Knowledge Base Construction for Product Configuration Systems using Executable Standard Design Descriptions

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ABSTRACT

Knowledge based product configuration systems are a cornerstone for the successful implementation of one-of-a-kind manufacturing. We propose the usage of graphical, standard software engineering design techniques to improve the development and maintenance process for these systems.

We show how a standard design method (UML) can be tailored with domain-specific modeling concepts for the configuration domain using built-in extensibility features. These conceptual models are not only used for representation purposes and for a better communicability of complex technical systems but can be transformed into a processible representation. A non-ambiguous transformation into a logic based representation is presented, which clearly defines the semantics of the employed concepts. After the (automatic) transformation, the resulting logical sentences can be exploited by general inference engines solving the configuration task.

1 INTRODUCTION

In many domains, product configuration systems (configurators) have proven to be a cornerstone for a successful implementation of the post-mass-production paradigm. Products are offered to customers in many variants or may be tailored (configured) with respect to the specific needs of the customer. Configurators support engineers and sales representatives to manage possibly thousands of variants and to configure complex technical systems, e.g., in the telecommunications domain.

The development and maintenance of the configuration knowledge base is a critical and time consuming task, since the technical knowledge is distributed among different people and organizational units within the company (Figure 1).

- **Product Management and Marketing:** According to the market demands it has to be decided which features of the product should be configurable and adaptable to the customer requirements.
- **Product Development and Engineering:** These departments have to state technical possibilities and restrictions for the configurable artifact.
- **Sales representatives:** The quality of their consulting service can be improved, if they understand the product structure and the restrictions of the configurable features.

Due to short development and maintenance cycles for configurable products and the accompanying configuration software, knowledge based configuration systems with domain specific, high level, formal description languages have become a successful application of AI-technology. These techniques can be exploited to (partially) automate the generation of software solutions.

Unfortunately, in many cases, these descriptions are difficult to communicate between people involved in the development of the product and the configurator and these techniques are not incorporated into the standard development process. Therefore, our goal is to make such descriptions more accessible both for the software engineering practitioners and domain experts with a technical background.

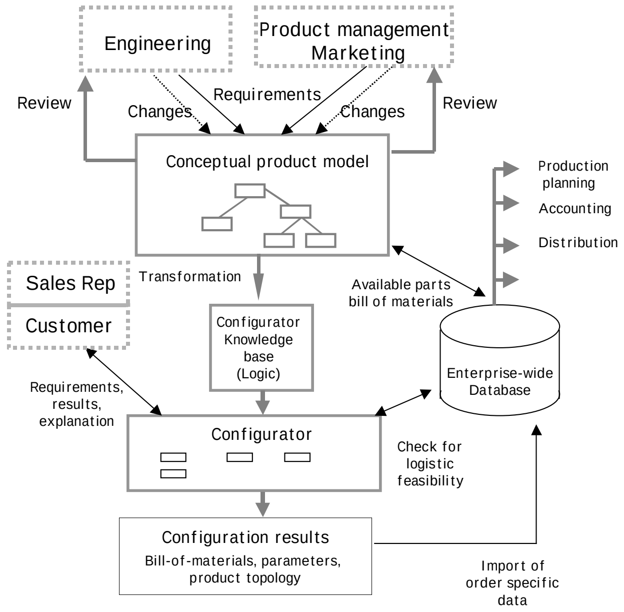

Engineering
Product management Marketing
Review
Changes
Requirements
Changes
Review
Conceptual product model
Production planning
Accounting
Distribution
Sales Rep
Customer
Transformation
Available parts bill of materials
Configurator Knowledge base (Logic)
Enterprise-wide Database
Requirements, results, explanation
Configurator
Check for logistic feasibility
Configuration results
Bill-of-materials, parameters, product topology
Import of order specific data

Figure 1 Configurator integration

Our approach proposes the usage of a wide-spread and easy-to-communicate modeling technique (Unified Modeling Language - UML[4]) for the design of a configurable product on a conceptual level for two reasons:

First, OMT and UML (as its successor) are widely applied in industrial software development as a standard design method. Second, we made excellent experiences in using OMT-designs for validation by technical domain experts. In order to use UML in this modeling domain, we extend the static model by broadly used configuration-specific modeling concepts utilizing the built-in extension mechanisms of UML (*stereotypes*). The extension of UML with domain specific concepts has shown to be a promising approach in other areas [12].

Since we are not only interested in conceptual models but in executable configuration applications, we define a non-ambiguous transformation from this level to a processible representation which is common to many existing configuration systems. The resulting system is based on a declarative, logic based, explicit representation of the configuration knowledge and can be exploited by a general configuration engine [3].

This transformation offers two main advantages:

- The development, maintenance and reviewing processes can be done on a graphical and conceptual model which can be transformed to an executable system. The need for a knowledge engineer for these tasks is minimized. Furthermore, the development of a knowledge based system is integrated into standard software engineering processes.
- The mapping to a logic-based representation defines a clear semantics for the modeling concepts used in the UML-model.

Finally, we formally define a logic based representation for a configuration result, which can be easily incorporated into standard enterprise databases, because the integration with these systems is an important factor for the success of configuration systems.

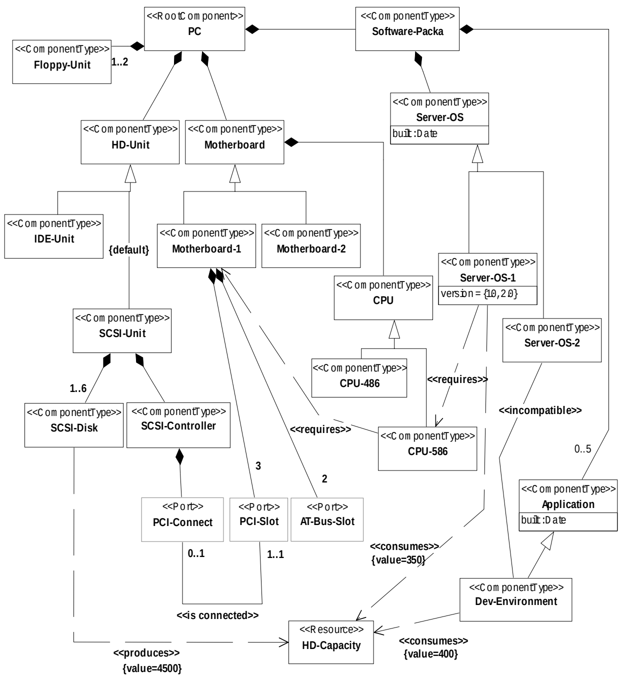
The rest of the paper is organized as follows. After giving a motivating example (Section 2), we describe the logical model of a configuration problem (Section 3). In Section 4 we describe typical modeling concepts for product configuration, their representation in UML and the transformation to logical sentences. Section 5 describes the application environment. Finally, Sections 6 and 7 contain related work and conclusions.

2 MOTIVATING EXAMPLE

The following example shows how a configurable product can be modeled using an UML static structure diagram. This diagram describes the generic product structure, i.e., all possible variants of the product. The set of possible products is restricted through a set of constraints which relate to customer requirements, technical restrictions, economic factors, and restrictions according to the production process.

For presentation purposes we introduce a simplified model of a configurable PC as working example. We use standard UML-concepts as well as newly introduced domain-specific stereotypes. The basic structure of the product is modeled using classes, generalization and aggregation of the well-defined parts (component-types) the final product can consist of. The applicability of these object-oriented concepts for configuration problems has been shown in [10].

Note, that compared to OO-analysis in unstructured domains, classes (component-types) in the configuration domain are easily identified.



<<RootComponent>> PC
<<ComponentType>> Software-Packa
<<ComponentType>> Floppy-Unit
1..2
<<ComponentType>> Server-OS
built:Date
<<ComponentType>> HD-Unit
<<ComponentType>> Motherboard
<<ComponentType>> IDE-Unit
{default}
<<ComponentType>> Motherboard-1
<<ComponentType>> Motherboard-2
<<ComponentType>> Server-OS-1
version = {1.0,2.0}
<<ComponentType>> CPU
<<ComponentType>> Server-OS-2
<<ComponentType>> SCSI-Unit
<<ComponentType>> CPU-486
<<requires>>
1..6
<<ComponentType>> SCSI-Disk
<<ComponentType>> SCSI-Controller
<<incompatible>>
<<requires>>
<<ComponentType>> CPU-586
0..5
3
2
<<ComponentType>> Application
built:Date
<<Port>> PCI-Connect
<<Port>> PCI-Slot
<<Port>> AT-Bus-Slot
<<consumes>> {value=350}
0..1
1..1
<<ComponentType>> Dev-Environment
<<is connected>>
<<Resource>> HD-Capacity
<<consumes>> {value=400}
<<produces>> {value=4500}

Figure 2 Product model of a configurable PC

Additional modeling concepts for configuration

Requires and incompatible The set of valid PC-configurations is restricted through stereotyped requires-relations and incompatible-relations between different components.

Ports and connections For some configuration domains it is important how different components are connected to each other. Components can be connected through connection points (ports). One port can only be connected to exactly one other port.

In our example, an SCSI-controller has a port called "PCI-connector". A motherboard of type "Motherboard-1" has three PCI-slots. The multiplicity of the stereotyped association "is connected" denotes, that a PCI-connector must be connected to a PCI-slot, whereas a PCI-slot can possibly be connected to a PCI-connector.

Resources A further enhancement of the model is expressed through resources which impose additional constraints on the possible product structure. Some components can contribute to a resource whereas others are consuming some of the resources. In an actual configuration the resources must be balanced, i.e., the consumed resources must not exceed the provided resources. The contribution and consumption of a resource is modeled through relations "consumes" and "produces". A tagged value denotes the actual value of production and consumption. In our example, the disk-capacity of the system must be greater or equal to the capacity consumed by the installed software.

Calculating configurations

After having defined the configurable product, the user (customer) can specify the requirements for the actual variant of the product, e.g., by selecting some key components. The product configuration system then searches for a valid configuration. In the configuration process additional components are selected and added to the final product according to the compatibility constraints. The configurator establishes the needed connections between components and checks whether the resources are balanced. The final product can then be viewed as an instance model for the conceptual configuration model.

The next section shows a formal definition of a configuration problem that serves as a basis for many existing configuration systems. In Section 4, we show how the generic model can be transformed to a logic theory for a configuration system built upon these definitions.

3 CONFIGURATION PROBLEM

The following definition of a configuration problem follows a consistency-based approach. A configuration problem can be seen as a logic theory that describes a component library, a set of constraints, and customer requirements. *Components* are described by attributes and ports. *Ports* are used as connection points between components [9]. The result of a configuration task is a set of components, their attribute values, and connections that satisfy the logic theory.

This model has proven to be simple and powerful to describe general configuration problems and serves as a basis for configuration systems as well as for representing technical systems in general ([9][13][14]). The model will now be treated more formally.

The formulation of a **configuration problem** can be based on two sets of logic sentences, namely *DD* (domain description) and *SRS* (specific requirements). We restrict the form of the logical sentences to a subset of range restricted first-order-logic with a set extension and interpreted function symbols. In order to assure decidability, we restrict the term-depth to a fixed number. Additionally, domain-specific axioms for configuration are defined, e.g., one port can only be connected to exactly one other port.

DD includes the description of the different component types, named ports, and attributes with their domains.

An example from the PC configuration problem:

types = {pc,cpu,motherboard,...}.
attributes(server-os-1) = {version}.
dom(server-os-1,version)= {1.0,2.0}.
ports(pc) = {hd-unit-port, motherboard-port,... }.
ports(motherboard) = {pc-port,cpu-port,...}.

Additionally, constraints are included, reducing the possibilities of allowed combinations of components, connections and value instantiations.

SRS includes the user-requirements on the product which should be configured. These user-requirements are the input for the configuration task.

The **configuration result** is described through sets of logical sentences (*COMPS*, *ATTRS*, and *CONNS*). In these sets, the employed components, the attribute values, and the established connections are represented.

COMPS is a set of literals of the form *type(c,t)*. *t* is included in the set of *types* defined in *DD*. The constant *c* represents the identification for a component.

CONNS is a set of literals of the form *conn(c1,p2,c2,p2)*. *c1* and *c2* are component identifications from *COMPS*, *p1* (*p2*) is a port of the component *c1* (*c2*).

ATTRS is a set of literals of the form *val(c,a,v)*, where *c* is a component-identification, *a* is an attribute of that component, and *v* is the actual value of the attribute.

Example for a configuration result:

type(p1,pc).
type (m1,motherboard-1).
type(c1,cpu-586).
conn(p1,motherboard-port,m1,pc-port).
conn(c1,motherboard-port,m1,cpu-port).

Note, that component *p1* of type *pc* has a port named "motherboard-port" reserved for connections to a motherboard. This port is defined in the domain description.

Based on these definitions, we are able to specify precisely the concept of a consistent configuration:

Definition: Consistent Configuration. If (*DD*, *SRS*) is a configuration problem and *COMPS*, *CONNS*, and *ATTRS* represent a configuration result, then the configuration is consistent exactly *iff DD* $\cup$ *SRS* $\cup$ COMPS $\cup$ *CONNS* $\cup$ *ATTRS* can be satisfied.

Additionally we have to specify that *COMPS* includes all required components and no spurious parts, *CONNS* describes all required connections, and *ATTRS* includes a complete value assignment to all variables in order to achieve a *complete* configuration. This is accomplished by additional logical sentences which can be generated using the domain description. A configuration, which is consistent and complete w.r.t. the domain description and the customer requirements, is called a *valid configuration*. A detailed formal exposition is given in [5].

4 TRANSFORMATION RULES

In order to allow automatic construction of the knowledge base from the conceptual model, we have to clearly define the semantics of the employed concepts. In our approach, we define the semantics through logical sentences for the configuration model defined in Section 3. These logical sentences[1] restrict the set of possible configurations. The result of the transformation is a set of logical sentences that form a domain description that can be used by a configuration system.

Component-types

Component-types describe the predefined parts a product is built of. We use a stereotype class for representing components since some limitations on these classes have to hold (e.g., there are no methods, attributes are limited to simple data types and enumerations). For each component-type in the UML-model, we extend the domain description as follows.

Definition: Given a component-type c in the graphical representation (*GREP*) then $c \in types$.

Given an attribute a of component-type c in *GREP* then $a \in attributes(c)$.

Given a domain description d of an attribute a of component-type c in *GREP* then $dom(c,a) = d$.

Generalization

Subtyping in the configuration domain means that attributes, ports, and constraints are inherited to the subtype. We assume disjunctive semantics for generalization which is the default semantics in UML, i.e., only one of the given subtypes will be instantiated. Additionally, no multiple inheritance is allowed in order to facilitate comprehensible semantics.

Definition: Let u and $d_1,...,d_n$ be classes where u is the superclass of $d_1,...,d_n$ and c is the set of all direct and indirect superclasses of u in *GREP* then
for $i = 1,...,n$

- the domain description is extended as follows:

  $type(ID,d_i) \quad type(ID,u).$
  $type(ID,u) \quad type(ID, d_1) \vee ,..., \vee type(ID, d_n).$
  $type(ID,X) \wedge type(ID,Y) \wedge X \in \{ d_1,...,d_n \}$
  $\quad Y \in (\{ u\} \cup c) \vee X=Y.$

- If $a \in attributes(u)$ then $a \in attributes(d_i)$.
- If $p \in ports(u)$ then $p \in ports(d_i)$.

Example for extensions to the knowledge base:

$type(ID,cpu\text{-}486) \quad type(ID,cpu).$
$type(ID,cpu)$
$\quad type(ID,cpu\text{-}486) \vee type(ID,cpu\text{-}586).$

Part-Refinement

UML differentiates between shared and composite aggregation. In the case of configuration modeling, semantics can be defined as follows: If a component is a compositional part of another component, we require *strong ownership* and it can not be part of another component at the same time. In the other case, we say that this component can be *shared* among different other components.

The multiplicity of the aggregation denotes of how many parts the aggregate can consist of and between how many aggregates a part can possibly be shared.

The aggregation relationship is modeled in the component-port-model through introduction of ports for connecting the aggregate with its parts (see Figure 4). For the following definitions no cycles in the part-of structure are allowed.

Composite aggregation

First, we extend the port definitions of the affected component-types. Ports are defined for the aggregate in the amount of the upper bound of the multiplicity of the part. One port is added to the part component-type to connect it with the aggregate. The ports are named according to the name of the aggregation. If no association name is specified, the name of the opposite component-type is used. The name can denote different roles a part can play in the aggregate.

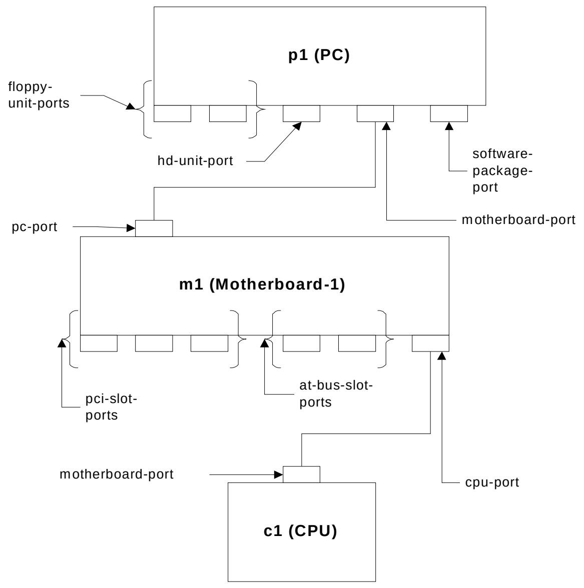


Figure 3 Aggregation in the component port model

[1] We employ a logic programming notation where variable names start with an upper case letter or are written as "_". The variables are all-quantified if not explicitly mentioned. We use the unique name assumption except for skolem constants.

Second, we derive logical sentences stating that, if an aggregate is in the configuration, components in the amount of at least the lower bound of the multiplicity of the part must be added too. Each part must be connected to (be part of) exactly one aggregate if the multiplicity of the aggregate is "1..1". If the multiplicity is "0..1", which is the only other possibility defined in UML, then no connection has to be established.

Definition: Let *w* and *p* be two component-types in *GREP* where *p* is a compositional part of *w* and *ub* is the upper bound and *lb* is the lower bound of the multiplicity of the part. Let *name* be the name of the association. We have to extend our configuration description in a way that:

$$\{name_1,\ldots,name_{ub}\} \subseteq ports(w).$$
$$name \in ports(p).$$

Example:

$$\{floppy\text{-}1,floppy\text{-}2\} \subseteq ports(pc).$$
$$pc \in ports(floppy).$$

At least *lb* parts must exist and be connected and the following constraint is derived:

$$type(ID,w) \quad \bigwedge_{i=1,\ldots,lb} ((\exists ID_i,Port\_part_i)\ type(ID_i,p) \wedge conn(ID,Port\_part_i,ID_i,name) \wedge Port\_part_i \in \{name_1,\ldots,name_{ub}\}) \wedge ID_1 \neq,\ldots,\neq ID_{lb}.$$

The parts have to be connected with the aggregate:

$$type(ID\_part,p) \quad \exists (ID\_agg,Port\_part)\ type(ID\_agg,w) \wedge Port\_part \in \{name_1,\ldots,name_{ub}\} \wedge conn(ID\_part,name,ID\_agg,Port\_part).$$

Example:

$$type(ID,pc) \quad \exists (F,Port)\ type(F,floppy) \wedge conn(ID,Port,F,pc) \wedge Port \in \{floppy\text{-}1,floppy\text{-}2\}.$$

$$type(ID,floppy) \quad \exists (P,Port)\ type(P,pc) \wedge conn(ID,pc,P,Port) \wedge Port \in \{floppy\text{-}1,floppy\text{-}2\}.$$

Shared aggregation

In the case of shared aggregation, additional ports have to be defined for the part, because the part can be part of (connected to) more than one aggregate. Connections have to be established according to the lower bound of the multiplicity.

Definition: Let *w* and *p* be two component-types in *GREP* where *p* is an aggregate part of *w* and *ubpart* is the upper bound and *lbpart* is the lower bound of the multiplicity of the part and *ubagg* is the upper bound and *lbagg* is the lower bound of the multiplicity of the aggregate. Let *name* be the name of the associations. We have to extend our configuration description in a way that:

$$\{name_1,\ldots,name_{ubpart}\} \subseteq ports(w).$$
$$\{name_1,\ldots,name_{ubagg}\} \subseteq ports(p).$$

We denote the set *{name$_1$,..., name$_{ubagg}$}* as *ports(p,name).*

A constraint is derived stating that at least *lbpart* ports have to be connected with different parts:

$$type(ID,w) \quad \bigwedge_{i=1,\ldots,lbpart} ((\exists ID_i,Port\_part_i,Port\_agg_i)\ type(ID_i,p) \wedge conn(ID,Port\_part_i,ID_i,Port\_agg_i) \wedge Port\_part_i \in \{name_1,\ldots,name_{ubpart}\} \wedge Port\_agg_i \in \{name_1,\ldots,name_{ubagg}\}) \wedge ID_1 \neq,\ldots,\neq ID_{lbpart}.$$

At least *lbagg* ports of the part have to be connected with the aggregate. If the lower bound is zero, then no connections are established:

$$type(ID,p) \quad \bigwedge_{i=1,\ldots,lbagg} ((\exists ID_i,Port\_agg_i,Port\_part_i)\ type(ID_i,w) \wedge conn(ID,Port\_agg_i,ID_i,Port\_part_i) \wedge Port\_agg_i \in \{name_1,\ldots,name_{ubagg}\} \wedge Port\_part_i \in \{name_1,\ldots,name_{ubpart}\}) \wedge ID_1 \neq,\ldots,\neq ID_{lbagg}.$$

The following additional constraints have to be added, too. First, if a component is a compositional part of an aggregate, it can not be a part of any other component at the same time. Second, an instance of a component-type being part of any part-of relationship must be connected to an instance of an aggregate type.

Definition: Let *p, a$_1$,...,a$_n$, c$_1$,...,c$_m$* be component-types where *p* is an aggregational part of *a$_1$,...,a$_n$* and a compositional part of *c$_1$,...,c$_m$* in *GREP*. Let *name_agg$_1$,...,name_agg$_n$* be the names of the aggregate associations in *GREP*, and *name_comp$_1$,...,name_comp$_m$* be the names of the composition associations.

Let *all_part_of_ports* be $\{name\_comp_1,\ldots,name\_comp_m\} \cup ports(p,name\_agg_1) \cup,\ldots,\cup\ ports(p,name\_agg_n)$.

To forbid other connections if one composite port is connected, the following constraint has to hold:

$$type(ID,p) \wedge conn(ID,C,\_,\_) \wedge C \in \{name\_comp_1,\ldots,name\_comp_m\} \wedge D \in all\_part\_of\_ports \wedge conn(ID,D,\_,\_) \quad C = D.$$

At least one of the ports must be connected.

$$type(ID,p) \quad \exists (Port, X)\ Port \in all\_part\_of\_ports \wedge conn(ID,Port,X,\_) \wedge type(X,W) \wedge W \in \{a_1,\ldots,a_n, c_1,\ldots,c_m\}.$$

Presuppositions on the part-of hierarchy

Any of the following constraints on the product structure derived from *GREP* must ensure that the involved components are within the same sub-configuration w.r.t. the part-of hierarchy, i.e., the involved components must be connected to the same instance of the component-type that represents the common root for these components. For a correct derivation of constraints, we postulate that the involved component types have a unique common component-type as predecessor and a unique path to this common root in *GREP*. All part-of relations within the common subtree must be compositions in order to ensure uniqueness of the common predecessor on the instance level. If this property is not satisfied, the meaning of the modeling concepts is ambiguous since a part can be part of different substructures in the part-of hierarchy. To eliminate this ambiguity, additional modeling concepts can be defined, allowing the domain expert to express further problem specific constraints.

For the derivation of constraints, we use the abbreviations (similar to macros) *navigation_expr* and *generating_expr,* which represent a path-expression through conn-predicates from a component to an instance of the common root. In the case of *generating_expr* the variables are existentially quantified and the expression may only be used on the right-hand-side of the implications.

For the definition of these two abbreviations, we view the class-model as a directed graph, where the component-types are the vertices V and the part-of relations are the edges E. We employ the graph using the inheritance property of ports, i.e., the inheritance of part-of relations, e.g., the component-type "CPU-586" has a port inherited from "CPU" to connect it with the motherboard. Because of this property, the part-of relations are inherited to the leave nodes of the generalization hierarchy. Therefore, the generalization hierarchy does not need to be considered for the construction of the path expression.

Let *path(a,p)* describe the path from component-type *a* to the common root *p* in *GREP* through an ordered list of predicates of the form *part_of(component-type-a, component-type-b, association-name).*

The following formula shows how *navigation_expr* and *generating_expr* are defined.

Given $path(a,p) = <part\_of(a,y,name\_y),...,part\_of(z,p,name\_p)>$
in *GREP* then *navigation_expr(ID_a, P)* is defined as

$$conn(ID\_a,name\_y,ID\_y,\_)\wedge ,..., \wedge conn(ID\_z,name\_p,P,\_).$$

and *generating_expr(ID_a, P)* is defined as

$$\exists (ID\_y ,..., ID\_z)\ conn(ID\_a,name\_y,ID\_y,\_) \wedge ,..., \wedge conn(ID\_z,name\_p,P,\_).$$

P is a variable identifying an instance of the type of the common root.

Example:
If $path(cpu\text{-}586,pc)= <part\_of(cpu\text{-}586, motherboard,\_), part\_of(motherboard, pc,\_)>$
is the path from a CPU-586 to the PC in *GREP* then *navigation_expr(ID_CPU,P)* is

$$conn(ID\_cpu,motherboard,ID\_motherboard,\_) \wedge conn(ID\_motherboard,pc,P,\_).$$

Requires
A relation *a requires b* in *GREP* denotes that the existence of an instance of component-type *a* requires that an instance of *b* exists and is part of (connected to) the same (sub-)configuration. In our example, Server-OS-1 requires a CPU-586 within the same PC, which is the common and unique root of both component-types.

Definition: Given the relation *a requires b* where *a* and *b* are component-types in *GREP*, we extend our domain description with the following formula:

$$type(ID\_a,a) \wedge navigation\_expr(ID\_a, P) \quad \exists (ID\_b)\ type(ID\_b,b) \wedge generating\_expr(ID\_b, P).$$

Example:

$$type(ID,server\text{-}os\text{-}1) \wedge conn(ID,software\text{-}package, S, \_) \wedge conn(S,pc,P,\_) \quad \exists (C)\ type(C,cpu\text{-}586) \wedge \exists (M)\ conn(C,motherboard,M,\_) \wedge conn(M,pc,P,\_).$$

The left-hand side of the implication describes a path to the common root (PC). The right-hand side of the implication requires the existence and connection of the components on the path from *b* to the common root.

Incompatible
This relation denotes the fact that two components can not be used within the same configuration. The incompatible relation is defined as a binary relation with a multiplicity of "1..1" in the UML-model.

Definition: Given the relation *a incompatible_with b* in *GREP* where *a* and *b* are component-types we extend the domain definition with the following constraint:

$$type(ID\_a,a) \wedge navigation\_expr(ID\_a, P) \wedge type(ID\_b,b) \wedge navigation\_expr(ID\_b, P) \quad false.$$

Note: If there exists a path through connections from components ID_a and ID_b to the common root (P), then *false* is derived.

Example:

$$type(ID,dev\text{-}environment) \wedge conn(ID,software\text{-}package, S, \_) \wedge type(OS,server\text{-}os\text{-}2) \wedge conn(OS,software\text{-}package,S,\_) \quad false.$$

Ports and Connections
Ports in the UML-model represent physical connection-points between components. These ports are added to the port definitions of the components. Possible and required connections are expressed through the stereotyped relation "is connected".

Definition: Let *c* be a component-type and *p* be a port where p is a part of *c* in *GREP* and where *n* is the multiplicity of the port. We extend **DD** as follows:

$$\{p_1 ,...,p_n\} \subseteq \quad ports(c)$$

We denote the set $\{p_1 ,...,p_n\}$ by *ports(c,p).*

Definition: Let *a* and *b* be component-types and *pa* and *pb* be ports, where *pa* is a port of *a* and *pb* is a port of *b* and *pa* and *pb* are connected in *GREP*.

If the multiplicity of *pb* is "1..1", expressing that the port must be connected, the following constraint is derived:

$$type(ID\_a,a) \wedge navigation\_expr(ID\_a, P) \wedge Port\_a \in ports(a,pa) \quad \exists (ID\_b, Port\_b)\ type(ID\_b,b) \wedge generating\_expr(ID\_b, P) \wedge Port\_b \in ports(b,pb) \wedge conn(ID\_a, Port\_a, ID\_b, Port\_b).$$

The definition is much the same as for "requires", because if we want to connect a port *Port_a* from *a* with a port *Port_b* of component *b*, the existence of an instance of type *b* is required. Only the additional connection has to be established.

If the multiplicity of *pb* is “0..1”, the following constraint is derived:

type(ID_b,b) $\wedge$ navigation_expr(ID_b, P) $\wedge$ Port_b $\in$ ports(b,pb) $\wedge$ conn(ID_b, Port_b,ID_a,Port_a)
$\exists$ (ID_a, Port_a) type(ID_a,a) $\wedge$ generating_expr(ID_a, P) $\wedge$ Port_a $\in$ ports(b,pa).

In this sentence we define that, if a component of type *b* exists and a connection from *Port_b* is established, then this connection must be established to a port of a component of type *a*.

Example for the PCI-Connector:

type(S,scsi-controller) $\wedge$ conn(S,scsi-unit,U,_) $\wedge$ conn(U,pc,P,_) $\wedge$ Port_S $\in$ ports(scsi-controller,pci-connector)
$\exists$ (M,Port_M) type(M,motherboard-1) $\wedge$ Port_M $\in$ ports(motherboard-1,pci-slot) $\wedge$ conn(S,Port_S,M,Port_M).

Resources
Resource constraints are modeled in the UML-model through stereotyped classes representing types of resources and stereotyped relations indicating production and consumption of these resources. Resources represent a balancing task [7] within the shared subtree of the part-of hierarchy of the product structure. To map the resource task to the component-port model, additional attributes have to be defined for the participating component-types holding the actual value of production and consumption. A constraint has to be derived ensuring, that resource values are balanced. In the example given, the component-type PC is the root for all consumers and producers of the resource *hard-disk capacity*. A constraint for the PC is constructed, ensuring that the sum of the produced capacity exceeds the sum of the consumed capacity. We therefore collect all the instances of SCSI-Disks that are part of this PC and the consumers that are part of the PC using the predicates

allconsumers(result_set,ID_Root) and

allproducers(result_set,ID_Root).

These predicates return a set of instances of consuming and producing components connected to the actual instance of the root component.

Definition: Let $g_1,...,g_n$ be producing component-types of resource *r* with attribute values gv_i and $c_1,...,c_m$ be consuming component-types with values cv_i. The values of cv_i and gv_i are determined by the tagged values of the "consumes" and "produces" relations.
We have to extend the domain description as follows:

r $\in$ attributes(g_i), for i = 1 to n.
r $\in$ attributes(c_i), for i = 1 to m.
val(g_i,r, gv_i) for i = 1 to n.
val(c_i,r, cv_i) for i = 1 to m.

Let *p* be the common and unique predecessor w.r.t. the part-of-hierarchy of all consumers and producers. We derive the following constraint:

type(P,p) $\wedge$ allconsumers(Consumer,P) $\wedge$ allproducers(Producer,P)

$$_{(o \in Consumer \wedge val(o,r,V))} V <= \quad _{(s \in Producer \wedge val(s,r,W))} W.$$

The predicates *allconsumers* and *allproducers* are defined as follows using LDL-notation [2]:

allconsumers(<Consumer>,P) $\Leftarrow$
C $\in$ {c_1,...,c_n} $\wedge$ type(Consumer,C) $\wedge$
navigtion_expr(Consumer,P) $\wedge$ type(P,p).

allproducers(<Producer>,P) $\Leftarrow$
G $\in$ {g1,...,gn} $\wedge$ type(Producer,G) $\wedge$
navigation_expr(Producer,P) $\wedge$ type(P,p).

Note: All component instances with one of the correct types are collected within *<Consumer>*. *navigation_expr(Consumer,P)* ensures that all these components are connected to the same instance *P* of the common root.

Additional modeling concepts and constraints
The modeling concepts described in Section 2 have shown to cover a wide range of application areas for configuration [11]. Despite this, some application areas may have a need for additional modeling concepts. To introduce a new modeling concept, two steps have to be taken: First, define the new concept (stereotype) and state the rules for its correct use within the model. Second, define the semantics of the concept for the configuration domain by stating the facts and constraints induced to the logic theory when using the concept. If there are constraints in the configurable product, which can not be expressed through predefined or newly introduced graphical concepts, the knowledge base has to be extended by a knowledge engineer.

When defining transformation rules or adding other constraints to the knowledge base, one has to consider the structure of the derived constraints, which must conform to the restrictions mentioned in Section 3.

5 CONFIGURATION TOOL: COCOS

The notion of the component-port-model is well-established for modeling and solving configuration problems [9]. In general, consistency-based tools basing on the component-port-model can use the logic theory derived from the UML-product-model. Since the output is a set of logical sentences, it can be transformed to the representation of different tools.

The configuration tool COCOS [14] has proven its usefulness in the configuration of large-scale electronic systems. By using a high level description language for expressing the configuration constraints we were able to reduce development effort (by 66% compared to a previous project) and maintenance costs significantly. In addition to these logical constructs, COCOS allows the definition of orderings, defaults, and preferences for instantiation of components and generation of connections. This control knowledge is specified by priority values, which can be easily incorporated in our UML-notation by additional attributes.

6 RELATED WORK

Bourdeau and Chen [1] give a formal semantics for object model diagrams based on OMT. This work is an important step in automating the process of obtaining a formal description from the information in the diagrams. Their goal is to support the assessment of requirement specifications in general. We view our work as complementary since our goal is to generate formal descriptions which can be interpreted by logic based problem solvers.

Peltonen et al. ([10], [11]) use product configuration as a practical application for a prototype based approach. They view configuration as a process where objects are created by specifying their parent and the inheritance of information. Our approach explicitly describes a valid configuration using a declarative language. The process of generating configurations is an automated search process. Using this approach we have a clear separation of procedural and declarative knowledge as well as a precise semantics of the configuration problem and the content of the knowledge base.

There is a long history in developing configuration tools in knowledge based systems (see [13]). However, the automated generation of logic-based knowledge bases by exploiting a formal definition of standard design descriptions like UML has not been discussed so far. Comparable research has been done in the fields of Automated Software Engineering, e.g., the derivation of programs in the Amphion project [7]. In this project, specifications are developed by end-users in a declarative manner using a graphical language for the astronomical domain. The focus of this project is software reuse, where a procedural program is constructed from software libraries, whereas our approach uses a constraint based inference engine optimized for solving configuration problems.

Structural information plays also an important role in the domain of Architecture Description Languages (ADL). In [6] common concepts for ADLs and an interchange format are defined. Architectures are (graphically) modeled and enhanced with first-order-logic constraints and assertions. This description may then be translated to other existing ADLs. The full semantics of the modeling concepts may vary, depending on the translation to other ADLs. However, in our approach, we use logic not only for representation and exchange, but use it directly to solve configuration problems.

7 CONCLUSIONS

Extensible standard design methods are able to provide a basis for introducing and applying rigorous formal descriptions of application domains. This approach helps us to combine the advantages of various areas. First, high level formal description languages reduce the development time and effort significantly because these descriptions are directly executable. Second, standard design methods like the UML static model are comprehensible and widely adopted in the established industrial software development process.

We defined a logic based formal semantics for UML constructs, which allows us to generate logical sentences and to process them by a problem solver. This enables us to automate the generation of specialized software applications and allows for rapid generation of prototypes. The design model is comprehensible for domain experts and can be reviewed, adapted and validated without specialists. Consequently, time and costs for the development and maintenance of configurators can be reduced significantly.

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