Semantic Modeling Supports the Integration of Concept-Decision-Knowledge

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Yili Jin[1] , Jinzhi Lu[*2], Guoxin Wang[*1], Ru Wang[1], Kiritsis Dimitris[2]

[1] Beijing Institute of Technology, Beijing 100089, China
[2] EPFL SCI-STI-DK, Station 9, CH-1015 Lausanne, Switzerland
jinzhi.lu@epfl.ch

Abstract. The semantics of product design enables to visualize the function of the product and promote communications between the products and the designers. However, the existing theories and methods of product design are lack research on the integration of modeling concepts, domain-specific knowledge, and decision-making. For this reason, this paper proposes a C-D-K theory which is supported by a semantic modeling approach. Firstly, KARMA modeling language, which is a semantics modeling approach, is used to support the formalization of concept space (C) and decision space (D), in which space C is expanded based on the RFLP design framework, and space D is based on PEI-X decision workflow to realize decision problem modeling. Then based on the Open service lifecycle collaboration (OSLC) specification, domain-specific knowledge is represented based on the unified expression of resources in the knowledge space (K), which is used to integrate knowledge to semantics models constructed by KARMA language. Finally, the feasibility and effectiveness of the proposed semantic modeling approach are verified by the case of an unmanned detection vehicle design. From the result, we find the semantics modeling approach enables to integrate semantic models and knowledge based on the C-D-K theory.

Keywords: Semantic Modeling, C-D-K Theory, MBSE， KARMA.

1 Introduction

In the context of Industry 4.0 and intelligent manufacturing, product design is challenged when developing a solution based on existing knowledge and make decisions for the different solutions [1], because of different data structures and lack of design tools. Currently, semantic modeling is the basis of describing product information using models and shareable data [2]. It often contributes to integrating domain-specific knowledge and development solutions with design frameworks. These frameworks are mainly used to identify concept and decision-making elements for product design.

To construct a design framework for the concept development and decision-making for product development, design theories are often used to capture and frame the topologies between concepts, decision-making, and knowledge across different domains. Currently, C-K theory has received wide attention for integrating concept design and domain knowledge. However, when implementing the trade-off between different concept solutions, due to the lack of research on the digitization and modeling representation of decision-making and design knowledge, there is still a challenge for C-K theory to support product design with decision-making.

This paper proposes a semantic modeling approach that supports C-K theory and makes use of a case study to verify its feasibility. The main scientific contributions of this paper include:

1. To support Decision-Based Design for product design, C−K theory is extended to C-D-K theory [3, 4].
2. The semantic modeling method of concept - decision - knowledge integration is proposed, KARMA is used which is a general modeling language based on the GOPPRR method[5], for realizing the formal description of heterogeneous concepts, decision-making, and knowledge of the product.
3. Open Services for Lifecycle Collaboration (OSLC) supports unified knowledge representations which is integrated into KARMA models referring to concept models and decision-making models [6].

In the following chapters, we will introduce in detail our proposed semantic modeling approach that supports the integration of Concept-Decision-Knowledge of product development. Section 2 describes the literature review. Section 3 describes the proposed approach, including the C-D-K theory, semantic modeling using KARMA language, and three specific formal expressions of C-D-K. Section 4 introduces a case study of an unmanned detection vehicle design to verify the feasibility of our proposed method.

2 Literature Review

C-K theory has received extensive attention since it was proposed. To understand and apply C-K theory, the existing literature extends C-K theory from different perspectives. Masson [7] focus on the process of collective creation for product development and puts forward the KCP theory based on the C-K theory. Besides, Kazakci [8] tried to apply C-K theory to the development of computer-aided design tools and developed a new C-K-E theory, which is more explanatory to the design process in a specific field. In the field of design, more and more scholars believe that decision is the basic structure of product design. To support the decision-making of concept models based on the existing knowledge, a C-D-K theory is proposed to integrate concept design, decision-making, and specific knowledge [3].

Semantic modeling is the most important part of the computer-aided design method based on C-D-K theory. In terms of semantic modeling, many methods have been proposed for different purposes. For example, System Modeling Language (SysML), Business Process Modeling Language (BPMN), semantic Web Modeling, and so on. These languages are always developed with different tools, which have their syntax. However, when integrating heterogeneous models in spaces of concepts, decision-making, and knowledge, there are not researchers proposing a semantic modeling approach based on C-D-K theory.

In summary, to support product design from the perspectives of concept design, decision-making, and domain-specific knowledge, a semantics modeling approach is investigated in this paper. Semantic modeling approach based on the previous research [5] is proposed to support C-D-K theory (previous research [3,4]). Through this approach, concepts and decision-makings are formalized which are integrated with web services of knowledge graph represented based on OSLC specification.

3 Semantic Modeling for Integrating Concept-Decision-Knowledge

3.1 Overview

Aiming at the characteristics of product design with domain-specific knowledge, decision-making process, and conceptual solutions, a C-D-K theory and its semantic modeling method are proposed. In the C-D-K theory, Decision Space (D) is defined as the bridge between Concept Space (C) and Knowledge Space (K) during the whole design process. The semantic modeling approach that supports C-D-K theory is shown in Fig 1. Due to the heterogeneity of information in these three spaces, this paper uses the KARMA unified modeling language to support the formal description of the C-D-K three-dimensional heterogeneous space. KARMA language [5] is a semantic language with textual grammar based on GOPPRR-E approach. The purpose of Space C is to obtain a satisfactory solution through the product design process. Thus, the concept models are developed using KARMA libraries based on Requirement, Function, Logical and Physical (RFLP) design processes and SysML specifications [9]. Space D aims to formalize the decision-making processes when implementing the trade-off processes of the product concept selections. Thus, the decision-making models are developed using KARMA libraries based on decision support problem (DSP) and PEI-X diagram model[10], for describes the decision-making process across RFLP. Space K represents the existing specific knowledge for support concept development and decision-making. Thus, OSLC specifications is used to transform the heterogeneous knowledge data to a unified description of web services. Such web services can be integrated with KARMA models presenting Space C and Space D.

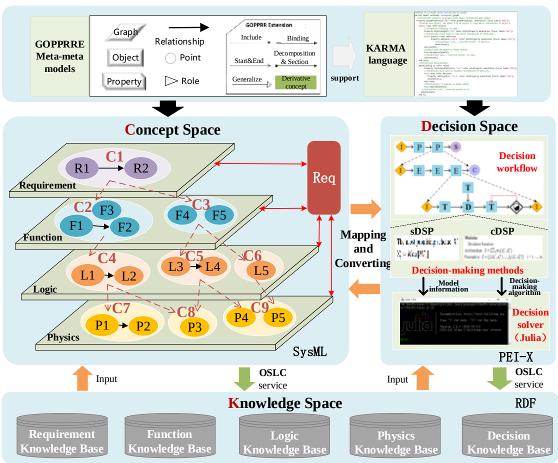

Fig. 1. Semantic Modeling method of C-D-K Theory

3.2 C-D-K theory

C-D-K theory is an extension of C-K theory by introducing an extra Space D. It refers to an entire product design framework that contains the perspectives of concept design, decision-making, and existing knowledge. The three spaces are defined as follows.

- **Space C**

Space C refers to multiple alternative models based on the RFLP modeling process, which have a series of attributes: *A1*, *A2*, … , *An*. Thus, Space C can be expressed as:

$$ConceptSpace=\sum OptionalSolution_{i,j}\ (\sum Attribute_{i,j,n}) \quad (1)$$

Where the $\sum OptionalSolution_{i,j}$ represents the set of alternative concept solutions based on the RFLP workflow which is described using KARMA language and SysML specification. The i refers to the design processes of RFLP ($i\in\{R, F, L, P\}$). The j refers to the j^{th} concept solution ($j\in\{1,2,\ldots j\}$), The $\sum Attribute_{i,j,n}$ represents the n^{th} attribute set of the j^{th} concept solution of phase i ($n\in\{1,2,\ldots n\}$).

- **Space D**

Space D refers to the decision process based on DSP. DSPs mainly includes selection decision, compromise decision, so Space D can be expressed as:

$$DecisionSpace = \sum (sDSP,\ cDSP) \quad (2)$$

Where the *sDSP* is a generic class of multi-attribute decision making, which evaluates and ranks the performance of all feasible options quantitatively to determine the most tendentious options. *cDSP* is a generic class of multi-objective decision-making, which is a mixed multi-optimal solution based on mathematical programming and goal programming.

- **Space K**

Space K contains all kinds of existing knowledge resources to support the concept solutions of Space C and the decision-making processes of Space D. When constructing the product concepts and decision-making processes, the previous knowledge is considered as the reference models. Therefore, Space K can be expressed as:

$$KnowledgeSpace= \sum (RK, FK, LK, PK, DK) \quad (3)$$

Where the *RK* represents the existing requirement models and related reference resources; the *FK* represents existing function models and related reference resources; the *LK* represents existing logical models and related reference resources; the *PK* represents existing physical models and related reference resources; the *DK* represents existing decision-making models and related reference resources.

3.3 Semantic Modeling of the C-D-K Theory

This paper uses KARMA language to construct the models related to the formal expressions based on C-D-K theory. As shown in Fig.2, the KARMA language is a semantic modeling language based on the GOPPRR method including the meta-meta models, meta-models, and models in an M3-M0 modeling framework. The details are as follows:

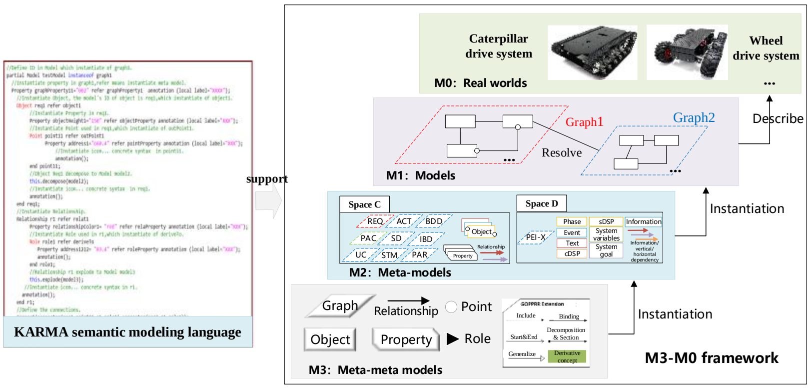

Fig. 2. M3-M0 modeling framework

- **M3**：Meta-meta models are the basic elements for constructing meta-models. KARMA language is developed based on the GOPPRR meta-meta models. The six key meta-meta models of GOPPRR are introduced based on the related definitions proposed by Kelly et al [11].
    a. *Graph* is a collection of *Objects*, *Relationships*, and their connections which refers to the diagram of the model.
    b. *Object* refers to one entity in *Graphs* (for example, one class concept in SysML), which represents a model composition.
    c. *Property* refers to one attribute of the other five meta-meta models describing its characteristics.
    d. *Point* refers to one port in *Objects*.
    e. *Relationship* refers to one connection between the different *Points* of *Objects* or *Objects*.
    f. *Role* is at both ends of the *relationship*, which is used to indicate how *objects* are connected.
- **M2**：Meta-models refers to the model compositions which construct the model library, such as KARMA SysML library. The developed meta-models are used to represent the compositions of concept solutions and activities of decision-making processes.
- **M1**：Models are developed based on the meta-model.
- **M0**：Architectural views in the real world described by models.

（1）Semantic modeling for Space C

When developing the concept models for product design, requirement models, functional models, logical models, and physical models enable to define one concept solution for one product using KARMA SysML library [12]. In KARMA SysML library, there are nine graphs developed based on SysML specification including requirement diagram (REQ), package diagram (PAC), use case diagram (UC) and activity diagram(ACT), sequence diagram (SD), and state machine diagram(STM), block definition diagram(BDD), internal block diagram(IBD) and parameter diagram (PAR). Through these graphs, requirement, functional, logical, and physical models are constructed in order to define the product concepts. The details of the SysML meta-model library based on the GOPPRR approach are shown in Table 1.

Table 1. Space C meta-model library (*C_graph* refers to *graph* for concept modeling)

C_graph	*C_object*	*C_relationship*	Description
REQ	Package, Test case, Constraint modules, Comments, Requirements	Include, Trace, Reuse, Improve, Satisfy, verify	**Requirement:** Used to describe the requirements of product design, such as functional requirements.
PAC	Package, Module, Interface module, Model, Model base, Feature, Constraint module, Value type	Generalization, Association, Introduction, Combination	**Functional:** Used to realize the functional analysis of the product, such as functional division, interaction between stakeholders, and the system.
UC	Package, Participant, Interface module, Module, Use case	Include, Generalize, Associate, Extend	
ACT	Packet, Action, Send action, Shunt, Fork, Node, Accept event, Select, Start, Terminate, End	Object flow, Control flow	
SD	Modules, Operator, Lifeline object, Selection, Cycle	Deliver message, Reply message, Create message	**Logical:** Used to realize the logical analysis of the product, such as the time interaction of the activities in the system and the expression of the system state.
STM	Fork, Start, End, Selection, Status, Historical mark	Conversion	
BDD	Package, Interface block, Block, Constraint block, Value type, Comment	Generalization, Association, Project flow, Composition	**Physical:** Used to describe the physical implementation structure of the product, such as the module composition of the product, the internal elements and relationships of the module.
IBD	Interface block, Internal block, Comment	Object stream	
PAR	Parameter, Interface block, Constraint block	Parameter flow	

（2）Semantic modeling for Space D

There are mainly two kinds of decisions involved in engineering design, namely, selection decision and compromise decision. To formalize the decision-making processes for the trade-off of product concept solution, a domain-specific modeling language, the PEI-X diagram, is used to describe the decision analysis process within Space D. The details of the Space D meta-model library based on the GOPPRR method are shown in Table 2.

Table 2. Space D meta-model library (*D_graph* refers to *graph* for decision-making modeling)

D_graph	*D_object*	*D_relationship*	Description
PEI-X diagram	Phase, Event, Text, cDSP, sDSP, System variables, System alternative, System goal, System constraint, System boundary, Information	Information Dependency, Vertical Dependency, Horizontal Dependency	Describe the decision workflow in Space D.

（3）Integrating Semantic models with Space K

Knowledge in Space K is represented as RFLP and decision-making models and related materials. When developing the models of Space C and Space D, knowledge can be used to develop or be integrated into concept and decision-making models. As shown in Fig. 3, models and related resources are transformed to OSLC services through the developed OSLC adaptors. Such OSLC services have their URIs which are presented as OSLC RDF. Through service discovery, OSLC services can be input into concept and decision-making models. Through OSLC services, related knowledge information can be configured into different models. For example, when developing the REQ model, the property of one model composition can be configured as knowledge information through OSLC services.

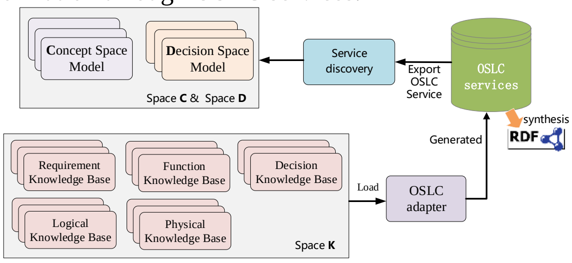

Fig. 3. OSLC service generation

4 Case Study

A case study of an unmanned detection vehicle design is used to evaluate the proposed approach. The vehicle is constructed by mechanical components, electronics, and an embedded system. Its design process is a knowledge-intensive and complex decision-making process. Traditional design methods cannot achieve a unified description of product conceptual schemes, design decisions and design knowledge, resulting in difficulties in design information transmission and low design efficiency. Therefore, the concept-decision-knowledge integrated modeling method proposed in this paper is used to model and digitize the design process of unmanned vehicles.

As shown in Fig.4, based on KARMA language, requirement models, function models, logic models, and physical structure models are developed based on SysML specifications. The vehicle has different concept solutions as shown in Table 3. Different motor and battery construct different vehicle concepts which lead to different KARMA models for each concept solution. The decision-making processes for the trade-off of the given different concept solutions are formalized using the KARMA language based on PEI-X specification. When developing such concept models and decision-making models, the previous KARMA models are referenced to configure the property values through OSLC services. And the decision-making algorithms used in the decision-making processes are created in JULIA [13]. The developed JULIA script enables to capture of property values in concept solution models and decision-making models. Then after the JULIA script implementation, the optional concept solution model can be selected based on the results obtained from JULIA script implementation.

As shown in Fig. 4, the semantic model of the Space C and Space D is built using a domain modeling tool MetaGraph (http://www.zkhoneycomb.com/). The OSLC adapter for Space K is designed and built by an OSLC designer tool DataLinks (http://www.zkhoneycomb.com/). As shown in Table 3, different components construct different solutions. Thus, all the solutions are developed based on KARMA language in MetaGraph. Moreover, the sDSP decision model is built to formalize the decision-making processes in MetaGraph. Associated with the sDSP models, JULIA algorithms are developed and solved using the Julia solver in the MetaGraph tool. Through the decision-making algorithm results generated after JULIA implementation, the assessment results of all the alternatives are obtained as shown in Table 3. From the result, we can find the concept solution 1 can be accepted

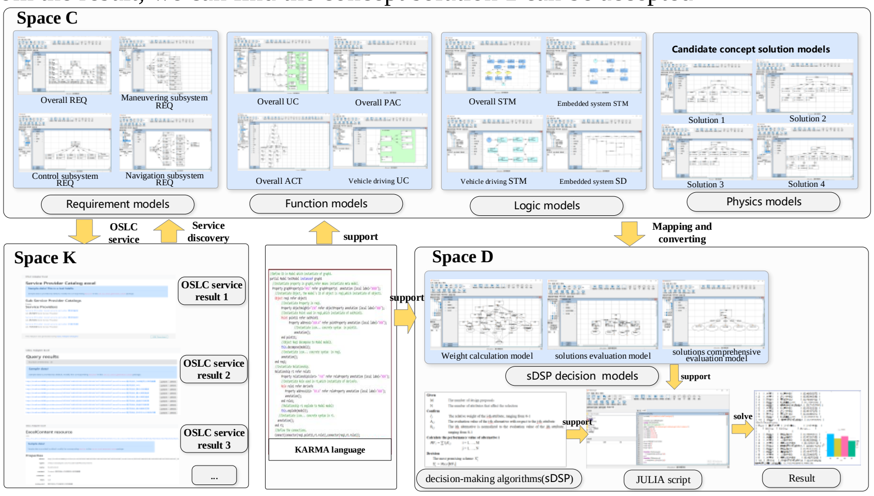

Fig. 4. The design process of unmanned detection vehicle based on C-D-K Theory

Table 3. Alternative concept solutions and their trade-off results

Solution	Power battery	Motor	Drive system	Performance value
1	Lithium-ion battery	Permanent magnet brushless DC motor	Crawler type	0.74329
2	Lithium-ion battery	Permanent magnet brushless DC motor	Wheel type	0.59169
3	Lithium-ion battery	Switched reluctance motor	Crawler type	0.66742
4	Lithium-ion battery	Switched reluctance motor	Wheel type	0.51582

5 Discussion

The C-D-K theory provides a basic framework to integrate product concept, decision-making for concept trade-off, and specific knowledge. Using semantic modeling with KARMA language and OSLC, product concept solutions are developed as different sets of KARMA models. Moreover, decision-making processes are also developed as KARMA models. When developing such models, OSLC services representing resources of knowledge can be load to configure the KARMA models automatically. To select the optimized concept solution, JULIA scripts are used to develop the decision-making algorithm used in the decision-making processes described by the KARMA models. Then an optimized solution can be selected after implementing the JULIA scripts. Compared with the existing research, the contributions of this paper are as follows:

- The proposed semantic modeling approach enables to formalize candidate concept solutions and decision-making processes using a unified semantic representation through KARMA language.
- OSLC specifications are used to capture the information from knowledge that is used to configure the KARMA models.
- Through all the semantics modeling techniques, the C-D-K theory is realized to support the product concept development and decision-making based on the given knowledge.

6 Conclusion

In this paper, a C-D-K theory is proposed to support the integration of concept design, decision-making, and knowledge, which provides a theoretical framework to support product development with semantic modeling. A KARMA language is used to develop concept and decision-making models and OSLC is used to construct web services of domain knowledge. Through OSLC services, concept and decision-making models can be configured automatically. The feasibility of this approach is verified by an unmanned detection vehicle design case.

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