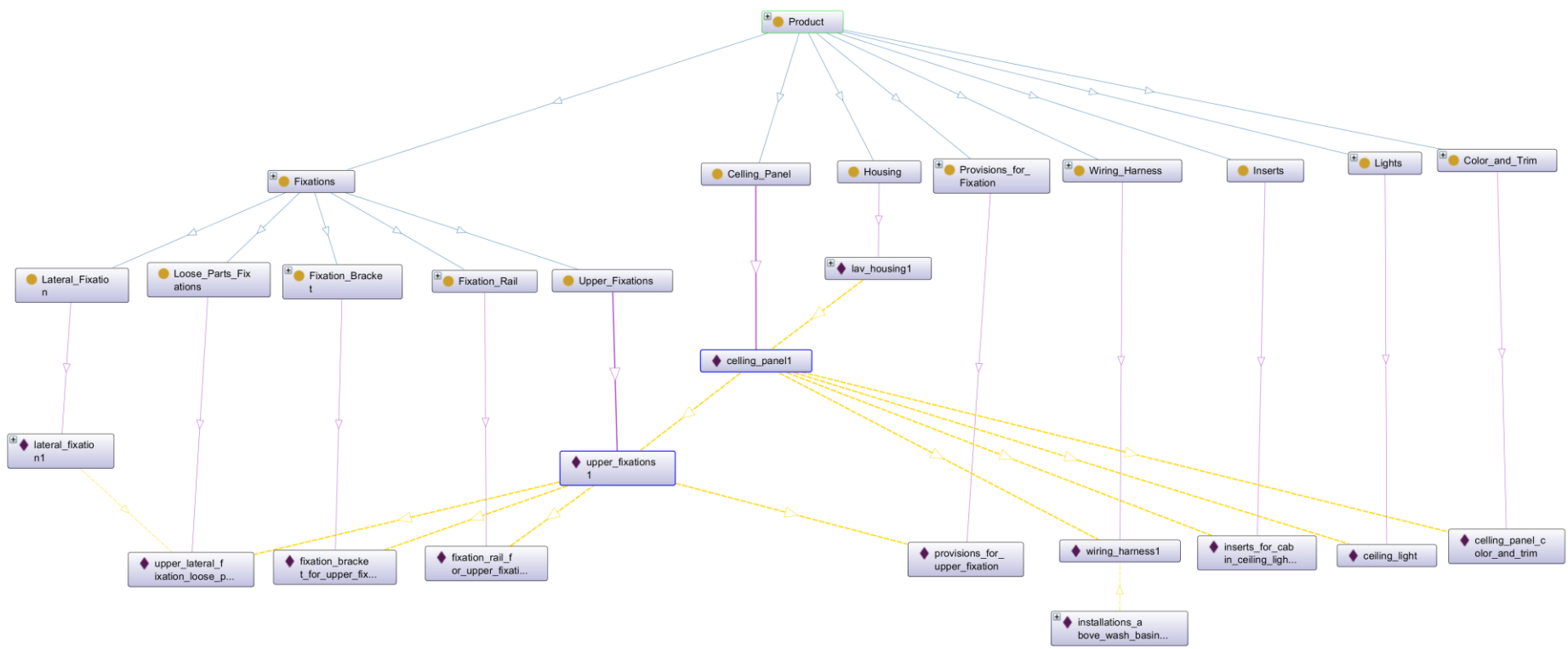


Figure 7. Example of relationships between products and product classes in the TDMS ontology.

360 *4.3 TDMS User Interface*

In the tendering process, once the user selects the CfT to respond to, the next step is to use the TDMS to find suitable business partners to jointly respond to the CfT. Figure 8 presents the initial screen shown to the user. Before the user starts interacting with the user interface (UI), the tool’s back-end has received information regarding the target item of the selected CfT; therefore, the front-end can display the item structure as a hierarchy of parts/sub-parts/services needed to produce that item. The TDMS UI shown in Figure 8 divides the interaction with the user into three screens: (1) Search prospective teams, (2) Review teams & replace members, and (3) Review assignments.

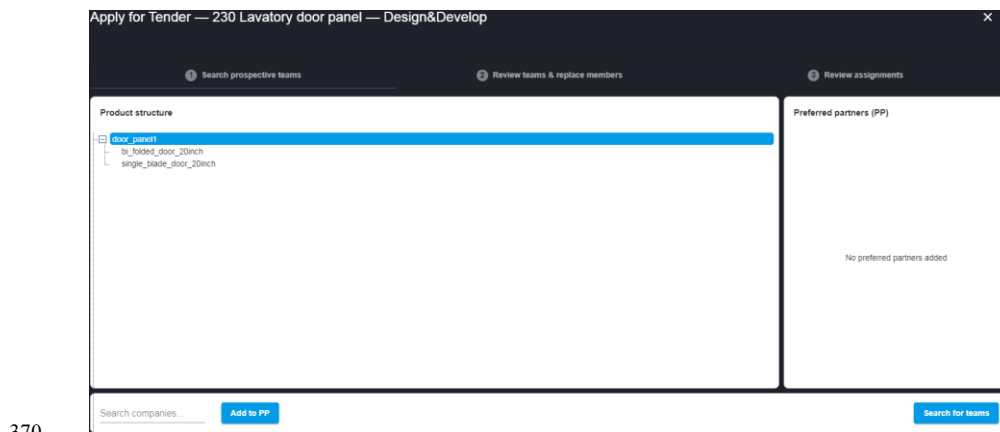
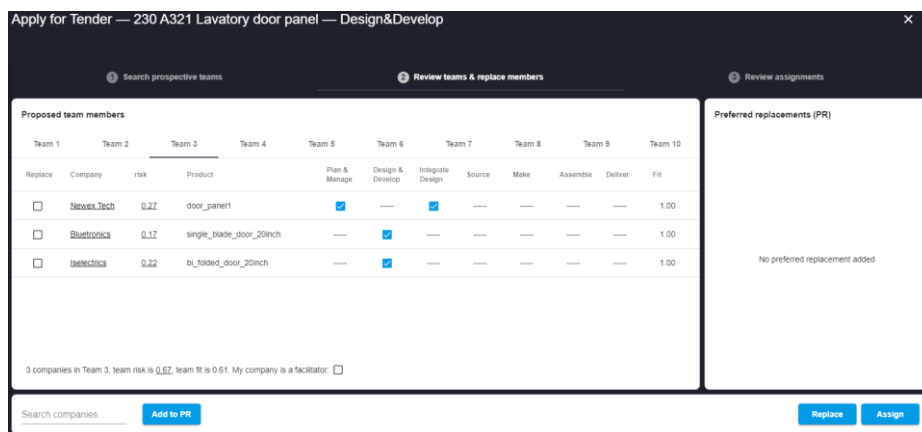


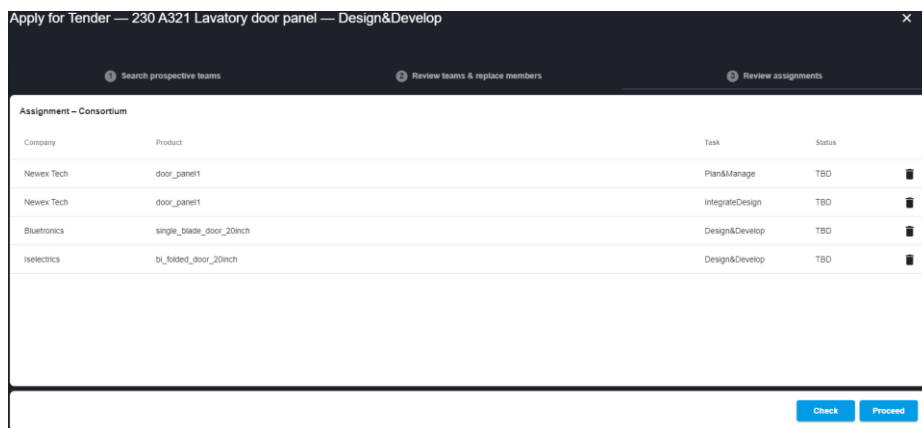
Figure 8. Example of the TDMS UI: first screen ‘Search prospective teams’ with a specific element of the product structure highlighted.

In Figure 8, we use an example of a CfT requesting work on a lavatory door panel as part of an aircraft’s lavatory. The TDMS shows the decomposition tree of this product in the ‘Search prospective teams’ screen. Figure 9 shows what is displayed after clicking the ‘Search suppliers’ button, where the tool looks for matching teams of suppliers that can provide the selected part/service. Finally, Figure 10 shows the UI after the user has selected the preferred suppliers to be invited to form a collaborative team. Tasks for the items for which no supplier was found, will be shown as open

380 positions without an assigned supplier. After confirming the selection, the user can click on the ‘Proceed’ button to continue to another service that would manage the collaboration process once a collaborative team is formed. The TDMS can also be used later to update the team.



385 *Figure 9.* Example of the TDMS UI: second screen ‘Review teams & replace members’. *Note:* risk indicators were supplied by an external service hosted by DIGICOR [48].



390 *Figure 10.* Example of the TDMS UI: third screen ‘Review assignments’ with the team selected by the user in the previous screen.

4.4 Decision Support Approach and Tool Functionality: Users' Perspective

Our approach involves two major supply chain network analytical functionalities: (A) decomposition, and (B) matchmaking; and three decision support functionalities: (C) team evaluation, (D) specification of preferred companies, replacement of a company, and (E) team assignment. These functionalities were derived from the requirements and understanding captured during the exploratory activities (Table 3) and the gaps described in Section 2. The functionalities were designed to cover the gaps identified, such as the need for enabling higher resource allocation efficiency (decomposition), agile formation of collaborations (matchmaking), means to promote trust between collaborating organisations (team evaluation, specification of preferred companies), ability to scale and adapt to market needs (replacement of companies), and the possibility to compose teams of multiple companies (team assignment).

Figure 11 presents a flowchart of user interaction with the TDMS. The first part of the interaction (revolving around item decomposition) is shown in section A of Figure 11. The user can request matchmaking for the entire product or its individual parts and, thus, build a team incrementally. If the selected item is part of the target item, then the associated goals are derived from the goals specified in the CfT through their decomposition.

Section D1 of Figure 11 shows that before applying the matchmaking functionality, the user can search and add preferred partners. The matchmaking algorithm respects this preference so that the team compositions containing preferred partners are listed first, ordered by decreasing team fit.

The functionality shown in section B of Figure 11 corresponds to matchmaking. By executing the matchmaking algorithm, the TDMS returns recommended team(s) able to provide the user-selected item.

If there are several recommend teams, the user can select a given one to be shown in the UI and check its details; this corresponds to section C of Figure 11.

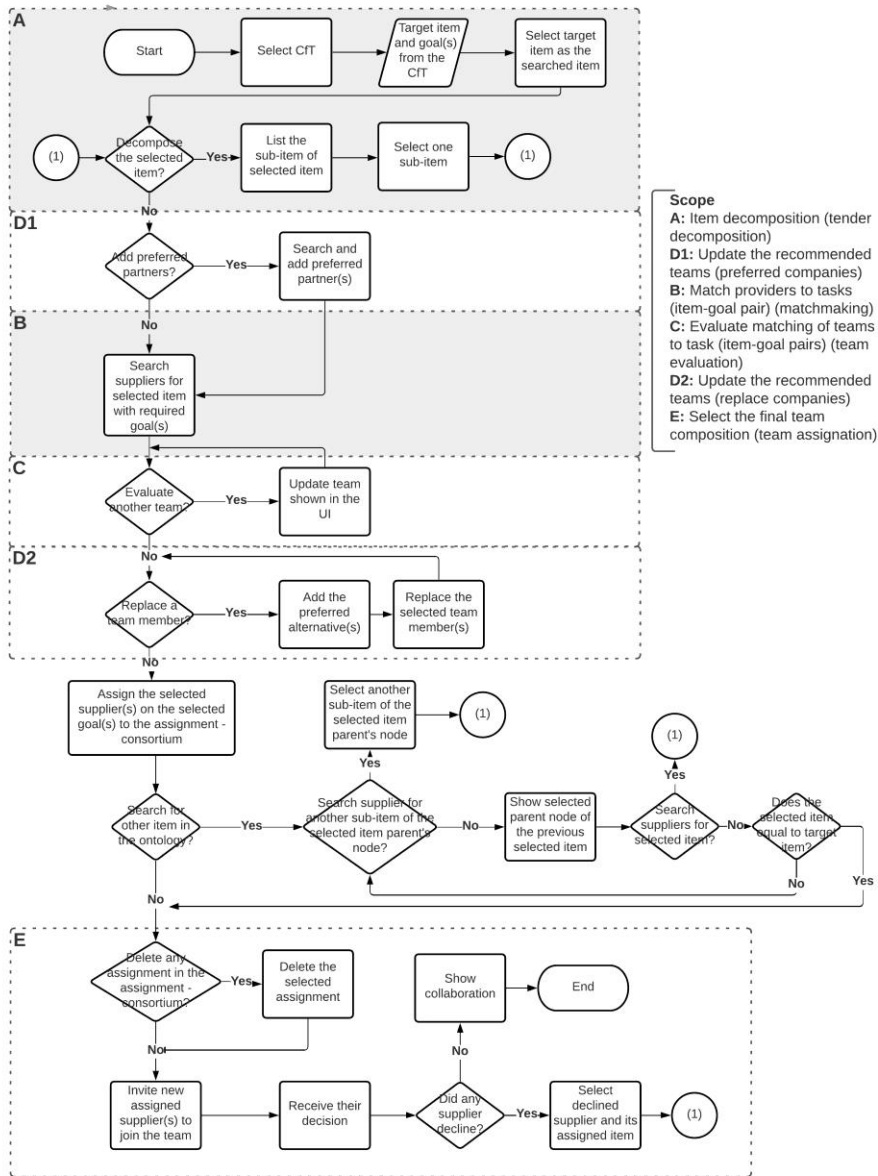


Figure 11. Flowchart of user interaction with the TDMS. Matchmaking and decomposition functionalities (A, B) are highlighted.

If the user wishes to replace a team member on a particular task, they can use the replacement function as depicted in section D2 of Figure 11. The tender decomposition and matchmaking algorithm will look for prospective sub-teams that can fulfil the goals associated with the given item, and will automatically pick the one with the highest team fit.

Section E of Figure 11 shows the last part of the approach, i.e. selecting the final team composition. This is done by the user assigning the tasks to companies. Finally, the user can invite all assigned supplier(s) to join the team. If any invitation is declined, the user can look for alternatives by using TDMS again. They can also examine the team composition for specific gaps and/or redundancies and address outstanding team formation issues by iteratively applying TDMS functionalities [65].

5. Evaluation and Results

5.1 Verification

We used test cases to verify the correctness of team compositions proposed by the TDMS in response to a CFT, as described in Section 4. Following Section 3.1, in the example below we utilise a CFT that hypothesises an OEM requesting to *Make and Source aircraft lavatory door handles*. Figure 12 depicts the target item's decomposition tree.

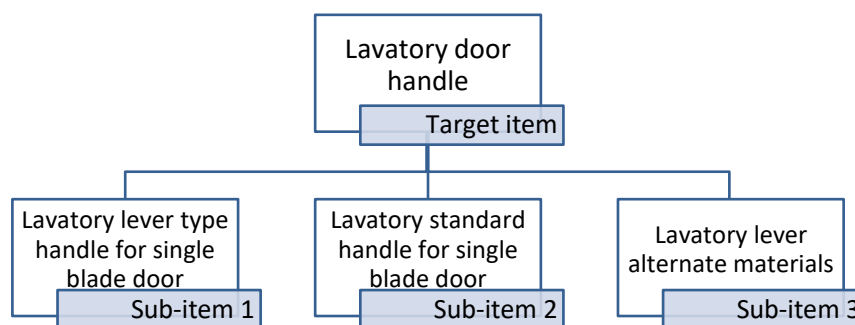


Figure 12. Decomposition tree for the CFT requiring a lavatory door handle.

In terms of expected results, considering the CfT data and the 14 companies' data [50], no suitable company can fulfil the task of 'lavatory door handle – Make'; in this case, one possible solution is to leave this task as a vacant position and wait for a new company, able to fulfil this task, to register later in the marketplace. Another solution is to decompose the task and assemble the target item from its sub-items: 'lavatory lever type handle for single blade door' (i.e. handle lever on the inside – sub-item 1), 'lavatory standard handle for single blade door' (i.e. handle lever on the outside – sub-item 2), and 'lavatory lever alternate materials' (i.e. fixings – sub-item 3). In this example, the tool needs to find companies which can make these three sub-items, deliver, and assemble them, considering that when a Make goal is decomposed, an Assemble goal is added for the overall target item, and a Deliver goal is added per each sub-item. Furthermore, a company to Plan & Manage this process is also needed.

Table 4 presents the expected results for the example CfT, where three possible teams are shown. Figure 13 shows the teams formed by the decision support tool.

Table 4. *Expected teams for Make and Source aircraft lavatory door handles CfT. Key: 'not available' (NA), Plan & Manage (PM), Design & Develop (DD), Integrate Design (I), Source (S), Make (M), Assemble (A) and Deliver (D).*

<i>Tender description: lavatory door handle (target item) — Make, Source (goals)</i>								
<i>Company</i>	<i>Category</i>	<i>PM</i>	<i>DD</i>	<i>I</i>	<i>S</i>	<i>M</i>	<i>A</i>	<i>D</i>
<i>Team 1</i>								
Openlane Plc	target item	✓	–	–	✓	–	–	–
NA	target item	–	–	–	–	✓	–	–
<i>Team 2</i>								
Openlane Plc	target item	✓	–	–	✓	–	✓	–
CoUK coop	sub-item 1	–	–	–	–	✓	–	–
ABC Aviation	sub-item 1	–	–	–	–	–	–	✓
ABC Aviation	sub-item 2	–	–	–	–	–	–	✓
NA	sub-item 2	–	–	–	–	✓	–	–
Design Vital Ltd	sub-item 3	–	–	–	–	✓	–	✓
<i>Team 3</i>								
Openlane Plc	target item	✓	–	–	✓	–	✓	–
CoUK coop	sub-item 1	–	–	–	–	✓	–	–
ABC Aviation	sub-item 1	–	–	–	–	–	–	✓
ABC Aviation	sub-item 2	–	–	–	–	–	–	✓
NA	sub-item 2	–	–	–	–	✓	–	–
CoUK coop	sub-item 3	–	–	–	–	–	–	✓
Design Vital Ltd	sub-item 3	–	–	–	–	✓	–	–

Team 1 presents an option where the company 'Openlane Plc' is recommended to Plan & Manage the target item, as well as to fulfil the Source goal. As mentioned

earlier, no single company is capable of fulfilling the Make goal for lavatory door handles on its own; therefore, this position is indicated as ‘not available’ in this team.

Team 1

Replace	Company	risk	Product	Plan & Manage	Design & Develop	Integrate Design	Source	Make	Assemble	Deliver	Fit
<input type="checkbox"/>	Openlane Plc	0.21	lavatory_door_handle1	<input checked="" type="checkbox"/>	-----	-----	<input checked="" type="checkbox"/>	-----	-----	-----	1.0
<input type="checkbox"/>	<not available>	1.00	lavatory_door_handle1	-----	-----	-----	-----	<input type="checkbox"/>	-----	-----	0.0

Team 2

Replace	Company	risk	Product	Plan & Manage	Design & Develop	Integrate Design	Source	Make	Assemble	Deliver	Fit
<input type="checkbox"/>	Openlane Plc	0.21	lavatory_door_handle1	<input checked="" type="checkbox"/>	-----	-----	<input checked="" type="checkbox"/>	-----	<input checked="" type="checkbox"/>	-----	1.00
<input type="checkbox"/>	CoUK Coop	0.30	lavatory_lever_type_handle_for_single_	-----	-----	-----	-----	<input checked="" type="checkbox"/>	-----	-----	1.00
<input type="checkbox"/>	ABC Aviation	0.27	lavatory_lever_type_handle_for_single_	-----	-----	-----	-----	-----	-----	<input checked="" type="checkbox"/>	1.00
<input type="checkbox"/>	ABC Aviation	0.27	lavatory_standard_handle_for_single_b	-----	-----	-----	-----	-----	-----	<input checked="" type="checkbox"/>	1.00
<input type="checkbox"/>	Design Vital Ltd.	0.27	lavatory_lever_alternate_materials1	-----	-----	-----	-----	<input checked="" type="checkbox"/>	-----	<input checked="" type="checkbox"/>	1.00
<input type="checkbox"/>	<not available>	1.00	lavatory_standard_handle_for_single_b	-----	-----	-----	-----	<input type="checkbox"/>	-----	-----	0.00

Team 3

Replace	Company	risk	Product	Plan & Manage	Design & Develop	Integrate Design	Source	Make	Assemble	Deliver	Fit
<input type="checkbox"/>	Openlane Plc	0.21	lavatory_door_handle1	<input checked="" type="checkbox"/>	-----	-----	<input checked="" type="checkbox"/>	-----	<input checked="" type="checkbox"/>	-----	1.00
<input type="checkbox"/>	CoUK Coop	0.30	lavatory_lever_type_handle_for_single_	-----	-----	-----	-----	<input checked="" type="checkbox"/>	-----	-----	1.00
<input type="checkbox"/>	CoUK Coop	0.30	lavatory_lever_alternate_materials1	-----	-----	-----	-----	-----	-----	<input checked="" type="checkbox"/>	1.00
<input type="checkbox"/>	ABC Aviation	0.27	lavatory_lever_type_handle_for_single_	-----	-----	-----	-----	-----	-----	<input checked="" type="checkbox"/>	1.00
<input type="checkbox"/>	ABC Aviation	0.27	lavatory_standard_handle_for_single_b	-----	-----	-----	-----	-----	-----	<input checked="" type="checkbox"/>	1.00
<input type="checkbox"/>	Design Vital Ltd.	0.27	lavatory_lever_alternate_materials1	-----	-----	-----	-----	<input checked="" type="checkbox"/>	-----	-----	1.00
<input type="checkbox"/>	<not available>	1.00	lavatory_standard_handle_for_single_b	-----	-----	-----	-----	<input type="checkbox"/>	-----	-----	0.00

465 *Figure 13.* The teams proposed by the TDMS for the Lavatory door handle Cft. *Note:* risk indicators have been supplied by an external service hosted by DIGICOR [48].

470 Team 2 proposes ‘Openlane Plc’ to fulfil the three goals associated with the target item – Plan & Manage, Source, and Assemble – where the Assemble goal appears because of the Make goal being decomposed. Thus, to fulfil the Make goal for the lavatory door handle, Team 2 adopts a decomposition according to the corresponding tree (Figure 12) and shows companies whose capabilities include the goal Make for the required sub-items; the associated Delivery goal for each sub-item is also taken into account. In this team, the sub-item 2, lavatory standard handle for single blade door, lacks a company able to fulfil the Make goal.

Finally, Team 3 adopts a different assignment of the required tasks. The difference
 475 between Teams 2 and 3 is that the latter presents the tasks associated with sub-item 3
 ('lavatory lever alternate materials – Make' and 'lavatory lever alternate materials –
 Deliver') to be fulfilled by two different companies, instead of a single one as it is in
 Team 2. TDMS enables decomposition and assignment of CfT goals using 'a
 contracting function' which helps to identify the best fitting partner or a set of
 480 partners for forming a team to fulfil a CfT.

5.2 Validation

As indicated in Section 3.1, the expert feedback study aims to capture expert views
 about the expected utility and effectiveness of the tool in facilitating Industry 4.0 team
 formation. The study confirms whether or not the idea of a system such as TDMS is
 485 the right artefact to support the formation of collaborative supply chains, and validates
 that the TDMS as designed is a suitable approach to address such formation. Section
 3.1 explains the procedure for this validation study.

The survey used three questions to capture the respondents' background: (i) field of
 work, (ii) level of expertise in smart manufacturing/Industry 4.0, and (iii) roles or
 490 positions held. Table 5 presents the results.

Table 5. *Expert feedback survey. Respondents' background results.*

<i>Field</i>		<i>Expertise</i>		<i>Role / position</i>	
academic	5	basic	28.6%	academic	3
professional	8	intermediate	42.9%	IT developer / systems engineer / architect	4
both	1	expert	28.6%	business / IT consultant	1
				executive / manager	2
				operations / supply chain professional	5
				others	3

The different purposes that the TDMS tool would serve in their company has been
 indicated by the respondents as follows: (a) Forming a team/finding partners (12
 responses), (b) exploring/understanding the supplier market (4), (c) finding alternative
 495 team compositions (5), (d) replacing team members (4), (e) diversifying the supplier
 base (7), and (f) other (1): applying for current and future EU projects.

The study then explored the most frequently used method for collaborative tender preparation, with answers showing the use of ‘existing networks such as professional and personal contacts’ as the mostly used method at 78.6%, followed by ‘finding partners through industry events/fairs’ (14.3%), with the least used method being ‘IT-assisted solutions such as the TDMS’ (0%); however, 7.1% did not indicate any method. Further, based on the respondents’ experience, they were asked to rate the effectiveness of the methods used for collaborative tender preparation. The rating was based on a five-point Likert scale: ineffective (1), slightly effective (2), rarely effective (3), effective (4), and very effective (5). The findings show that on average, the use of ‘existing networks such as professional and personal contacts’ was rated highest at 4.2, then ‘finding partners through industry events/fairs’ (2.9), closely followed by the use of ‘IT-assisted solutions such as the TDMS’ (2.8).

Next, respondents were required to indicate the expected benefits of using a system such as the TDMS and were able to make multiple choices. The results are as follows: (a) Reduced time and cost to fulfil related tasks (11 responses), (b) Broaden access to supplier market (8), (c) Increased number of successful CfT submissions (5), (d) Improved manufacturing capacity utilisation (6), and (e) Other (2): i) Cash and carry – other branches, automotive suppliers; ii) Broader view for collaboration.

Also, based on their experience, respondents were requested to rate the expected benefits on the scale from 1 to 5: not beneficial (1), slightly beneficial (2), rarely beneficial (3), beneficial (4), and very beneficial (5). The results indicate that on average the benefits of using a tool such as the TDMS (Figure 14) were rated as follows: the ‘reduced time and cost to fulfil related tasks’ at 3.86, followed by ‘broadening access to supplier market’ (3.79), then improved ‘manufacturing capacity utilisation’ (3.5). The lowest rated was the ‘increased number of successful CfT submissions’ (3.36). The top three benefits provide clear indicators of the value derived from such a tool in addressing challenges of finding and integrating suitable suppliers into highly fragmented supply chains, moreover doing so at speed and scale (for reference see our problem framing and gap identification in Sections 1 and 2).

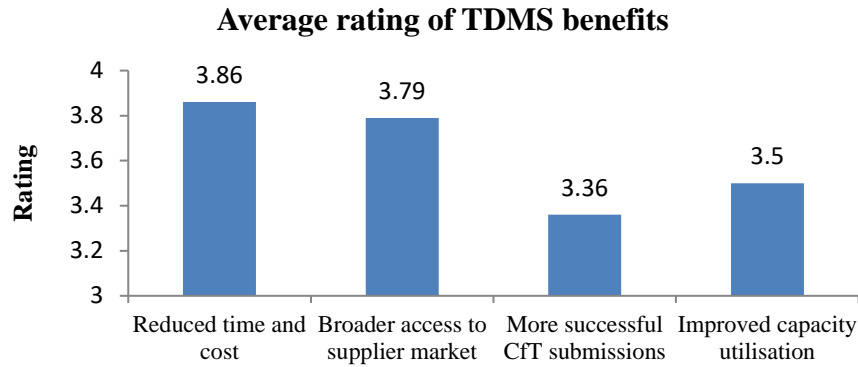


Figure 14. Average respondent rating of TDMS benefits.

The study then explored the concerns that might prevent respondents from using the TDMS. Respondents were allowed to make multiple choices. The following results were obtained: (a) System security and integrity (8 responses), (b) Data privacy (7), (c) Industry regulatory compliance (6), (d) System training costs (3), (e) Auditability of the system (6), and (f) Other (1): system complexity should be an issue/ease of use (Figure 15). Furthermore, respondents' likelihood to recommend the use of the TDMS to their organisation or business partners was assessed by asking respondents to indicate the likelihood on the scale from 1 (very unlikely) to 10 (very likely). The following likelihood was indicated: 8 (6 responses), 7 (4), 6 (3), and 2 (1).

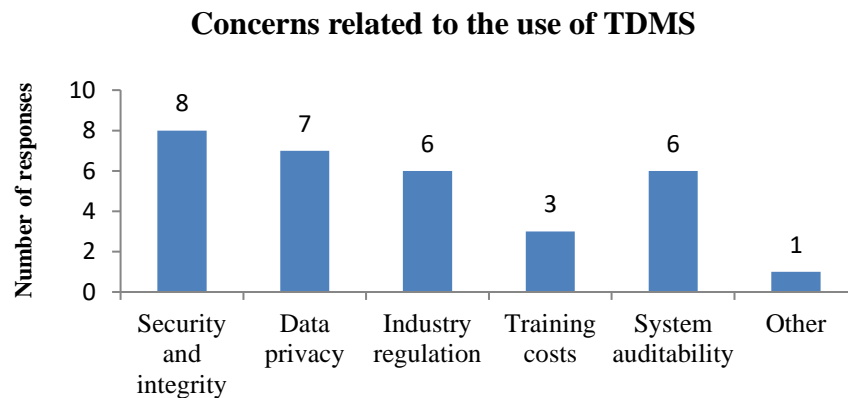


Figure 15. Concerns related to the use of the TDMS.

540 Finally, respondents' views were sought on several general aspects about the
TDMS' functionality which they had to rate on a Likert scale from 1 to 5: strongly
disagree (1), disagree (2), neither agree nor disagree (3), agree (4), and strongly agree
(5). The findings show that the average level of agreement to the statements asked
was as follows: I find the tender decomposition useful (4.29); I find the TDMS
545 suitable for composing a team (3.79); I find the use of ontologies in the description of
products useful to support tender preparations (3.36); I find that the specification of
goals supported by the TDMS is suitable for tender preparation (3.86), and, I find that
the TDMS matchmaking criteria are suitable for tender preparation (3.64).

6. Impact and Managerial Implications

550 The proposed approach and decision support tool applied to the formation of
collaborative supply chain networks increases the likelihood of complex production
requirements specified as digital CfTs to be fulfilled by a wider pool of enterprises
joining capacities/capabilities and forming temporal supply chain collaborations
[66,67]. This also *facilitates SME integration into the manufacturing supplier pool*,
555 allowing SMEs to bid for large-scale business opportunities involving dynamic and
complex tasks as part of a collaborative supply network, with benefits to supply chain
and B2B market efficiency [68]. TDMS can be used by companies of any size,
however, it is particularly suitable for SMEs because they often lack capacities and
capabilities to fulfil CfTs alone [69,70]. A larger pool of suppliers searchable and
560 integrated into the digital platform matchmaking algorithms also *allows OEMs and
Tier-1 enterprises to rapidly react to supply chain disruptions* and adds more
transparency and visibility to both the supply and demand sides of the marketplace.
There is also more *flexibility towards selecting suppliers* by rapidly assessing several
team combinations with different risk/quality/cost trade-offs.

565 Based on feedback from supply chain experts, 'reduced time and cost to fulfil
related tasks' came on top of the list of expected benefits pointing to a positive impact
of TDMS in *increasing organisational agility* by speeding up collaboration formation.
Being able to rapidly form teams and search for replacements in scenarios of supply

570 disruptions from a wide pool of suppliers also has the indirect benefit of *increasing supply chain resilience*.

In contrast to other approaches that form collaborations after individual pre-selection of suppliers [27,38,41–43], our approach supports ‘on-the-fly’ team formation, with a holistic multi-tier view of supply-chain collaboration. This facilitates the *search for global optimal team combinations* to respond to a CfT.

575 Finally, the digitalisation of the tendering and team formation process advances the state-of-the-art towards formation of contractual team collaborations, defining, settling and enforcing contractual obligations as important step towards the implementation of ‘Smart Contract’ [71] solutions for global supply chains.

7. Conclusions and Future Work

580 The fourth industrial revolution [72,73] is increasing the pace of automation, with offline business processes replaced by digitalised versions based on human–machine collaborations. Digitalisation has reached a tipping point where high-value-added processes involving decision-making traditionally carried out offline are being digitalised using assistive decision support technologies [72,74,75].

585 In this paper, we have discussed the design, implementation and validation of an approach and decision-support tool offering search, matchmaking, team composition and multi-criteria evaluation of teams regarding suitability to collaborate as a supply network by sharing capabilities and capacities.

The tool automating the team formation approach applies domain knowledge
590 codified as machine-readable ontologies to assist users in their decision process of selecting potential partners; this is done by proposing compositions of suitable partners for fulfilling the elements of a CfT. In this way, the ontologies used by the tool represent a conceptualisation of the real-world products and relationships between them, companies’ capabilities, CfT requirements, and other terms essential
595 for forming and maintaining supply-chain collaborations. The top-level concepts in the ontology and their structural relationships presented here are part of a wider effort which also covers the process coordination aspects of team collaboration using the

Coordination Theory [34,68,76] and explores the potential of ontological relationships and axioms to support reasoning and enable automated inference about team, product
600 and process composition alternatives, exploring the relationships between parts and products and suitability of prospective suppliers for fulfilling specific tasks.

The decision support capabilities of the tool include recommendations to business users regarding candidate sets of companies considered best suited towards forming a collaborative team. The recommendations are based on multiple attributes addressing
605 CfT requirements and companies' collective capabilities. The validation based on expert feedback indicated the usefulness and acceptance potential of the proposed approach and tool. Our solution is unique in integrating industry domain ontologies, assistive human–computer interaction techniques, and multi-criteria decision support towards semi-automation of the process of forming collaborative supply chains, which
610 contrasts with current practices that are reliant on manual processes, networking via face-to-face events and peer referencing.

Future work will involve understanding the motivations of end-users in the manufacturing domain to accept automated B2B advice from decision support systems, particularly addressing trust and security issues [77,78], and also investigate
615 algorithm aversion in supply chain decision-making support [79,80].

Acknowledgements

[Blinded]

References

- [1] J. Schadel, M. Lockström, R. Moser, N. Harrison, Readiness for supply chain collaboration and supplier integration —Findings from the Chinese automotive industry, in: K.S. Pawar, H. Rogers, A. Potter, M. Naim (Eds.), *Dev. Logist. Supply Chain Manag.*, Palgrave Macmillan, London, UK, 2016: pp. 125–137.
620
- [2] N. Fähnrich, M. Kubach, Identity management and cloud computing in the automotive industry: First empirical results from a quantitative survey, in: D. Hühnlein, H. Roßnagel, R. Kuhlisch, J. Ziesing (Eds.), *Lect. Notes Informatics - Proceedings*, Ser. Gesellschaft Fur Inform., Open Ident, Gesellschaft für Informatik e.V. (GI), Bonn, Germany, 2015: pp. 15–27.
625 <https://subs.emis.de/LNI/Proceedings/Proceedings251/15.pdf> (accessed March 3, 2018).
- [3] É. Lefebvre, L.A. Lefebvre, G. Le Hen, R. Mendgen, Cross-border e-collaboration for new product development in the automotive industry, in: *Proc. 39th Annu. Hawaii Int. Conf. Syst.*

- 630 Sci., IEEE, Kauia, HI, USA, 2006.
- [4] J. Oh, S. Rhee, The influence of supplier capabilities and technology uncertainty on manufacturer - supplier collaboration, *Int. J. Oper. Prod. Manag.* 28 (2008) 490–517.
- [5] F. Wiengarten, P. Humphreys, A. McKittrick, B. Fynes, Investigating the impact of e-business applications on supply chain collaboration in the German automotive industry, *Int. J. Oper. Prod. Manag.* 33 (2013) 25–48.
- 635 [6] H.A. Nguyen, N. Hoang, N. Ha, H.T. Nguyen, A.C. Phan, Y. Matsui, Empirical study on the role of collaboration in new product development in manufacturing companies, *Int. J. Qual. Res.* 12 (2018) 363–384.
- [7] F. Ferreira, J. Faria, A. Azevedo, A.L. Marques, Industry 4.0 as enabler for effective manufacturing virtual enterprises, in: L.S.A. Afsarmanesh H., Camarinha-Matos L. (Ed.), *Collab. a Hyperconnected World. PRO-VE 2016. IFIP Adv. Inf. Commun. Technol.*, Springer, Cham, Porto, Portugal, 2016: pp. 274–285.
- 640 [8] R.C. Beckett, M. Jones, Collaborative network success and the variable nature of trust, *Prod. Plan. Control.* 23 (2012) 240–251.
- [9] F. Meng, N. Wang, Y. Xu, Interval neutrosophic preference relations and their application in virtual enterprise partner selection, *J. Ambient Intell. Humaniz. Comput.* (2019) 1–30.
- 645 [10] A. Ghadge, M. Er Kara, H. Moradlou, M. Goswami, The impact of Industry 4.0 implementation on supply chains, *J. Manuf. Technol. Manag.* 31 (2020) 669–686.
- [11] L.S. Dalenogare, G.B. Benitez, N.F. Ayala, A.G. Frank, The expected contribution of Industry 4.0 technologies for industrial performance, *Int. J. Prod. Econ.* 204 (2018) 383–394.
- 650 [12] Y. Lu, Industry 4.0: A survey on technologies, applications and open research issues, *J. Ind. Inf. Integr.* 6 (2017) 1–10.
- [13] A.G. Frank, L.S. Dalenogare, N.F. Ayala, Industry 4.0 technologies: Implementation patterns in manufacturing companies, *Int. J. Prod. Econ.* 210 (2019) 15–26.
- 655 [14] F. Chiarello, L. Trivelli, A. Bonaccorsi, G. Fantoni, Extracting and mapping industry 4.0 technologies using wikipedia, *Comput. Ind.* 100 (2018) 244–257.
- [15] E. Hofmann, M. Rüscher, Industry 4.0 and the current status as well as future prospects on logistics, *Comput. Ind.* 89 (2017) 23–34.
- [16] A. Gunasekaran, E.W.T. Ngai, Information systems in supply chain integration and management, *Eur. J. Oper. Res.* 159 (2004) 269–295.
- 660 [17] J. Smit, S. Kreutzer, C. Moeller, M. Carlberg, Industry 4.0 - Study for the ITRE Committee, Brussels Dir. Gen. Int. Policies, Policy Dep. A Econ. Sci. Policy, Eur. Parliam. (2016).
- [18] L. Da Xu, E.L. Xu, L. Li, Industry 4.0: State of the art and future trends, *Int. J. Prod. Res.* 56 (2018) 2941–2962.
- 665 [19] S. Mittal, M.A. Khan, D. Romero, T. Wuest, A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs), *J. Manuf. Syst.* 49 (2018) 194–214.
- [20] European Commission, Annual Report on European SMEs 2018/2019, 2019.
- [21] L.M. Camarinha-Matos, H. Afsarmanesh, N. Galeano, A. Molina, Collaborative networked organizations – Concepts and practice in manufacturing enterprises, *Comput. Ind. Eng.* 57 (2009) 46–60.
- 670 [22] L.F. Mesquita, R. Ragozzino, J.J. Reuer, Collaborative strategy: Critical issues for alliances and networks, Edward Elgar Publishing, 2017.
- [23] X.G. Huang, Y.S. Wong, J.G. Wang, A two-stage manufacturing partner selection framework for virtual enterprises, *Int. J. Comput. Integr. Manuf.* 17 (2004) 294–304.
- 675

- [24] S.A. Petersen, M. Divitini, Using agents to support the selection of virtual enterprise teams, *AOIS@AAMAS*. 59 (2002).
- [25] S.A. Petersen, Virtual enterprise formation and partner selection: an analysis using case studies, *Int. J. Netw. Virtual Organ.* 4 (2007) 201–215.
- 680 [26] H.O. Nyongesa, G.W. Musumba, N. Chileshe, Partner selection and performance evaluation framework for a construction-related virtual enterprise: a multi-agent systems approach, *Archit. Eng. Des. Manag.* 13 (2017) 344–364.
- [27] I. Polyantchikov, E. Shevtshenko, T. Karaulova, T. Kangilaski, L.M. Camarinha-Matos, Virtual
685 enterprise formation in the context of a sustainable partner network, *Ind. Manag. Data Syst.* 117 (2017) 1446–1468.
- [28] V. Roblek, M. Meško, A. Krapež, A complex view of Industry 4.0, *SAGE Open*. 6 (2016).
- [29] K.-H. Lüke, J. Walther, D. Wäldchen, Innovation management methods in the aviation industry, in: M. Hodoň, G. Eichler, C. Erfurth, G. Fahrnberger (Eds.), *Innov. Community Serv. I4CS 2018. Commun. Comput. Inf. Sci.*, Springer, Cham, Žilina, Slovakia, 2018: pp. 161–177.
- 690 [30] J.F. Sowa, Knowledge representation: logical, philosophical and computational foundations, Brooks/Cole Publishing Co., 1999.
- [31] W3C, Ontologies - W3C, Semant. Web. (2015).
<https://www.w3.org/standards/semanticweb/ontology>.
- [32] L. Mikhailov, Fuzzy analytical approach to partnership selection in formation of virtual
695 enterprises, *Omega*. 30 (2002) 393–401.
- [33] T.J. Norman, A. Preece, S. Chalmers, N.R. Jennings, M. Luck, V.D. Dang, T.D. Nguyen, V. Deora, J. Shao, W.A. Gray, N.J. Fiddian, Agent-based formation of virtual organisations, *Knowledge-Based Syst.* 17 (2004) 103–111.
- [34] N.D. Mehandjiev, I.D. Stalker, M.R. Carpenter, Recursive construction and evolution of
700 collaborative business processes, in: D. Ardagna, M. Mecella, J. Yang (Eds.), *Bus. Process Manag. Work. BPM 2008. Lect. Notes Bus. Inf. Process.*, Springer, Berlin, Heidelberg, Milano, Italy, 2009: pp. 573–584.
- [35] C. Wu, D. Barnes, A literature review of decision-making models and approaches for partner selection in agile supply chains, *J. Purch. Supply Manag.* 17 (2011) 256–274.
- 705 [36] S. Vinodh, S.R. Devadasan, K.E.K. Vimal, D. Kumar, Design of agile supply chain assessment model and its case study in an Indian automotive components manufacturing organization, *J. Manuf. Syst.* 32 (2013) 620–631.
- [37] C. Wu, D. Barnes, Formulating partner selection criteria for agile supply chains: A Dempster-Shafer belief acceptability optimisation approach, *Int. J. Prod. Econ.* 125 (2010) 284–293.
- 710 [38] J. Chai, J.N.K. Liu, E.W.T. Ngai, Application of decision-making techniques in supplier selection: A systematic review of literature, *Expert Syst. Appl.* 40 (2013) 3872–3885.
- [39] B. Huang, C. Gao, L. Chen, Partner selection in a virtual enterprise under uncertain information about candidates, *Expert Syst. Appl.* 38 (2011) 11305–11310.
- [40] L.M. Camarinha-Matos, ICT infrastructures for VO, in: L.M. Camarinha-Matos, H. Afsarmanesh (Eds.), *Virtual Organ.*, Springer, Boston, MA, 2005: pp. 83–104.
- 715 [41] L. De Boer, E. Labro, P. Morlacchi, A review of methods supporting supplier selection, *Eur. J. Purch. Supply Manag.* 7 (2001) 75–89.
- [42] F. Tahriri, M.R.R. Osman, A. Ali, R. Mohd, A review of supplier selection methods in manufacturing industries, *Suranaree J. Sci. Technol.* 15 (2008) 201–208.
- 720 [43] K. Zimmer, M. Fröhling, F. Schultmann, Sustainable supplier management - A review of models supporting sustainable supplier selection, monitoring and development, *Int. J. Prod. Res.* 54 (2016) 1412–1442.

- [44] P. Agarwal, M. Sahai, V. Mishra, M. Bag, V. Singh, A review of multi-criteria decision making techniques for supplier evaluation and selection, *Int. J. Ind. Eng. Comput.* 2 (2011) 801–810.
- 725 [45] G. Pishchulov, A. Trautrim, T. Chesney, S. Gold, L. Schwab, The Voting Analytic Hierarchy Process revisited: A revised method with application to sustainable supplier selection, *Int. J. Prod. Econ.* 211 (2019) 166–179.
- [46] M.T. Martinez, P. Fouletier, K.H. Park, J. Favrel, Virtual enterprise – organisation, evolution and control, *Int. J. Prod. Econ.* 74 (2001) 225–238.
- 730 [47] A. Hevner, S.T. March, J. Park, S. Ram, Design Science in Information Systems Research, *MIS Q.* 28 (2004) 75–105.
- [48] DIGICOR, Decentralised Agile Coordination Across Supply Chains, (2016). <https://www.digicor-project.eu/>.
- 735 [49] S. Cisneros-Cabrera, A. Ramzan, P. Sampaio, N. Mehandjiev, Digital marketplaces for Industry 4.0: A survey and gap analysis, in: L.M. Camarinha-Matos, H. Afsarmanesh (Eds.), *Collab. a Data-Rich World. PRO-VE 2017. IFIP Adv. Inf. Commun. Technol.*, Springer, Cham, Vicenza, Italy, 2017: pp. 18–27.
- [50] S. Cisneros-Cabrera, G. Pishchulov, Z. Liu, P. Sampaio, N. Mehandjiev, Call-for-tenders & Companies Synthetic Data, Mendeley Data. V1 (2020).
- 740 [51] J. Venable, J. Pries-Heje, R. Baskerville, FEDS: A Framework for Evaluation in Design Science Research, *Eur. J. Inf. Syst.* (2016).
- [52] APICS Supply Chain Council, Design Chain Operations Reference model (DCOR) 1.0, 2014. <http://www.apics.org/docs/default-source/scc-non-research/dcor-framework-a4.pdf> (accessed January 16, 2019).
- 745 [53] APICS Supply Chain Council, SCOR quick reference guide, 2017. https://www.apics.org/docs/default-source/scc-non-research/apicscce_scor_quick_reference_guide.pdf (accessed January 16, 2019).
- [54] S. Cisneros-Cabrera, G. Pishchulov, Z. Liu, P. Sampaio, N. Mehandjiev, Supply Chain Team Formation Data Model, Mendeley Data. V1 (2020).
- 750 [55] G. Pishchulov, S. Cisneros-Cabrera, P. Sampaio, N. Mehandjiev, Z. Liu, A framework for automated formation of demand-driven supply chain collaborations, Manchester, Working paper, 2020.
- [56] I. Nadareishvili, R. Mitra, M. McLarty, M. Amundsen, *Microservice architecture: Aligning principles, practices, and culture*, O'Reilly Media, Inc., 2016.
- 755 [57] D. Namiot, M. Sneps-Sneppé, On micro-services architecture, *Int. J. Open Inf. Technol.* 2 (2014) 24–27.
- [58] Angular v4, What Is Angular? (2017). <https://v4.angular.io/docs> (accessed August 20, 2019).
- [59] L. Richardson, S. Ruby, *RESTful web services*, O'Reilly Media, Inc., 2007.
- 760 [60] C. Pautasso, O. Zimmermann, F. Leymann, Restful web services vs. “big” web services: making the right architectural decision, in: *Proc. 17th Int. Conf. World Wide Web*, Beijing, China, 2008: pp. 805–814.
- [61] C. Richardson, Event-driven architecture, (n.d.). <https://microservices.io/patterns/data/event-driven-architecture.html> (accessed August 20, 2019).
- 765 [62] G. Pishchulov, A. Jimenez-Arriaga, S. Cisneros-Cabrera, Q. Quboa, Z. Liu, A. Ramzan, N. Kazantsev, P. Sampaio, N. Mehandjiev, Forming Supply-Chain Collaborations using DIGICOR's Tender Decomposition and Matchmaking Service: A White Paper on using TDMS as a Standalone Service, Univ. Manchester. (2019). [https://www.research.manchester.ac.uk/portal/en/publications/forming-supplychain-collaborations-using-digicors-tender-decomposition-and-matchmaking-service\(35996a8f-5aa7-](https://www.research.manchester.ac.uk/portal/en/publications/forming-supplychain-collaborations-using-digicors-tender-decomposition-and-matchmaking-service(35996a8f-5aa7-)

- 770 453f-b832-2a02a3634ced).html.
- [63] N. Guarino, Formal ontology in information systems: Proceedings of the 1st international conference, IOS press, Trento, Italy, 1998.
- [64] C. Roussey, F. Pinet, M.A. Kang, O. Corcho, An introduction to ontologies and ontology engineering, in: *Adv. Inf. Knowl. Process.*, 2011.
- 775 [65] DIGICOR, Digicor Portal User Manual, 2019. https://6c97d07e-2d66-4f14-9c19-8c5872c4c3ba.filesusr.com/ugd/2512a7_1adcfe4f0c6148b9868f0649eccd9341.pdf.
- [66] S. Cisneros-Cabrera, P. Sampaio, N. Mehandjiev, A B2B team formation microservice for collaborative manufacturing in Industry 4.0, in: *2018 IEEE World Congr. Serv.*, IEEE, San Francisco, CA, USA, 2018.
- 780 [67] L.M. Camarinha-Matos, R. Fornasiero, H. Afsarmanesh, Collaborative networks as a core enabler of Industry 4.0, in: L.M. Camarinha-Matos, H. Afsarmanesh, R. Fornasiero (Eds.), *Collab. a Data-Rich World. PRO-VE 2017. IFIP Adv. Inf. Commun. Technol.*, Springer, Cham, Vicenza, Italy, 2017: pp. 3–17.
- [68] N. Mehandjiev, P. Grefen, S. Ristol, Introduction, in: N. Mehandjiev, P. Grefen (Eds.), *Dyn. Bus. Process Form. Instant Virtual Enterp.*, Springer-Verlag London, 2010: pp. 3–12.
- 785 [69] A. Macpherson, A. Wilson, Enhancing SMEs' capability: opportunities in supply chain relationships?, *J. Small Bus. Enterp. Dev.* (2003).
- [70] P. Hong, J. Jeong, Supply chain management practices of SMEs: From a business growth perspective, *J. Enterp. Inf. Manag.* (2006).
- 790 [71] K. Korpela, J. Hallikas, T. Dahlberg, Digital Supply Chain Transformation toward Blockchain Integration, in: *Proc. 50th Hawaii Int. Conf. Syst. Sci.*, 2017.
- [72] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, M. Hoffmann, *Industry 4.0*, *Bus. Inf. Syst. Eng.* 6 (2014) 239–242.
- [73] Y. Liao, F. Deschamps, E. de F.R. Loures, L.F.P. Ramos, Past, present and future of Industry 4.0 - A systematic literature review and research agenda proposal, *Int. J. Prod. Res.* 55 (2017) 3609–3629.
- 795 [74] M. Brettel, N. Friederichsen, M. Keller, M. Rosenberg, How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 perspective, *Int. J. Mech. Ind. Sci. Eng.* 8 (2014) 37–44.
- 800 [75] H. Kagermann, Change through digitization - Value creation in the age of Industry 4.0, in: H. Albach, H. Meffert, A. Pinkwart, R. Reichwald (Eds.), *Manag. Perm. Chang.*, Springer Gabler, Wiesbaden, Wiesbaden, 2015: pp. 23–45.
- [76] T.W. Malone, K. Crowston, The interdisciplinary study of coordination, *ACM Comput. Surv.* (1994).
- 805 [77] R.R. Hoffman, M. Johnson, J.M. Bradshaw, A. Underbrink, Trust in automation, *IEEE Intell. Syst.* 28 (2013) 84–88.
- [78] K.A. Hoff, M. Bashir, Trust in automation: Integrating empirical evidence on factors that influence trust, *Hum. Factors.* 57 (2015) 407–434.
- [79] B.J. Dietvorst, J.P. Simmons, C. Massey, Algorithm aversion: People erroneously avoid algorithms after seeing them err, *J. Exp. Psychol. Gen.* 144 (2015) 114–126.
- 810 [80] S. Cisneros-Cabrera, N. Mehandjiev, A. Felfernig, P. Sampaio, S. Kununka, A Laddering Approach to Explore the Motivations of Taking Computer Advice for Supply Networks Formation., in: *PACIS*, 2020: p. 218.

Appendix A1. Survey instrument

Research Study on the Tender Decomposition and Matchmaking Service (TDMS)

Participant information

Thank you for your time. All the data you provide will remain fully anonymous and subject to General Data Protection Regulation (GDPR) and the United Kingdom (UK) data protection laws. In case of any queries please contact Dr Grigory Pishchulov at grigory.pishchulov@manchester.ac.uk

The aim of this anonymous questionnaire is to establish your views about the TDMS in relation to your work. The findings will contribute to further improvements to the TDMS so as to enable the system to provide a seamless user experience of its functionalities.

Please indicate your consent for using the responses provided in the questionnaire for research purposes by ticking this box: Date: _____

Background (please tick all that apply)

Field:
 Academic
 Professional / Industry

Level of expertise in Smart Manufacturing / Industry 4.0:
 Basic
 Intermediate
 Advanced

Role / Position:
 Academic IT Developer / Systems Engineer / Architect Business / IT Consultant
 Executive / Manager Operations / Supply Chain Professional Other:

1. What purposes would the TDMS serve in your company? (please tick all that apply)

a. Forming a team / finding partners
 b. Exploring / understanding the supplier market
 c. Finding alternative team compositions
 d. Replacing team members
 e. Diversifying the supplier base

Other, please specify:

2. Please indicate the method most frequently used by your organisation for collaborative tender preparation. (choose *only ONE* answer)

a. IT-assisted solutions such as the TDMS
 b. Relying on existing networks such as professional and personal contacts
 c. Finding partners through industry events / fairs

3. Based on your experience, please rate the effectiveness of the following methods for collaborative tender preparation, on the scale from 1 to 5:
ineffective (1), slightly effective (2), rarely effective (3), effective (4), very effective (5).

		1	2	3	4	5
a. IT-assisted solutions such as the TDMS	ineffective	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very effective
b. Relying on existing networks such as professional and personal contacts	ineffective	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very effective
c. Finding partners through industry events / fairs	ineffective	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very effective

Please flip ...

4. What benefits do you expect from using a system such as the TDMS? (please tick all that apply)

a. Reduced time and cost to fulfil related tasks
 b. Broaden access to supplier market
 c. Increased number of successful call-for-tender submissions
 d. Improved manufacturing capacity utilization

Other, please specify:

5. Based on your experience, please rate the following benefits, on the scale from 1 to 5:
not beneficial (1), slightly beneficial (2), rarely beneficial (3), beneficial (4), very beneficial (5).

		1	2	3	4	5
a. Reduced time and cost to fulfil related tasks	not beneficial	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very beneficial
b. Broaden access to supplier market	not beneficial	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very beneficial
c. Increased number of successful call-for-tender submissions	not beneficial	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very beneficial
d. Improved manufacturing capacity utilization	not beneficial	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	very beneficial

6. What concerns might prevent you from using the TDMS? (please tick all that apply)

a. System security and integrity
 b. Data privacy
 c. Industry regulatory compliance
 d. System training costs
 e. Auditability of the system

Other, please specify:

7. Considering the TDMS description, how likely would you be to recommend its use to your organization or business partners — on the scale from 1 (*very unlikely*) to 10 (*very likely*)?

1 2 3 4 5 6 7 8 9 10
 very unlikely very likely

8. Is there any functionality that is desired but not currently captured by the TDMS?

.....

9. Please provide the following information and tick (✓) where appropriate:
strongly disagree (1), disagree (2), neither agree nor disagree (3), agree (4), strongly agree (5).

		1	2	3	4	5
a. I find the tender decomposition useful.	disagree	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	agree
b. I find the TDMS suitable for composing a team.	disagree	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	agree
c. I find the use of ontologies in the description of products useful to support tender preparations.	disagree	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	agree
d. I find that the specification of goals supported by the TDMS is suitable for tender preparation.	disagree	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	agree
e. I find that the TDMS matchmaking criteria are suitable for tender preparation.	disagree	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	agree

Thank you very much for your cooperation! ☺

Appendix A2. TDMS events and REST calls

TDMS events

<i>Group identifier</i>	<i>Name</i>	<i>Produced when</i>
<i>Produced by TDMS</i>		
TeamFormed	TeamFormed	A new team has been selected
	TeamUpdated	An existing team has been updated
<i>Consumed by TDMS</i>		
Call-for-tenderData	CfTcreated	A new CfT has been created
	CfTupdated	A CfT has been modified
	CfTdeleted	A CfT has been deleted
CompanyData	CompanyCreated	A new company profile has been created
	CompanyUpdated	A company profile has been modified
	CompanyDeleted	A company profile has been deleted
CollaborationCreated	CollaborationCreated	A collaboration area for the team has been created by a service that controls the collaboration lifecycle
CollaborationDecision	CollaborationDecision	A company accepts or rejects an invitation to join a team, or quits a team

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TDMS REST calls

<i>Group identifier</i>	<i>Name</i>	<i>Description</i>	<i>REST call syntax</i>
CompanyData	addCompany	Creates a company in the ontology	
	readCompany	Reads all companies' data from the ontology	
	updateCompany	Updates a company's data in the ontology	updatecompany/companyID
	deleteCompany	Deletes a company from the ontology	deletecompany/companyID
CfTData	addCfT	Creates a CfT in the ontology	
	readCfT	Reads all CfTs' data from the ontology	
	readCfTById	Reads a specified CfT from the ontology	cftbodyid/cfID
	updateCfT	Updates a CfT data in the ontology	updateCfT/cfID
	deleteCfT	Deletes a CfT data from the ontology	deleteCfT/cfID
Matchmaking	Matchmaking	Executes the matchmaking algorithm	matchmaking/targetItemID/cfID matchmaking/subItemID/cfID
Product & Enums	rootItems	Reads the list of root items from the ontology	
	treeStructure	Reads the structure of a specified item	treeStructure/Item
	itemClassSearch	Reads the hierarchy of product categories	
	enums	Reads the ranges of <i>enum</i> attributes from the ontology	
TeamsData	replaceTeam	Replaces team members	replaceTeam/targetItemID/cfID
	checkTeam	Checks for possible gaps in the team compositions	checkteam/targetItem/cfID
	addTeam	Adds a team to the ontology	Addteam/targetItem/cfID
	updateTeam	Updates a team in the ontology	Updateteam/targetItem/cfID/teamID

Appendix A3. Ontology excerpt

