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DISTRIBUTION OF ENGINEERING DESIGN KNOWLEDGE WITHIN THE DEVELOPMENT OF MULTI-AGENT DESIGN SYSTEMS

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1. Introduction

Today, product development is often characterised by struggling with requirements initially defined by the customer. Thus, the compliance of requirements is a crucial task of every design engineer which could be solved by using Design for X (DfX) guidelines**.** Products designed in accordance with specific DfX guidelines are more efficient and effective to develop. For example, a certain product which has been optimised according to the rules of Design for Assembly (DfA) requires less time and steps to assemble [Meerkamm 2005]. However, knowledge must be transferred from the assembly to the design stage. This transfer of knowledge, i.e. the time for knowledge transfer, is unfavourable for the value-added proportion of design engineers. This includes the fact that design engineers need considerable time to collect and assess information as well as transform this information into knowledge within the real process [Stokes 2001].

All of these challenges described above have already been at least partially addressed by methods in the field of knowledge-based engineering (KBE) to develop knowledge-based systems. However, fully satisfactory results were not produced [Stokes 2001]. Multi-agent design systems (MADS) are one kind of knowledge-based system, but they show three characteristics which support solving the problems at hand: first, they have a higher capability to map engineering design processes than conventional knowledge-based systems (i.e. rule-based systems), and second they are able to produce solutions as real domain experts do. Finally, MADS deliver a highly modular system in which agents can be instantiated and executed according to the actual product model in a CAD system. Hence, MADS are able to adjust themselves to altered conditions. If, for example, the design engineer adds a roller bearing to the assembly, then the system instantiates a new object agent dedicated to represent this design element. This agent has its own knowledge, its own rights and its own behaviour [Kratzer 2011]. At last, MADS are better to maintain and to re-use than conventional knowledge-based systems. Thus, they reduce costs because “maintenance consumes 50% to 80% of an application’s lifecycle cost” [Lander 1997].

However, the effectiveness and efficiency of MADS is highly dependent on how agents deal with knowledge. Amongst other things, the relationship between roles (related to agents) and knowledge is a crucial fact [Russel 2003]. Basically, considering the fundamental concepts of agent-based software engineering, autonomy and goal orientation, a distribution of knowledge is necessary because agents are working on their own (autonomy) and striving for their own goals (goal orientation) [Wooldridge 2009]. In accordance with Lander [Lander 1997] the knowledge which is assigned to a certain agent is essential to handle conflicts. If agents have the right knowledge to overcome conflicts, the system is more effective and efficient. With respect to the two main strengths of agent-based systems, communication and cooperation, Stollberg [Stollberg 2002] postulates a peripheral distribution of

knowledge within the system. Both aspects can only be put into effect if the number of agents with adequate knowledge is greater than one and the knowledge is distributed, respectively. The number of agents must be greater than one in order to classify the system as an agent system. The knowledge-to-role structure (KRS) describes the way in which the elements of knowledge are related to each agent. The KRS could actually vary between two extreme points. On the one hand, there are many agents each including a single knowledge element. On the other hand there is only one agent with all knowledge elements included.
This KRS will be established within the development of MADS and is a product of the knowledge distribution which describes a certain knowledge domain (here: engineering design). Figure 1 presents a section of the generic procedure for how to develop MADS and depicts this step with the semantic network on the right hand side and the knowledge distribution in the middle. Here, the knowledge engineer analyses the knowledge base and creates a unique knowledge distribution for this special application.

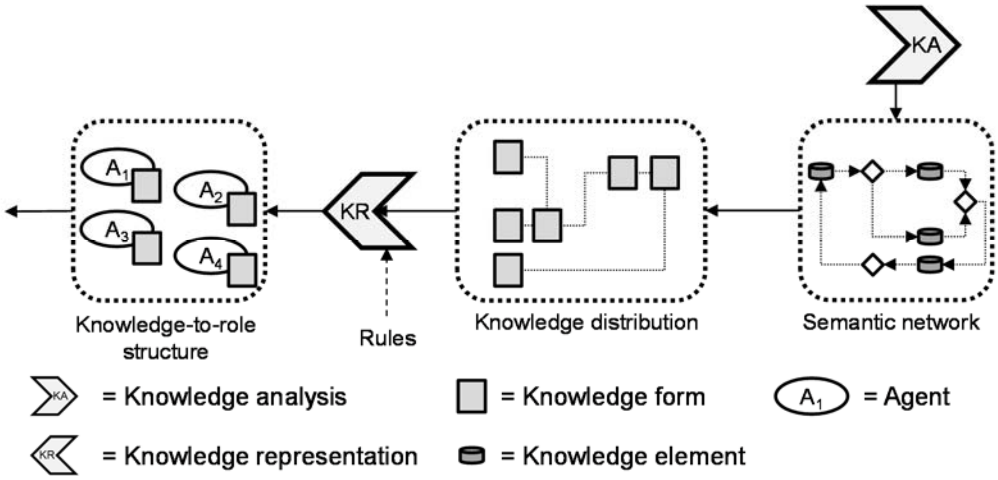

Figure 1. The steps of knowledge analysis and knowledge representation within the procedure for building MADS

Finally, the ability of agents to find solutions is highly dependent on the knowledge distribution. In turn, these factors determine the efficiency and effectiveness of the system.

2. Problem statement and goals

Considering the knowledge distribution within the development of multi-agent design systems, the problem is that an optimal distribution in the field of engineering design is not known. Due to the fact that there are nearly infinite possibilities to establish a distribution of a knowledge domain, which depends on a specific case, knowledge engineers are confused by this variety. Thus, they do not know how to methodically derive an optimal distribution from the semantic network as a prerequisite for the knowledge-to-role structure. As stated before, the optimal distribution is always related to a specific case and is hardly transferable to other cases. But there has to be a generic distribution of knowledge from which instantiated distributions (related to a case) can be derived. The main research question is how a generic knowledge distribution looks in order to subsequently instantiate optimal distributions related to specific cases. Considering the effectiveness and the efficiency of the MADS, initial development and concurrent optimisation are necessary. Therefore, the goal of this contribution is to establish a generic knowledge distribution within the development of MADS neglecting side effects such as mistakes during the transformation of the semantic network into the knowledge distribution. This will be shown on the example of the interference fit as one optimal distribution. Based on the main research question a hypothesis can be formulated: *By means of the Characteristics-Properties Modelling (CPM) in accordance with Weber [Weber 2007], and the ProKon-knowledge forms [Kratzer 2011] a generic distribution of knowledge is established in an adequate way to instantiate optimal distributions of knowledge related to specific cases.*

Finally, the goal of this contribution provides concrete results for the knowledge engineer. The first result is the generic distribution of knowledge. The second result is a procedure which defines the way from the semantic network to the optimal knowledge distribution (instantiation). As third result, guidelines and usage instructions respectively give support to this procedure. Considering the main research question and the hypothesis, several research questions have been derived to operationalise the research approach. Thus, these research questions are answered step-by-step within this paper. In accordance with the Design Research Methodology by Blessing and Chakrabarti [Blessing 2009], the research questions can be divided into different research phases: research clarification, descriptive study I, prescriptive study and descriptive study II. Table 1 shows an overview of the research questions and their appearance in the contribution.

Following the research questions presented in Table 1, Section 3 presents the generic procedure for developing MADS. Section 4 as the central part of this contribution comprises a detailed description of the knowledge distribution and guidelines for the transformation from the semantic network to the knowledge distribution. For this purpose research question 4 will be split into eight answerable questions. The results are discussed in Section 5. A conclusion is drawn and an outlook is given in Section 6.

Table 1. Overview of the research questions answered in this contribution (S = section)

Research Question	S 1 & 2	S 3	S 4	S 5
1. Why is the KRS and the knowledge distribution substantial to the effectiveness and efficiency of MADS?	■			
2. What is the relationship between the knowledge distribution and the knowledge-to-role structure?	■			
3. How should MADS be developed?		■		
4. How does the knowledge distribution work?			■	
5. How could the evaluation of the knowledge distribution look with regard to the functionality of the MADS?				■

3. Procedure for developing multi-agent design systems

In order to systematically answer the main research question it is necessary to describe the whole procedure for developing multi-agent design systems (MADS). Thus, in this section one possibility of how to develop MADS will be presented in brief (see Figure 2). Basically, the whole procedure is processed by the knowledge engineer up to the vertical black bold bar. The procedure is built upon a generic model-based structure with four models to be developed: organisation model (OM), agent model (AM), knowledge model (KM) and system model (SM) [Kratzer 2011]. These models prescribe the actions knowledge engineers must undertake to develop MADS. The starting point is the real organisation embracing the organisational structure (real knowledge-to-role structure), the process structure (real design process) and the real design artefact. Based on the real design process and on the real design artefact, the organisational model and the agent model will be developed. As a conscious decision the process structure is the beginning of the development process as knowledge acquisition must be guided step-by-step by the process. Merely asking designers what they know is not expedient. It must be asked which knowledge is relevant in each step. Thus, in the organisation model, knowledge engineers analyse the process and derive a target knowledge portfolio on the level of process sections. In this phase, the as-is state of knowledge will consciously be disregarded as it is incorrect in terms of its distribution. In parallel, the outcome of the agent model considering generic agent classes are first agent roles (R) with defined goals, and second ways of communication between agents. These two results are combined and thus form the input of the knowledge structuring (KS, see Figure 2). In turn, the results of this phase are concrete knowledge locations (e.g. domain expert, database) where knowledge engineers are able to elicit the actual knowledge (knowledge elicitation, KE, see Figure 2).

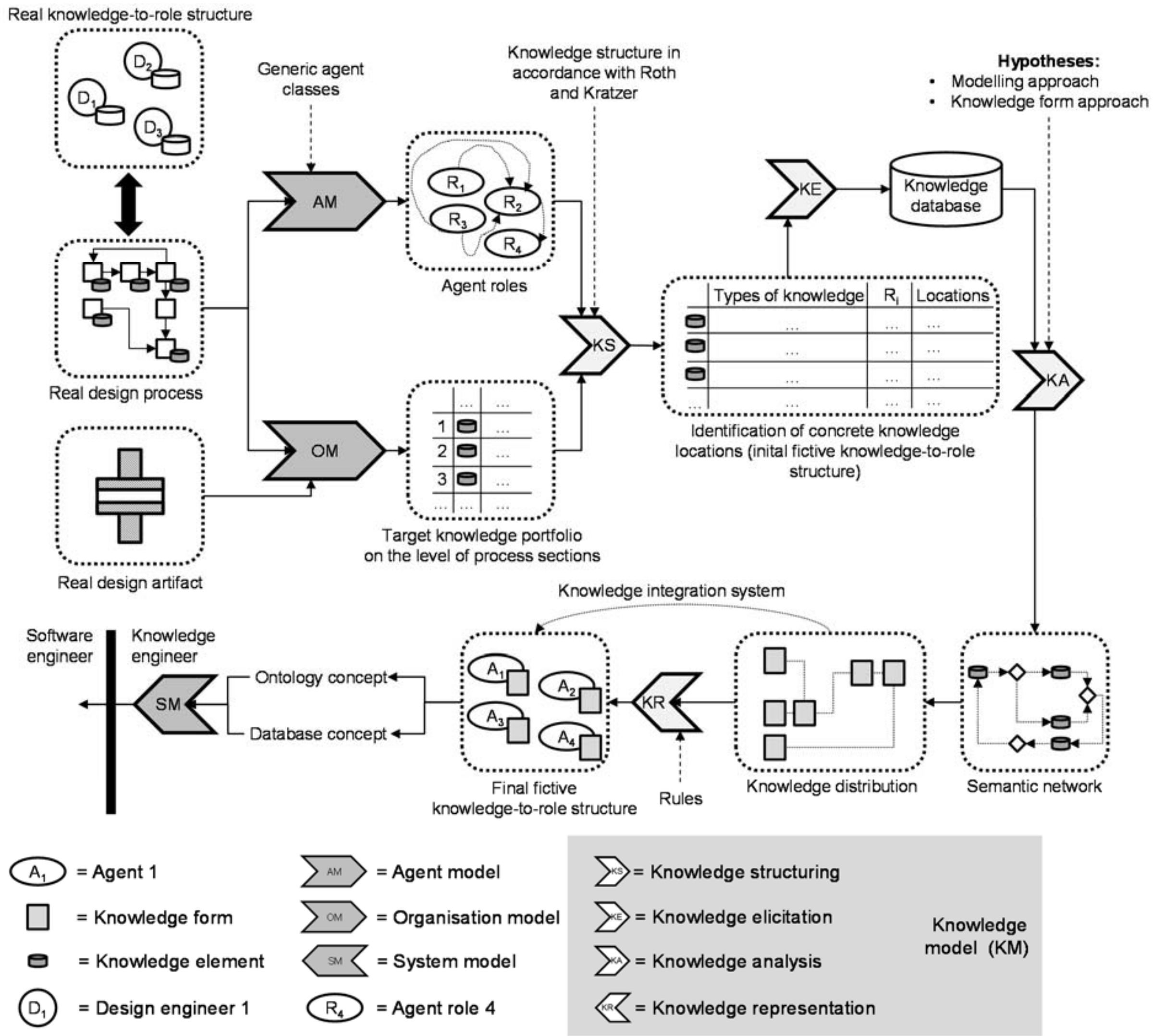

Figure 2. The generic procedure for building MADS

After establishing the knowledge database, the knowledge analysis (knowledge analysis, KA, see Figure 2) deals with structuring the knowledge by a semantic network and transforming the knowledge into the knowledge distribution. This step has to be supported, inter alia, by a possibility to transform the knowledge elements from the semantic network to the knowledge distribution in a standardised manner (e.g. by means of the known ICARE forms developed by Stokes [Stokes 2001]). Unfortunately, these ICARE forms are not completely suitable for the development for agent-based systems. This is because of three reasons:

- Stokes has only provided five types of ICARE forms, of which two are not necessary to describe the knowledge domains in the ProKon project (I = Illustration, A = Activity). The types E = Entity, R = Rules and C = Condition have been taken over.
- ICARE forms are not suitable to fill in a formal description of the content, which is readable by MADS.
- ICARE forms do not provide a possibility to firstly assign knowledge elements to agents.

These are the reasons to adapt them and to develop the PKF. In the ProKon project there are six types of PKF: rule (R), formula (F), entity (E), parameter (P), table (T) and condition (C). This number is sufficient to describe the whole knowledge domain, which was evaluated in concrete but limited scenarios. The specific content of each PKF will be presented later in this contribution. Then, rules are necessary to build up the final fictive knowledge-to-role structure. This phase is called knowledge representation (knowledge representation, KR, see Figure 2). Finally, the system model is established to develop the connection to the CAD system and to develop the knowledge integration system. In the following section, the knowledge distribution will be described. Additionally, guidelines for the transformation from the semantic network to the knowledge distribution are postulated.

4. Distribution of engineering design knowledge

As postulated by Lander [Lander 1997], Russel [Russel 2003], Stollberg [Stollberg 2002] and Wooldridge [Wooldridge 2009], a methodical creation of the knowledge-to-role structure is necessary. Obviously, the input of this structure, the knowledge distribution, also predefines the success of the MADS. Before carrying out the KRS, it is necessary to establish a proper knowledge distribution which is described in this contribution (the KRS is the next step and is neglected here). Keeping Table 1 in mind, research question 4 ("How does the knowledge distribution work?") has to be divided into answerable questions. The following list presents these questions.

- How is the semantic network built up? (4a)
- In which way are knowledge elements aggregated to one PKF? (4b)
- How does a generic distribution of knowledge look like? (4c)
- What is the general content of the container called "use case"? (4d)
- What is the general content of the container called "issue"? (4e)
- How is the assignment of PKF regulated to a specific use case and issue? (4f)
- How are PKF assigned to each other? (4g)
- How does the formalised transformation process look like? (4h)

To describe these research questions more precisely and placing them into the context of this contribution, Figure 3 presents the transformation of the knowledge domain from the semantic network (left hand side) to the knowledge distribution (right hand side). The recently presented research questions are placed where they occur.

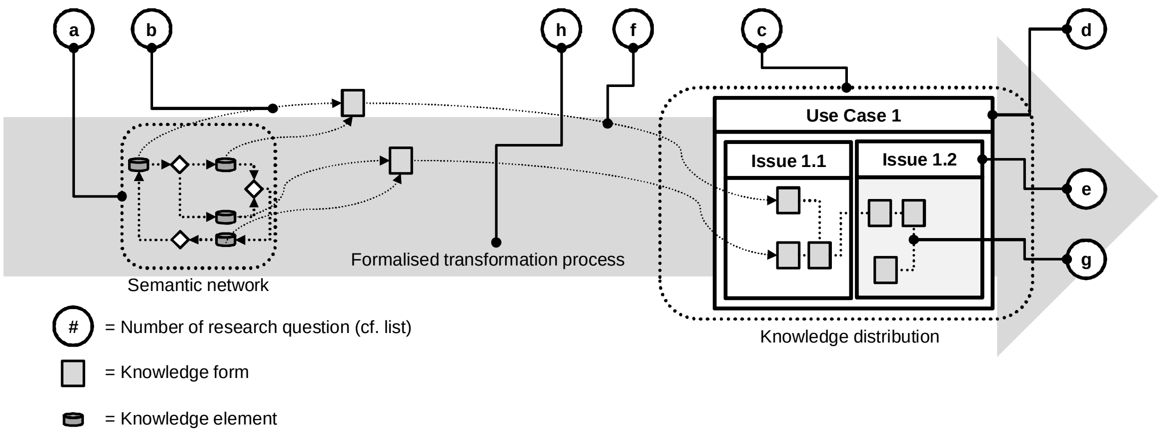

Figure 3. Transformation of the knowledge domain with research questions

In the following, each research question is answered. Due to reasons of space, research questions *4a* and *4b* are limitedly answered but sufficiently to be a foundation for the upcoming questions. Thus, the research focus lies on answering questions *4c* to *4h*. Keeping Figure 1 and 2 in mind, at first, the semantic network will briefly be presented to clearly describe the input into the knowledge distribution (*4a*).

4.1 Description of the semantic network

The first step of the knowledge analysis is building a semantic network which provides a proper overview of the knowledge domain to the knowledge engineer. An exemplary result of this step is presented in Figure 4. This step is not to be confused with creating ontology by using a software tool such as Protégé. Specific knowledge elements from the knowledge database are analysed and structured by using relations and terms. Considering relations, there are merely ten types of relations which are sufficient to describe the whole examined knowledge domain. The ten types are: *isA*, *isEqualTo*, *consistsOf*, *belongsTo*, *dependsOn*, *resultsFrom*, *hasFunction*, *hasProperty*, *hasUnit* and *has*. This fact reduces the degree of freedom for the knowledge engineer, but makes the procedure applicable. After creating the semantic network, knowledge engineers have a proper insight into the knowledge domain and know which relationships exist between two knowledge elements (see Figure 4, terms). With this insight and by following the process according to Figure 2, the knowledge engineer must establish the knowledge distribution. This distribution is the next level of structuring the knowledge after the semantic network. The task to be performed by the knowledge engineer is to rearrange the content of the semantic network in order to create the knowledge distribution. Respecting certain guidelines allows for methodical problem solving (*4b*). For this reason, the semantic network has to be analysed regarding the type of PKF (listed in Section 3 and described in detail in Section 5). By analysing the semantic network in Figure 4, for example, an entity PKF could be established, which describes the structure of the interference fit (interference fit consists of shaft and hub). Thus, the relations *consists of* and *hasFunction* are indicators for the entity PKF (cf. Figure 6). Regarding every type of PKF, concise indicators are inductively derived in the ProKon project. Due to reasons of space, they will not be presented within this contribution.

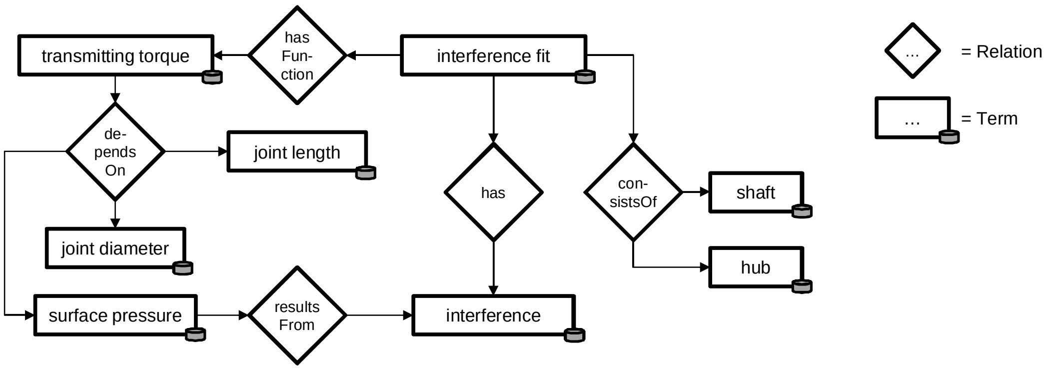

Figure 4. A section of the semantic network in the domain of interference fits

Regarding the main research question and the hypothesis, research questions *4c*, *4d* and *4e* are fundamental and thus are answered in the following in detail.

4.2 Derivation of the knowledge distribution

As one possibility to answer the questions, the CPM approach in accordance with Weber [Weber 2007] and the ProKon-knowledge forms (PKF) mentioned by Kratzer et al. [Kratzer 2011] are taken into consideration. Using these two approaches, the knowledge in the semantic network can continuously be structured and prepared for the knowledge-to-role structure by deriving guidelines. At first, the CPM approach is necessary to distribute engineering design knowledge in general. Specifically, the knowledge domain must be divided into several manageable containers considering the integration of knowledge from the semantic network into these containers. Otherwise, the knowledge domain is too large to analyse and to work with. Moreover, these containers guarantee reusability in terms of a library. The challenges here are to identify the necessary number of containers, the relationships between them in a hierarchy and the specific content of each container (cf. research question *4c*).

Weber [Weber 2007] states that every design process consists of the interplay between characteristics and properties connected by performing analysis and synthesis. The analysis of characteristics could be supported by using DfX guidelines. Due to the fact that ProKon, as a kind of MADS, support design engineers in using DfX guidelines and because DfX guidelines are a specific interpretation of the relationship between characteristics and properties, it is reasonable to start off by structuring the knowledge domain by methodically relating characteristics and properties to one another (see Figure 5). Therefore and due to modularity reasons, two types of containers can be distinguished. At the highest level of the hierarchy, one type of container is defined by a specific set of characteristics related to a specific part (e.g. interference fit with one set of characteristics), and a specific set of properties (e.g. functional properties). This container is called *use case* (cf. research question *4d*). At the lower level, *issues* are established as another type of a container which represent a more limited amount of the knowledge domain compared to the use case (cf. research question *4e*). Thus, one use case consists of one or more issues and hence, the set of properties is broken down into individual properties (e.g. transmitting the loaded torque). As characteristics are only useful in relation to a specific part, properties must also be aligned to the product concerned. This leads to the fact that describing a property (e.g. functional property) of interference fits requires another description than describing screw connections.

In simple words, use cases contain a specific DfX guideline whereas issues concern a rule (and supportive descriptions) within this superior DfX guideline. With these two types of containers, an abstraction of DfX guidelines as well as reusability and exchangeability are guaranteed. On the left hand side in Figure 5, the generic way of deriving the content of use cases and issues is depicted. An exemplary taxonomy as one optimal knowledge distribution is presented on the right hand side in Figure 5. Both sides correspond to each other by comparing on an equal level of height.

Merely using the CPM approach is not entirely applicable when knowledge engineers go through the process presented in Figure 2. Vajna et al. [Vajna 2009] agree with this statement and state that properties and characteristics must be broken down in detail to make them applicable. For this reason, the containers must be operationalised and filled with the knowledge elements from the semantic network. However, these knowledge elements remain too unstructured and non-uniform. Thus, standardised knowledge forms are needed to structure the knowledge elements by building up relationships between them. For example, to fulfil Issue 1.1 in Figure 4, all knowledge elements from the semantic network considering the transmitted torque in accordance with interference fits must be taken into consideration. Hence, Figure 5 includes the ProKon-knowledge forms as the operationalisation of an issue.

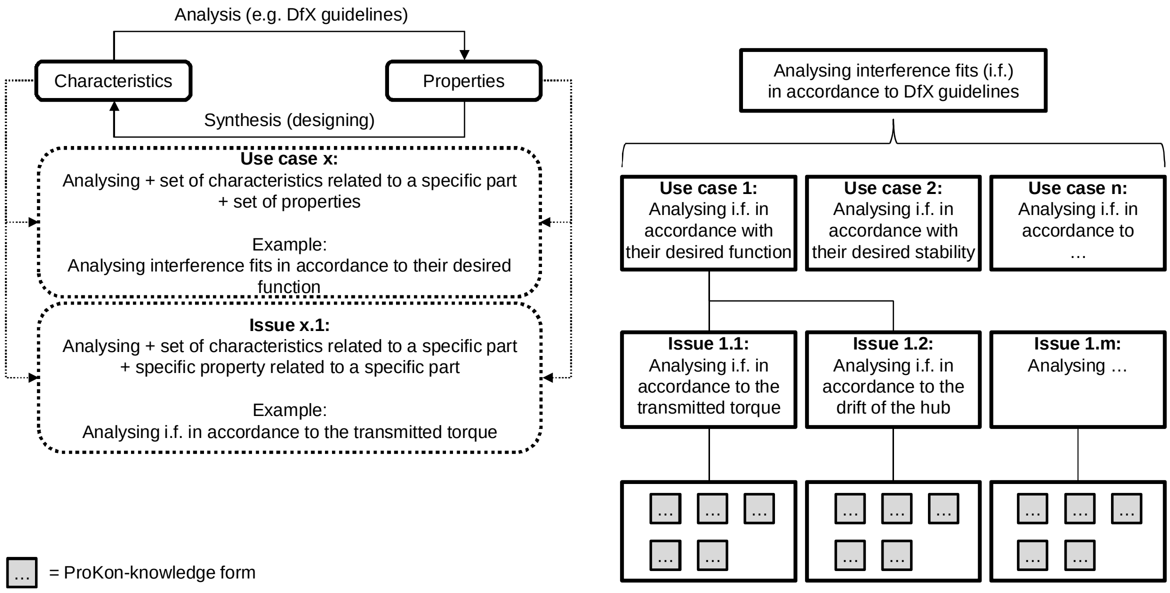

Figure 5. Deriving the content of use cases and issues by using the CPM approach considering interference fits

So far, the developed PKF are just mentioned by Kratzer et al. [Kratzer et al. 2011] but they did not describe them in detail, which is done in the following. Each form consists of the actual knowledge element and a header containing additional details (e.g. relationships to other forms, version, source, date). Altogether, six types of form exist. By relating them to one another, a defined set of PKF is able to formally describe every type of design situation (see Table 2 with the already mentioned knowledge forms: rule (R_1), formula (F_1), entity (E), parameter (P), table (T) and condition (C_1)). Table 2 presents these six types of PKF and answers the research questions *4f* and *4g* mentioned above discussing usage instructions. The usage instructions are directly applied to the example in Figure 6.

Table 2. Description and usage instructions of the six types of ProKon-knowledge forms (PKF)

Type of PKF	Description (content)	Usage instructions (interlinks, assignment)
Parameter P	The parameter form is primarily a central list of parameters to define the parameters system-wide. A parameter form consists of the definition of every variable, constant etc. used in all other PKF.	In most cases the parameter form is located outside of each use case and issue, because of its function as a central list which is suitable to avoid redundancy. Of course it is possible to split the central list into several smaller lists. Then redundancy checks must be performed. All other PKF in the represented knowledge domain are linked to the parameter form.
Table T	The table form includes the parameters from the parameter form and assigns them to concrete peculiarities (e.g. numbers or other properties).	This type of form is similar to the parameter form because of its central position. It is possible to establish one central table with all valued parameters or to split and distribute it over several use cases. Both possibilities have several advantages and drawbacks. The table form has no links to other types of PKF apart from the parameter form.
Entity E	In this type of form, a specific term (e.g. interference fit) is described in an ontological way. This means that others terms, which are defined by entity forms, too, need to be inherently aligned to the term with standardised relationships.	The decision on terms which must be defined through the entity form is difficult. It makes sense to define all machine elements and parts occurring within the final application scenario processed by the MADS. Obviously, this aspect must be clarified case-by-case. Within one entity, several parameters that are defined in the parameter form must be assigned to one term (e.g. term: interference fit, parameter: joint diameter). The entity form is only connected to the parameter form.
Condition C_1	A condition form includes parts of the rule form due to modularity reasons. Thus, defined conditions in rules can be reused system-wide.	The condition form is usually located in the same use case or issue as the related rule form. It consists of the evacuated assumption of a rule which is build up on an operational level (see Figure 6, $C_{1.1}$).
Formula F_1	Formulas support the rule form and calculate parameters if they are not included in the requirements list for example.	Formulas are mostly integrated into one specific issue and connected to rules, other formulas and parameters. But there are formulas which can be set outside of an issue because they can be applied to more than one issue. This is usually the case if these formulas are common in the area of engineering design and used by many other calculations too.
Rule R_1	The rule is primarily the central form in every use case and issue due to the fact that DfX guidelines are based on rules. Rules must be separated into main rules and operational rules. An operational rule comprises the characteristic of the X-System in the assumption (in accordance with Weber [Weber 2007]) and the property in the conclusion. The main rule summarises the assumptions (characteristics) of all subordinated operational rules and compares them with the compliance of the overall DfX guideline (see Figure 6).	Because of their importance, rules are always integrated into a use case or an issue. Specifically, a main rule (see Figure 6), R_1, is subdivided into further rules ($R_{1.1}$ and $R_{1.2}$), if the main rule is dealing with the general compliance of a DfX guideline. If a rule is built up on a more operational level ($R_{1.1}$ or $R_{1.2}$), the rule must be linked with a condition. All rules apart from the main rules are linked to the parameter form.

As a general usage instruction to interlink PKF, beginning at the main rule (see Figure 6, R_1), the linkage should always be comprehensible. Thus, by using these six types of PKF the previously defined semantic network can completely be mapped to the knowledge distribution. Hence, the investigated knowledge domain becomes manageable. Regarding the parameter PKF, table PKF and entity PKF, physical integration aspects within the final MADS must be considered. At last, parameters are located within ontology to guarantee a system-wide consistent vocabulary. This ontology can be compared to a tree without leaves. Leaves are the values defined in the table PKF and included within a database. Hence, three conclusions can be drawn. First, it is necessary to separate the value (table form) from the actual description of the parameter (parameter form). Second, the degree of mapping regarding the physical representation and the knowledge distribution is higher, if a system-wide parameter and table form exist. Third, the parameters must be defined only once. In accordance with Figure 5, one use case includes the analysis of Design for Function as one step within the analysis of the characteristics based on DfX guidelines. An excerpt of the use case and the containing issues regarding the analysis of an interference fit are subsequently described (see Figure 6).

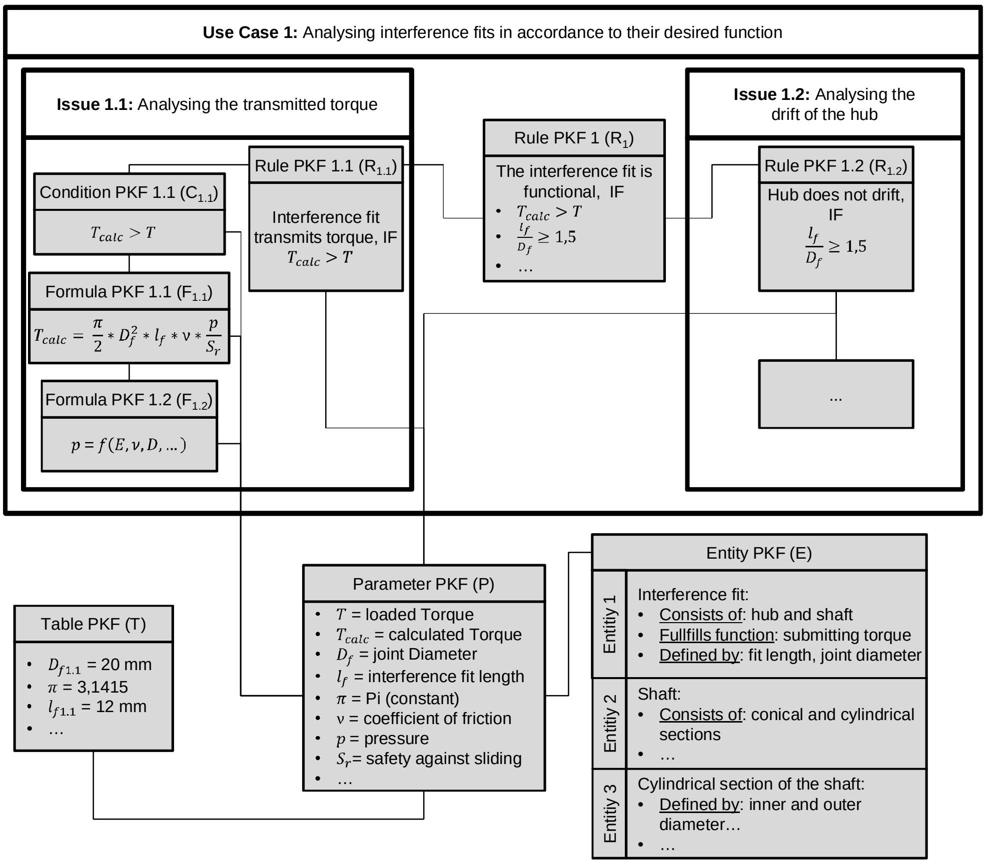

Figure 6. Representation of exemplary use cases and issues considering Design for Function (DfF) and interference fits

4.3 Example of an optimal knowledge distribution in the ProKon project

The main element of the use case is the main rule PKF 1 (R_1) which defines an analysis concerning the functionality of the interference fit. Only by complying with all conditions of the rule can the interference fit reliably fulfil its function. The testing of each of these rules is performed by an issue. Hence, every issue contains another rule PKF. The objective of issue 1.1 is the comparison of the calculated and loaded torque (rule PKF 1.1 ($R_{1.1}$)), the objective of issue 1.2 (rule PKF 1.2 ($R_{1.2}$) is the verification of whether the hub will drift or not. Each of these rules contains a condition. In the case of rule PKF 1.1 ($R_{1.1}$), the calculated torque must be greater than the loaded torque which is defined by the requirements list. This condition is part of the condition PKF 1.1 ($C_{1.1}$). All formulas, rules, and conditions which are necessary for analysing this condition are elements of the respective issue. The calculated torque must be determined, thus it is defined by a formula within the formula PKF 1.1 ($F_{1.1}$). The calculated torque is being defined, amongst others, by the variables joint diameter of the interference fit (D_F), interference fit length (l_f) and the pressure (p) as well as the constant Pi (π). Both, constants and variables, are part of the parameter PKF (P) and connected with their respective values which are elements of the table PKF (T). The pressure (p) must be calculated by another formula (formula PKF 1.2 ($F_{1.2}$)) and is dependent on the diameter, the Poisson´s ratio and the Young´s modulus of the shaft and the hub. The connections between one or more parts, the connections between the functions and the parts as well as between the parts and their parameters are defined by the entity PKF (E). For example, the interference fit which consists of a hub and a shaft has the objective to transmit a defined torque. Hereby, the interference fit is defined by the interference fit length and the joint diameter.

4.4 A concrete procedure for knowledge engineers

After answering the research question *4a* to *4g*, there has to be a concrete procedure for knowledge engineers to really transform the knowledge domain from the semantic network into an optimal knowledge distribution related to a specific case. The starting point is a consistent semantic network with knowledge elements to derive a PKF. From this point, knowledge engineers have to proceed like as follows:

1. Analyse the semantic network regarding the type of PKF by considering relations as indicators
2. Aggregate several knowledge elements (terms) to PKF
3. Analyse your requirement list regarding the DfX guidelines the MADS has to check
4. Establish the foundation of the knowledge distribution by using the approach in Figure 5
5. Derive all necessary use cases and issues
6. Fill out the use cases and issues with PKF considering the usage instructions in Table 2
7. Assign the chosen PKF to each other considering the usage instructions in Table 2

By using this procedure, the knowledge distribution can be used for a subsequent assigning of the knowledge to the agents, and furthermore, for creating the knowledge-to-role structure (KRS) in the next step.

5. Discussion of the results

The results of Section 4 and their limitations are critically discussed. At first, the validity of the hypotheses must be checked. As stated in Section 2, the hypothesis consists of two parts, namely the CPM approach and the ProKon-knowledge forms. Regarding these two parts, whether or not they contribute to the solution as expected must be considered here. Weber's CPM approach is applied to separate the knowledge domain into use cases and issues by using properties and characteristics in combination with the related DfX approach. The result of this separation is a generic distribution of knowledge. It must be stated that there was no systematic assessment and selection of several approaches as Weber's approach represents the inherent way of designing: transformation of properties into characteristics and vice versa by using analysis and synthesis. This could be stated as naive, however, every serious research starts with an axiom as a foundation. As stated in Section 4, knowledge of a specific DfX guideline becomes concrete only if it is applied to the product. Thus, a relationship between the structured knowledge domain and the actual subject of interest, namely the product, is essential, predictable but absolutely necessary (e.g. assignment of the structured knowledge to the interference fit).

A further critique could be stated regarding the separation of the knowledge domain into use cases and issues. By using the approach in accordance with Weber, a useful and reasonable division of DfX guidelines in the domain of interference fits was established. It may be discussed if this separation is arbitrary and if there is a need to insert more or less gradations. At last, the ProKon-knowledge forms (PKF) are used to operationalise the structure for knowledge engineers. As the actual properties of the PKF, the use case and the issue are subdivided into inseparable elements which represent the connection between the knowledge elements in the semantic network, the PKF in the knowledge distribution itself, and the elements assigned to the agents in the knowledge-to-role structure. Moreover, the assignment of PKF to a concrete issue is important (see Figure 6) but not necessarily unambiguous in all cases. By respecting the rules stated in Table 2, an orientation for knowledge engineers is given. In individual cases it can be discussed if one specific PKF should be located outside of a container or not.

Finally, the main point for knowledge engineers, the separation of the knowledge domain into use cases, issues, and the implementation of PKF respectively, should serve the purpose of methodically developing MADS. As it is the case for all methods and procedures, they must be applied with a professional mind-set. As stated before, the guidelines described in Table 2 provide support for knowledge engineers as well as the procedure stated in the end of Section 4. In summary, at least for the application of the knowledge distribution on interference fits, the hypothesis is verified. By means of this inductive approach, more knowledge domains must be examined to realise a proven theory. In the ProKon project, the knowledge domains to design a wheelset within a gearbox will be investigated.

To answer the last research question (No. 5, depicted in Table 1) on how to methodically evaluate the knowledge distribution, the whole procedure for developing MADS (see Figure 2) must be analysed. Obviously, just the physical knowledge-to-role structure which is developed and integrated by the software engineer is suitable to prove if the chosen distribution has a positive or negative influence on the functionality of MADS. The more the progress of developing MADS is passed from the end (physical knowledge-to-role structure, not represented in Figure 2) to the beginning, the more difficult it is to scientifically prove the influence of the knowledge distribution on the functionality of MADS. The reason is that more and more influencing factors are added by going through the process backwards. To evaluate the knowledge distribution carried out in this contribution, all subsequent influencing factors must be neglected or stated as constants. Hence at present, only an approximate evaluation is possible. The developed knowledge distribution is part of the ProKon project and was used to develop the current prototype described by Kratzer et al. [Kratzer 2011]. The resulting functionality was satisfactory, although the prototype is just dealing with shaft-hub connections. For evaluation purposes, the software engineer was able to work with the knowledge distribution and the knowledge-to-role structure, respectively. As an improvement it was suggested to already provide first recommendations, which PKF must be assigned to which agent. Thus, the transfer from the knowledge distribution to the knowledge-to-role structure could be made easier.

6. Conclusion and outlook

Based on the development of a multi-agent design system (MADS), the importance of the knowledge distribution was shown. A procedure with supportive usage instructions for creating a knowledge distribution from a semantic network was presented in this contribution. Moreover, a generic distribution of knowledge was developed. Although the DfX guidelines comprise only the knowledge elements which are necessary for the description of one part of the knowledge domain, this unstructured knowledge could not yet be used for assigning the knowledge to the agents by a knowledge-to-role structure (KRS). Therefore, to assign the knowledge to the agents of a MADS it is necessary to structure the knowledge. According to the CPM approach by Weber and the ProKon-knowledge forms by Kratzer et al., a knowledge distribution was developed by defining manageable parts of the knowledge domain which are also reusable. On the one hand, the knowledge elements of the knowledge domain must be collected and presented in a standardised form, for example the PKF. On the other hand, these PKF must be grouped. As a result, clearly delimited parts of the knowledge domain which are called use cases and issues, were defined. The use cases comprise all knowledge needed for checking compliance with a specific DfX guideline. Although a single use case contains only a limited part of the knowledge necessary for the analysis, this part of the knowledge domain is still too large for directly assigning it to the agents. Hence, the use cases are split into issues which are independent from one another. By using this procedure, the development of a knowledge distribution becomes possible, and clearly delimited parts of the knowledge domains can be defined. These parts can be assigned to the agents of the MADS, thus, the KRS can be defined. Keeping Figure 6 in mind, Figure 7 shows an example of a possible KRS for the interference fit. Within this KRS, knowledge is assigned to two agents and ontology. The aspect agent is responsible for the check regarding a specific DfX guideline, for example, the DfF. Hence, the main rule PKF 1 (R1) is assigned to the aspect agent. The knowledge that is required to check this main rule including formulas, conditions and rules for designing an interference fit is assigned to the specialist agent. This specialist agent is comparable to a specialised designer for interference fits. The parameters, the values within the table PKF (T) as well as the entity together form the ontology. This KRS is still arbitrary so that a methodological approach for assigning the knowledge to the agents by clear rules must be developed. Through this, the development of a KRS becomes completely methodical.

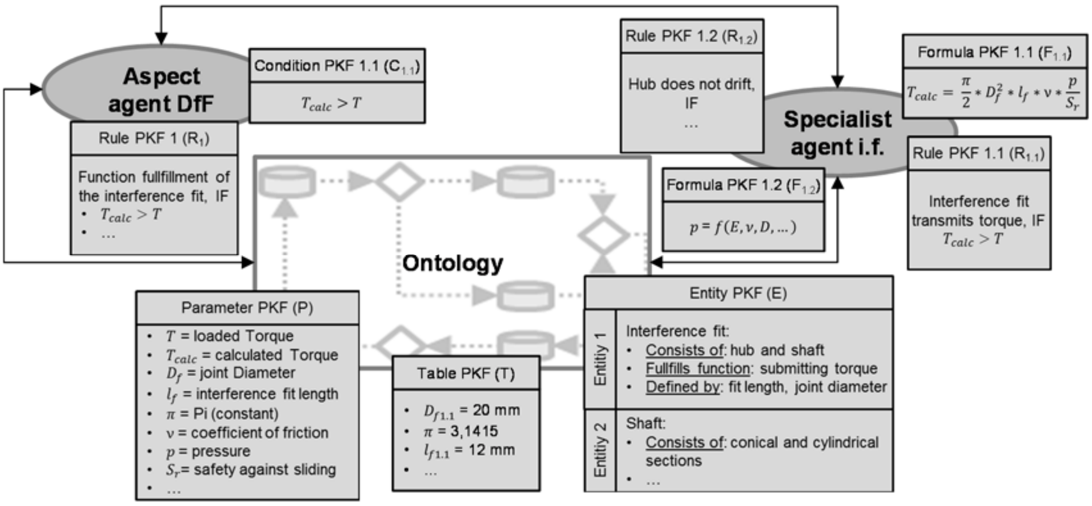

Figure 7. Exemplary knowledge-to-role structure as outlook for further research

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