A Graph Grammar-Based Formal Validation of Object-Process Diagrams

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Abstract

Two basic requirements from a system's conceptual model are correctness and comprehensibility. Most modeling methodologies satisfy only one of these apparently contradicting requirements, usually comprehensibility, leaving aside problems of correctness and ambiguousness that are associated with expressiveness. Some formal modeling languages do exist, but in these languages a complete model of a complex system is fairly complicated to understand.

Object-Process Methodology (OPM) is a holistic systems modeling methodology that combines the two major aspects of a system—structure and behavior—in one model, providing mechanisms to manage the complexity of the model using refinement-abstraction operations, which divide a complex system into many interconnected diagrams. Although the basic syntax and semantics of an OPM model are defined, they are incomplete and leave room for incorrect or ambiguous models.

This work advances the formal definition of OPM by providing a graph grammar for creating and checking OPM diagrams. The grammar provides a validation methodology of the semantic and syntactic correctness of a single Object-Process Diagram.

1. Introduction

Conceptual modeling is the field that is concerned with humans constructing models of complex systems at the concept level. We want these models to be simple, but at the same time they should also be expressive and formal enough to describe the system in detail and without ambiguity.

There are many ways to conceptually model a system. For small systems this can be done with ad-hoc methods – all the people involved get together and agree on a modeling technique, which can be graphic or textual, computer-based or hand-written. As systems grow larger and evolve over time, these techniques become hard to maintain and cannot describe all the things that have to be modeled in the system. Furthermore, these models would only be understood by the people that are familiar with the modeling technique, adding more problems when changes are involved or when the model has to be shared with external stakeholders.

As systems become more complex, these problems become ever more acute. System architects and designers, who create models and use them to communicate ideas, have realized that there is a need to establish methodologies that can describe their domain of interest, like an Esperanto of modeling.

To tackle this problem, this work proposes a formal framework for the creation of an Object-Process Diagram (OPD)—the graphic modality of Object-Process Methodology (OPM) —and its validation, extending the formal definitions in [6] and [23], and increasing the formality of the OPM language. The dynamic or execution semantics of OPM is outside the scope of this paper.

The paper is structured as follows: Section 2 provides a general background on software engineering as it can be seen as a sub-field of system engineering on which all of the described problems occur and where a number of solutions have been proposed. Section 3 provides theoretical background on OPM and on graph grammars – the mathematical formalism underlying the creation and verification of an OPD. Section 4 describes the formalization methodology, and Section 5 concludes the work.

2. Related Work

System modeling can be done in a number of ways. The common practice is mixing charts and drawing with plain text (which may or may not have a specific syntax), as is done in system architecture frameworks like DODAF [30]. While learning the basic methods is fairly easy, their use creates many problems because there is no underlying formal methodology for verifying that the model is consistent and does not contain internal contradictions.

On the other extreme there are formal methodologies that can be used for system modeling, including abstract state machines, the Z-notation [26], and Petri-nets [1]. While these methods have formal definitions, their drawback is that some of them are for a specific purpose (Petri-nets for distributed systems) and others (like the Z-notation) have complex notations or are not sufficiently abstract to define any kind of system at different abstraction levels.

The middle ground between these two approaches is compromised by many methodologies, the most popular being the Unified Modeling Language (UML), which "is a visual language for specifying, constructing and documenting the artifacts of systems. It is a general-purpose modeling language that can be used with all major object and component methods, and that can be applied to all application domains and implementation platforms." [22]. Although very popular, UML has been criticized for its complexity [17] and its lack of precise semantics [10], [11], [29]. To remedy this, ongoing effort are made to provide UML (or a subset of UML) with formal semantics using graph grammars [19], [13], [33], [12], [18], mathematical notation [3], Abstract State Machines [16], Petri Nets [27], Z-notation [4], [21], B language [24] and UML itself [28]. A survey of the work done on this field is provided in [20].

The descendant of UML – the System Modeling Language (SysML), an initiative to customize UML specifically for system engineering (and not software engineering as it was intended initially), removes some of the complexity found in UML, but this still "does not solve the question of lack of semantics in UML" [31].

3. OPM and Graph Grammars

In this section we briefly introduce OPM and graph grammars, which are the mathematical basis for the formal definition of an OPD.

3.1. Object-Process Methodology

Object-Process Methodology (OPM) [6] is a holistic modeling approach that combines the structure and behavior of the system in the same model, providing full integration of the important system aspects. OPM is an ontologically complete modeling language [25] according to the Bunge-Wand-Weber framework [32], a theoretical framework for understanding the modeling of information systems. OPM is defined by its reflective metamodel [23], which provides further understanding of the modeling language and provides a robust basis for code generation, model transformation and analysis. In what follows we present the basic concepts of OPM. A complete definition of OPM can be found in [6].

Since OPM has evolved as a holistic system modeling methodology along with the OPM language, hence a formal specification of the language has not been proposed, and this work lays out the foundations of such definition, emphasizing its syntactic aspects.

3.1.1. OPM Concepts and Building Blocks

The primary elements of OPM are entities and links. Entities are the generalization of things and states, and things are a generalization of objects and processes – the two primary building blocks in an OPM model. In OPM, an object is a thing that exists. A process is a thing that transforms at least one object. Transformation is object generation or consumption or change in the state of the object. Objects are represented in OPM as rectangles, and processes as ellipses. A state is represented as a "rountangle" (rounded edge rectangle) within the rectangle of its owning object, as shown in **Fig 1**.

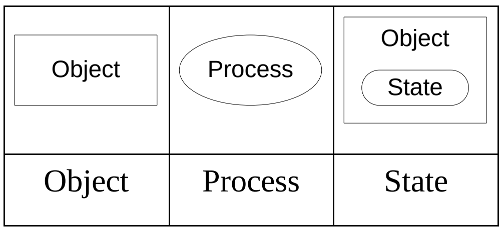


Fig 1 The OPM Entities

At any time, a stateful object (object with states) is in a specific state, and the state of the object is changed through a process.

A link is an element that connects two entities and represents a semantic relation between them. Links can be of two kinds: structural and procedural. A structural link represents a static structural relation between two entities, such as aggregation or generalization. A procedural link connects an entity with a process to denote a dynamic behavioral flow of information, matter, or energy. A further specialization of a procedural link is an event link, which indicates a specific event that happens at a particular moment or when specific preconditions are met. Each link is drawn as a line with a special symbol attached to one end or in the middle of the line depending on the link type. Some links types are drawn in **Fig 2**.

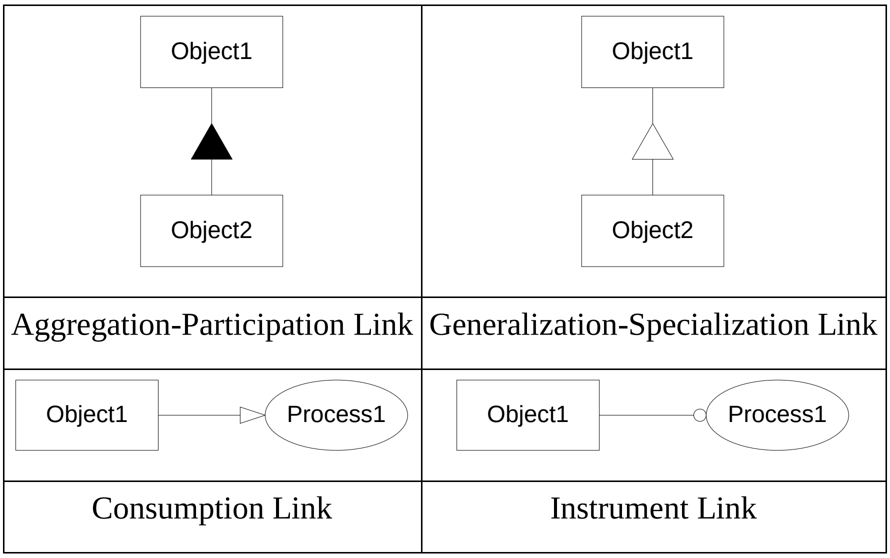
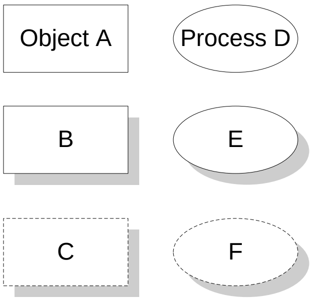
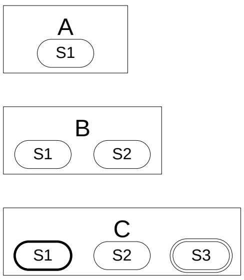
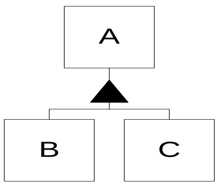
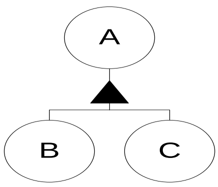


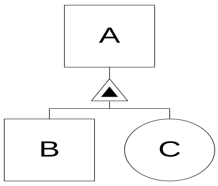
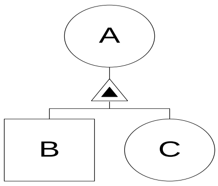
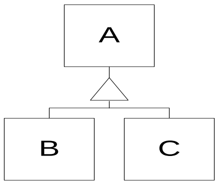
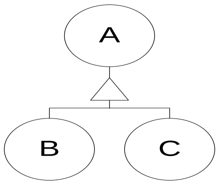
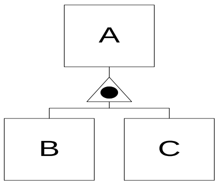
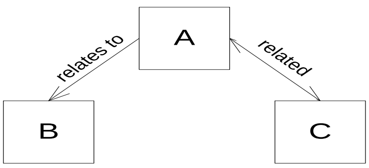
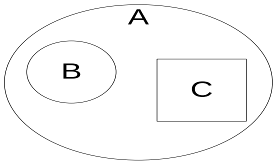
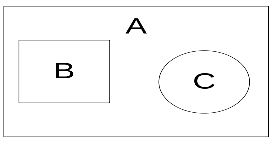
Fig 2 Examples of OPM links

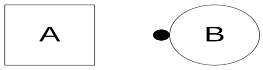
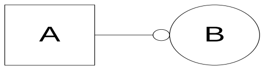
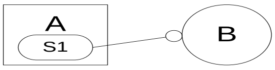
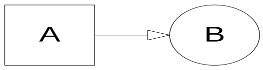
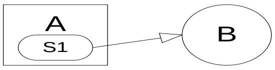
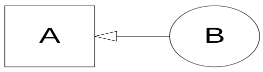
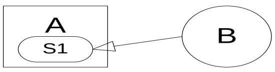
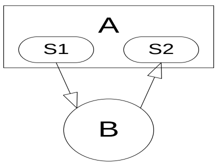
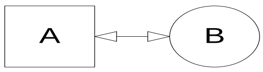
OPM things have other attributes, for example essence, which can be either physical – the modeled element is a physical object in the real world – or informatical – something that is not tangible but can be defined and used as a modeling element. Examples of physical things are *machine*, *raw material* and *product*; Examples of informatical things are *computing*, *account* and *transaction*.

The common constructs of OPM are shown in the following tables.

Entities				
Name		**Symbol**	**OPL**	**Definition**
Things	Object Process		B is physical. (shaded rectangle) C is physical and environmental. (shaded dashed rectangle) E is physical. (shaded ellipse) F is physical and environmental. (shaded dashed ellipse)	An object is a thing that exists. A process is a thing that transforms at least one object. Transformation is object generation or consumption, or effect—a change in the state of an object.
State			A is s1. B can be s1 or s2. C can be s1, s2, or s3. s1 is initial. s3 is final.	A state is situation an object can be at or a value it can assume. States are always within an object. States can be initial or final.

STRUCTURAL LINKS & COMPLEXITY MANAGEMENT				
Name		**Symbol**	**OPL**	**Semantics**
Fundamental Structural Relations	Aggregation-Participation		A consists of B and C.	A is the whole, B and C are parts.
			A consists of B and C.	

	Exhibition-Characterization		A exhibits B, as well as C.	Object B is an attribute of A and process C is its operation (method). A can be an object or a process.
			A exhibits B, as well as C.	
	Generalization-Specialization		B is an A. C is an A.	A specializes into B and C. A, B, and C can be either all objects or all processes.
			B is A. C is A.	
	Classification-Instantiation		B is an instance of A. C is an instance of A.	Object A is the class, for which B and C are instances. Applicable to processes too.
Unidirectional & bidirectional tagged structural links			A relates to B. (for unidirectional) A and C are related. (for bidirectional)	A user-defined textual tag describes any structural relation between two objects or between two processes.
In-zooming			A exhibits C. A consists of B. A zooms into B, as well as C.	Zooming into process A, B is its part and C is its attribute.
			A exhibits C. A consists of B. A zooms into B, as well as C.	Zooming into object A, B is its part and C is its operation.

ENABLING AND TRANSFORMING PROCEDURAL LINKS				
	Name	**Symbol**	**OPL**	**Semantics**
Enabling Links	Agent Link		A handles B.	Denotes that the object is a human operator.
	Instrument Link		B requires A.	"Wait until" semantics: Process B cannot happen if object A does not exist.
	State-Specified		B requires s1 A.	"Wait until" semantics: Process B cannot happen if object A is not at state s1.
Transforming links	Consumption Link		B consumes A.	Process B consumes object A.
	State-Specified Consumption Link		B consumes s1 A.	Process B consumes object A when it is at state s1.
	Result Link		B yields A.	Process B creates object A.
	State-Specified Result Link		B yields s1 A.	Process B creates object A at state s1.
	Input-Output Link Pair		B changes A from s1 to s2.	Process B changes the state of object A from state s1 to state s2.
	Effect Link		B affects A.	Process B changes the state of object A; the details of the effect may be added at a lower level.

3.1.2. Object Process Diagrams - OPDs

A System Model is an OPM model that defines a system. A system model consists of a set of Object Process Diagrams (OPDs). The OPDs in a system model are related via in-zooming or unfolding. At any stage in the modeling process, the modeler can decide to increase the level of detail for a specific thing in a model, and this is by refinement through the in-zooming and unfolding operations.

This work concentrates on a single-level system model, i.e., a model that is completely specified in a single OPD, with no in-zooming or unfolding operations.

3.2. Graphs and Graph Grammars

Graph Grammars (or Graph Transformations) is a field of Graph Theory that formalizes the creation or transformation of graphs using predefined transformation rules. Following the definitions in [5] and [9], the initial notion below is that of a graph.

Definition 1 *Directed Typed Graph*

- A Directed Typed Graph (also known as Directed Labeled Graph), over two label alphabets Ω_V and Ω_E, is a tuple $G = \langle G_V, G_E, s^G, t^G, lv^G, le^G \rangle$ where:
  - G_V is the set of vertices (or nodes)
  - G_E is the set of edges (or arcs)
  - $s^G, t^G : G_E \to G_V$ are the source and target vertex function for each edge, and
  - $lv^G : G_V \to \Omega_V$ and $le^G : G_E \to \Omega_E$ are the vertex and edge type (label) functions respectively.

A graph is normally represented visually, as shown in **Fig 3**.

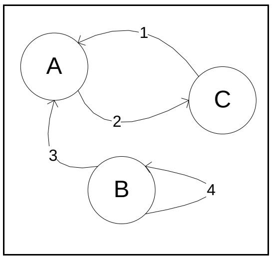


Fig 3 Example of a Directed Typed Graph

Definition 2 *Object-Process Diagram*

Based on the above definition of Directed Typed Graph, an Object-Process Diagram (OPD) is a Directed Typed Graph over the following two alphabets:

- Ω_V^{OPM} *={Object, Process, State}* – the node alphabet.
- Ω_E^{OPM} *={Object-State, Tagged, Aggregation-Participation, Exhibition-Characterization, Generalization-Specialization, Classification-Instantiation, Agent, Instrument, Consumption, Result, Effect, Input-Output pair, Invocation, Event, Consumption Event, Condition, Exception}* – the edge alphabet.

Although this is the formal notation for the OPM graph, its graphical OPD representation is more straightforward and easier to understand, so this is the notation used throughout this work. Furthermore, OPM states are not stand-alone entities and are drawn inside the object that owns them. The object ownership relation is abstracted by adding a new type of link, *Object-State*, which denotes that a state belongs to the object. Since the notation in OPM is more expressive and is part of the OPD syntax, we use it, bearing in mind that it can be changed to the formal Object-State link representation by detaching the state from the owning object, moving it out of the object, and adding a link between the object and the detached state.

An OPM model is a graph of graphs, where each node in the model is an OPD and the links between these nodes are defined by the refinement/abstraction (in- zooming/out-zooming or unfolding/folding) relations between the OPDs.

Before we delve into the formalisms of graph grammars, we need to define the following concepts.

Definition 3 *Graph Morphism*

- Let $G = \langle G_V, G_E, s^G, t^G, lv^G, le^G \rangle$ and $G' = \langle G'_V, G'_E, s^{G'}, t^{G'}, lv^{G'}, le^{G'} \rangle$ be two graphs over the same label alphabets Ω_V and Ω_E. A Graph Morphism $f : G \to G'$ is a pair of functions $f = \langle f_v : G_V \to G'_V, f_e : G_E \to G'_E \rangle$ such that:
  - $\forall e \in G_E$, $f_v(s^G(e)) = s^{G'}(f_e(e))$ (source node preservation)
  - $\forall e \in G_E$, $f_v(t^G(e)) = t^{G'}(f_e(e))$ (target node preservation)
  - $\forall v \in G_V$, $lv^G(v) = lv^{G'}(f_v(v))$ (node label preservation)
  - $\forall e \in G_E$, $le^G(e) = le^{G'}(f_e(e))$ (edge label preservation)

Graph morphism is a function that matches two graphs, preserving its structure (nodes and edges) and the labels on the edges.

Definition 4 *Subgraph*

- Suppose A, B, and B' are sets, such that $B' \subseteq B$, and there exists a mapping $m : B \to A$. The operator $m' = m|_{B'}$ defines a new mapping m' such that $\forall b \in B', m'(b) = m(b)$.
- Let G be a graph as defined above. A *subgraph* $S = \langle S_V, S_E, s^S, t^S, lv^S, le^S \rangle$ of G, written $S \subseteq G$, is a graph having $S_V \subseteq G_V$, $S_E \subseteq G_E$, $s^S = s^G|_{S_E}$, $t^S = t^G|_{S_E}$, $lv^S = lv^G|_{S_V}$ and $le^S = lv^G|_{S_E}$.

Simply put, a subgraph is a part of a graph that is also a valid graph.

Definition 5 *Partial Graph Morphism*

- A partial graph morphism $m: G \to G'$ is a graph morphism of a subgraph of G to G'.

Having defined the above terms, we can now turn to the definitions of the graph grammar needed in this work. The basic operation in graph grammars is graph transformation, defined by a rule. There are two major approaches to defining transformation rules: the *double pushout approach* (known as DPO) and the *single pushout approach* (known as SPO). We use SPO since it is simple to define and understand and we have no need for the strong properties that the DPO approach features.

Definition 6 *SPO Production Rule*

- A production $p: L \xrightarrow{r} R$ consists of a production name p and a partial graph morphism r, called the production morphism. L and R are graphs called the left-hand graph and the right-hand graph, respectively.

The left-hand graph of the production describes the context needed for the production to be applied, and the right-hand graph shows how the original part of the graph will look like after the application of the production rule. The morphism r specifies which element (node or edge) in the left-hand graph is matched with which element in the right-hand graph. To apply this production to a graph, each element missing in the right-hand graph is deleted, and if this deletion causes dangling edges, they are deleted as well. Elements missing in the left-hand graph that exist in the right-hand graph are added. Formally, the application of a production is defined as follows.

Definition 7 *Production, Derivation*

- A match for $p: L \xrightarrow{r} R$ in some graph G is a graph morphism $m: L \to G$. Given a production p and a match m for p in graph G, the **direct derivation** from G with p at m, written $G \overset{p,m}{\Rightarrow} H$, is done as follows:
  - Using morphism m, delete vertices and edges of G that occur in L and do not occur in R.
  - Add to G all vertices and edges that occur in R but do not occur in L.
  - If a node or an edge is both kept and deleted, solve the conflict by deletion (a node or an edge is kept and deleted if it has two pre-images in L, one in R and the other not in R).
  - Delete all dangling edges from G.

Example 1

We demonstrate the basic graph grammar concepts on a small OPD. The grammar's set of production rules is given in **Fig 4**. Recall that an OPM object is denoted as a rectangle and a process—as an ellipse.

Production 1:

Consumption Link Insertion

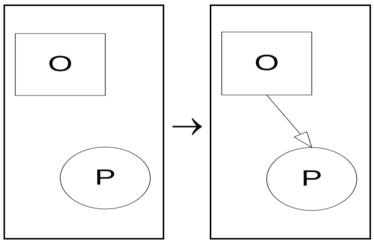


Fig 4 The production of Example 1

The initial graph for our example is G_1, shown in **Fig 5**.

G_1 =

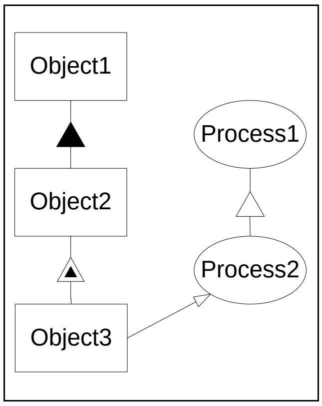


Fig 5 Initial graph of Example 1

Let us apply Production 1 – *Consumption Link Insertion* on G_1. The first step is to find a subgraph of the graph G_1 that matches the left-hand side of Production 1. There are six possible matches: {**Object1**, **Process1**}, {**Object1**, **Process2**}, {**Object2**, **Process1**}, {**Object2**, **Process2**}, {**Object3**, **Process1**} and {**Object3**, **Process2**}. We choose to apply the rule on {**Object1**, **Process1**}, resulting in graph G_2, shown in **Fig 6**.

G_2 =

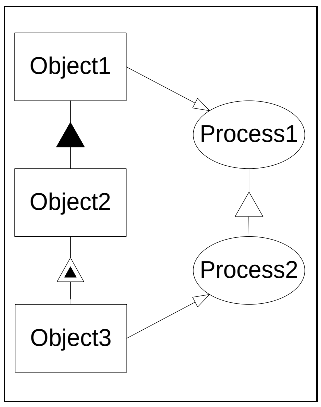


Fig 6 Example 1 graph after application of Production 1 – *Consumption Link Insertion*

Using derivations, we can describe how graphs are legally transformed into other graphs. However, specifying when these transformations can be applied is limited by the positive condition in the left-hand graph. This is extended with *application conditions*, which specify contexts in which the transformation can be applied.

To add application conditions, we specify not just one left-hand side graph L, but a set of graph morphisms $\{L \xrightarrow{l} \hat{L}\}$ called *constraints* [15], [8], [14]. Each constraint represents a structure on the left-hand graph that must exist for positive constraints and must not exist for negative constraints.

Definition 8 Application Conditions

- An application condition over a graph L is a finite set $A = \{L \xrightarrow{l} Q\}$ of graph morphisms of the form $L \xrightarrow{l} Q$ called constraints.
- Let $p : L \xrightarrow{r} R$ be a production, $a : L \xrightarrow{l} Q$ a positive constraint, and $m : L \to G$ a match for L in graph G. We say that m satisfies a, denoted by $m \models a$, if there exists a graph morphism $n : Q \to G$ such that $n \circ l = m$, where $\circ$ is the mathematical function composition operator, which means that we apply morphism l to L and then we apply morphism n to the result.
- A negative constraint is defined as a regular constraint for which morphism n must not exist.
- A match m satisfies an application condition A over L, denoted by $m \models A$ if it satisfies all the constraints $a \in A$.

Usually, the specified constraints are negative, since the positive constraints can be modeled in the left-hand side graph of the production. Negative constraints can also be embedded in the left-hand side graph of the production, where the common notation is to draw them inside a shaded area, as shown in Example 2.

Definition 9 Conditional Production

- A conditional production $\hat{p} = (L \xrightarrow{p} R, A)$ is a pair consisting of a partial graph morphism p and an application condition A over L.

Definition 10 Direct Conditional Derivation

- Production $\hat{p}$ is applicable to graph G at $L \xrightarrow{m} G$ if $m \models A$. This is called a direct conditional derivation, denoted as $G \overset{\hat{p},m}{\Rightarrow} H$.

Example 2

Continuing with the transformation in Example 1, we revise Production 1 to include a negative constraint, which removes the possibility of creating duplicate consumption links between two entities. The result is shown in **Fig 7**.

Production 1n:
Consumption Link Insertion

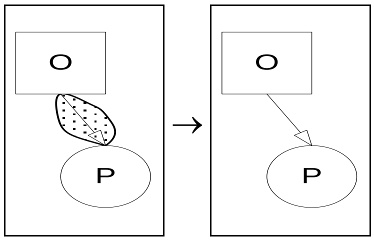


Fig 7 Production 1 with a negative constraint

The rephrased Production 1, called Production 1n, simply means that a consumption link can only be added if a consumption link between the two entities does not yet exist. The addition of the negative constraint does not change the resulting graph in **Fig 6**, but it rules out the option (Object3, Process2) from the set of possible matches.

4. Formal Validation of an OPD using Graph Grammars

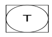
There are two possible approaches to maintaining the syntactic correctness of an OPD:

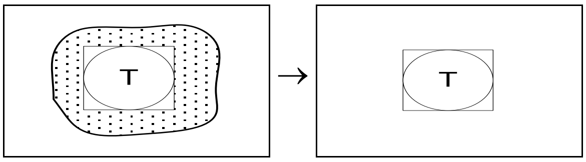
1) Proactive Verification: Maintaining syntactic correctness of the OPD at modeling time by proactively verifying that each modeling operation is legal as it is being executed by the system designer, so the model is guaranteed to be syntactically correct by construction at any time. This approach is fairly complicated and may encumber the user, because there may be intermediate situations in which the model needs to be temporarily inconsistent.
2) Retroactive Verification: Verifying retroactively that the OPD has remained syntactically correct after applying one or more modeling operations to the OPD.

Our syntactic correctness checking algorithm combines the proactive and retroactive verification approaches. We limit the OPD construction process by defining transformation rules stipulating what is and what is not permitted in OPD construction while allowing for temporary inconsistencies.

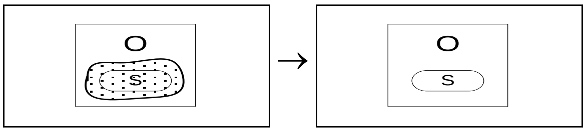
This section shows part of a graph grammar for creating and validating a system model in a single OPD. The zooming and folding OPM capabilities are not handled since for syntactic purposes an OPM model that consists of many OPDs can be recursively converted into a single OPD by "flattening" the OPD hierarchy via successive model element assignments without loss of model information. The complete definition of the OPD graph grammar can be found in [2].

4.1. OPD Creation – Sample OPD Graph Grammar Productions

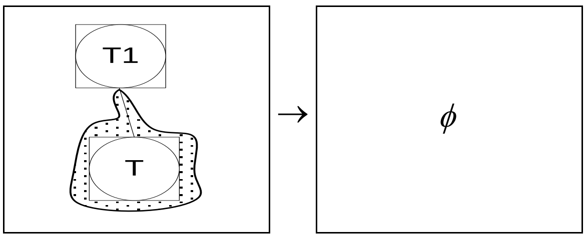
The creation of an OPD starts with an empty graph, and from this empty graph any number of productions is applied until the desired model is achieved. Some of the productions that can be used to create an OPD are shown in Fig 8. Note that  is the symbol of a Thing (Object or Process). For example, Production 1, Simple Thing Creation, states that if Thing T does not exist, it can be created. Also note that in some cases links are modeled using wildcard notations, meaning that the link can be matched either to any link kind (when the links is drawn as a straight line), to structural links (a straight line with an ‘s’ in the middle) or procedural links (a straight line with a ‘p’ in the middle.



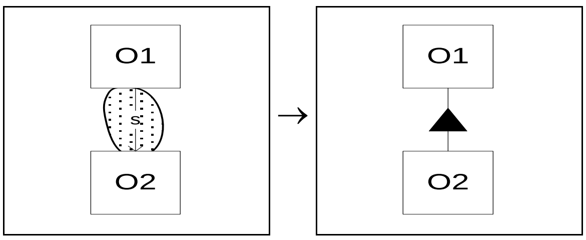
Production 1 Simple Thing Creation



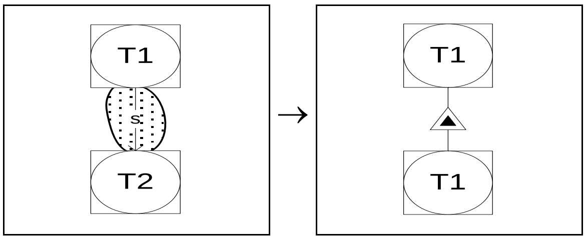
Production 2 New State Creation



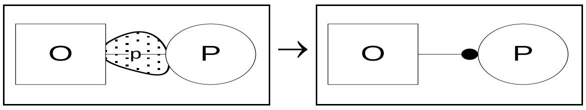
Production 3 Thing Removal



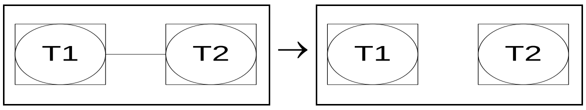
Production 4 Object-Pair Aggregation-Participation Link Creation



Production 5 Exhibition-Characterization Link Creation



Production 6 Agent Link Creation



Production 7 Link Removal

Fig 8 Sample Productions of the OPD graph grammar

4.2. OPD Validation

Validation of an OPD employs the OPD Abstraction algorithm, defined below. The validation is done by searching for illegal constructs during the abstraction process. If the algorithm does not find any illegal constructs, then the OPD is valid, at least syntactically.

As noted, this work is applicable to a single OPD. A single OPD may contain a complete OPM model or only part of a greater system model with other interconnected OPDs.

The word abstraction is used in this context differently than in OPM, therefore it needs to be clarified. *Abstraction* is used to denote reduction of the amount of syntactic and semantic information in the model without contradicting the original semantics of the model. In the context of an OPD, an element of the OPD can be abstracted into another element if the new element does not contradict the meaning of the original element, and no other element can abstract the original element being abstracted without losing more semantic information.

The best way to understand this is by an example, as shown in **Fig 9**.

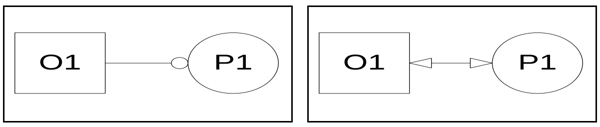


Fig 9 Abstraction of a simple OPM link

The left hand side diagram of **Fig 9** shows that the object **O1** is an instrument of the process **P1**. The semantics of this OPD is that **O1** is required for **P1**'s execution. In the right hand side diagram the instrument link is changed to an effect link. Semantically, an effect link also denotes that **P1** requires **O1**, but it adds to this that **P1** affects **O1** by changing its state. There is loss of information, because the effect link has a broader definition. However, since the effect link does not contradict the semantics of the original instrument link, the former link can abstract the latter.

A more complex and realistic example is shown in **Fig 10**.

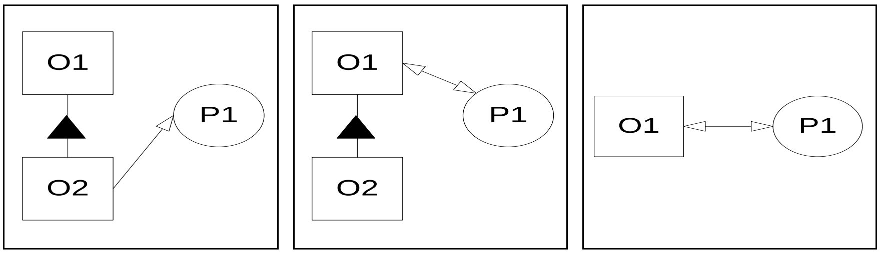


Fig 10 Abstraction of the link of a part

The diagram on the left hand side of **Fig 10** shows that **O1** consists of **O2**, and **O2** is consumed by **P1**. The middle diagram shows an intermediate step in the abstraction process, in which **O1** is affected (its state is changed) by **P1**. Since **O1** consists of **O2**, the semantics of the original diagram is not contradicted, but information on the specific change done to **O1**, namely, the consumption of its part **O2**, has been lost. The OPD on the right hand side reduces the amount of information even more by deleting **O2**. The new diagram does not contradict the original diagram and it still contains a "watered-down" version of the semantics of the original OPD.

The abstraction of the OPM Model is done by successively applying graph grammar productions to the OPD until no further abstraction can be done (no production rule can be applied). We call the resulting model the *final abstraction* of the OPD. Even though the final abstraction of the OPD is valid as an OPM model, it must be checked by the modeler, because only the modeler can validate that the semantics of this model matches the original semantics she or he wanted it to represent.

This section is divided as follows: Subsection 4.2.1 provides basic definitions needed in the algorithm definition, Subsection 4.2.2 shows some Graph Grammar productions used in the abstraction algorithm, Subsection 4.2.3 shows some Illegal Constructs used by the algorithm, Subsection 4.2.4 explains the logic behind Generalization and Classification abstraction and how it is done, and Subsection 4.2.5 presents the full abstraction algorithm and an example execution of it.

4.2.1. Definitions and Notation

1. Temporary Link: The abstraction algorithm defined below works iteratively, trying to abstract one **thing** in every iteration. During the abstraction process, there are cases when new links are inserted into the OPD. These are called *temporary links* and are modeled with a curved connection, as shown in **Fig 11**.

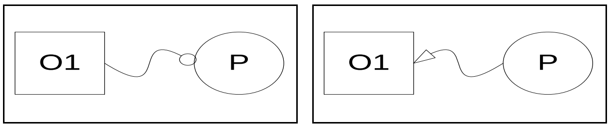


Fig 11 Temporary instrument link (left) and result link (right)

The difference between *temporary links* and regular links is that during the one algorithm iteration the type of temporary links may be changed by the abstraction algorithm. For example, suppose the algorithm received the context shown in the left-hand graph of **Fig 12**. This can occur if **P** uses another aggregate of **O1** as an instrument (not shown in the drawing) which was previously abstracted. Since the instrument link from **O1** to **P** was created by the abstraction algorithm, it can be further abstracted to an effect link as shown in the right-hand graph of **Fig 12**.

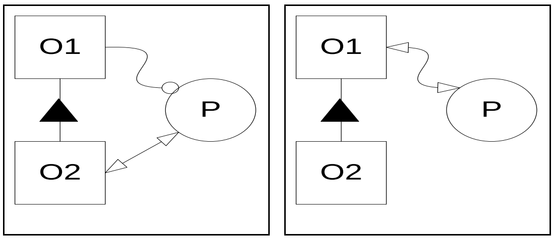


Fig 12 Example of uses of temporary link

In contrast, if the instrument link was not temporary, but rather a modeling decision (made by a modeler), the algorithm would not be able to change its type and we would have an illegal construct in the model, This is so because a change of a part cannot be abstracted by the whole being an instrument, since an instrument is by definition an enabler that cannot be changed.

2. Structural Parent: the structural parent of a thing t_1 is a thing t_2 that is a source of a structural relation ending at t_1 (relations like Generalization and Instantiation are structural relations). The set of structural parents of a thing t_1 is denoted by $SP(t_1)$.

3. Modeling Height: *Modeling height* of a thing denotes how far it is from its farthest ancestor. A thing t_1 that has no structural parent is defined to have height 0: $h(t_1) = 0$. The height of any other thing in the OPD is defined as $h(t_i) = 1 + \max(h(t_j \in SP(t_i))$. **Fig 13** shows an example of the modeling height in a sample OPD.

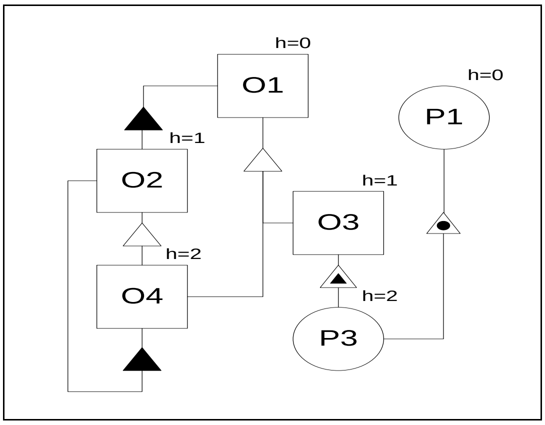


Fig 13 Modeling heights of things in a sample OPD

4.2.2. Graph Grammar Productions for OPD Abstraction

The OPD Abstraction productions are divided into four groups: 1) State Change Abstraction: abstraction of links that start and end at a state, 2) State-Specified Link Abstraction: abstraction of links that either start or end at a state, 3) Procedural Abstraction: abstraction of procedural links, and 4) Thing Removal: removing things that have no more procedural or outgoing structural links. This grouping was created because the abstraction algorithm, specified below, must apply the production groups in a specific order.

Following are examples of the OPD abstraction productions with a short explanation of the logic behind them. Note that this is only a small subset of all the productions. The complete set of productions can be found in [2]. Classifying the productions into the groups shown above, Production 1 is part of the State Change Abstraction group, Productions 2-5 are part of the Procedural Abstraction Group, and Production 6 is part of the Thing Removal Group.

Production 1 – State Change Abstraction: Changing an input-output links pair into an effect link (see **Fig 14**). This can be an intermediate step to remove (abstract) the object's state.

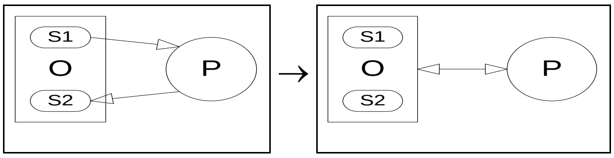


Fig 14 State Change Abstraction production

Production 2 – Promotion of Part Consumption to Aggregate Effect: Consumption of a part object affects the aggregate object. Since in the diagram there is no specified relation between **O1** and **P**, the fact that it is affected by **P** must be added to the diagram. After this is done, the link between **O2** and **P** is removed. The production is shown in **Fig 15**.

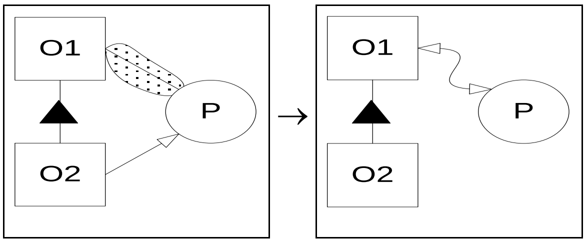


Fig 15 Promotion of Part-Consumption to Aggregate Effect production

Production 3 – Part Consumption Removal while Abstracting Instrument to Effect: Consumption of a part means change to the aggregate. Since in **Fig 16** the link between **O1** and **P** was created by the abstraction algorithm, its kind can be changed as long as its new kind expands the meaning of the original link. Here, the instrument link between **O1** and **P** can be abstracted to an effect link, and then removed.

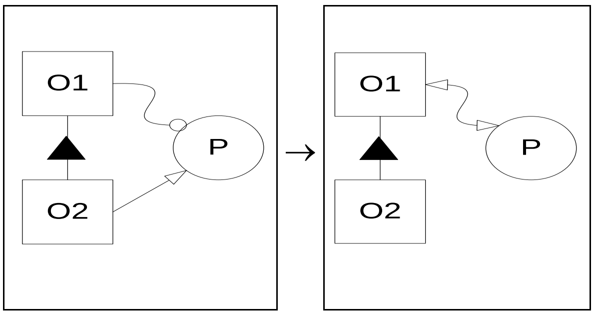


Fig 16 Part Consumption Removal while Abstracting Instrument to Effect production

Production 4 – Part Effect Removal via Result: In **Fig 17**, the process **P** on the left hand side OPD yields **O2** as a part of **O1**, so the result link from **P** to **O2** can be removed. The production also uses a shorthand notation for the link between **O1** and **P**, meaning that it can be applied regardless of whether the link is temporary or not.

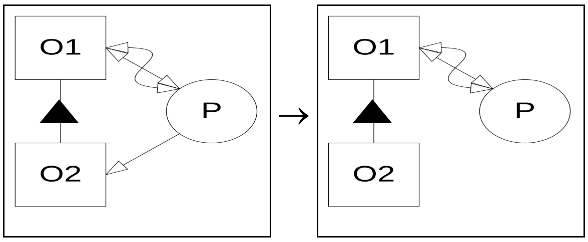


Fig 17 Part Effect Removal via Result production

Production 5 – Part Effect Removal via Agent: An agent link implies optional effect to the object, therefore the aggregate process **P1** implies optional effect to **O**, which abstract effect caused by **P2**, so the link between **P2** and **O** is removed. The production is shown in **Fig 18**.

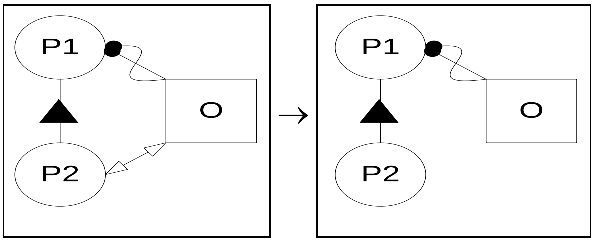


Fig 18 Part Effect Removal via Agent production

Production 6 – Thing Removal: If the thing being considered for removal has no procedural link or outgoing structural links, it can be removed from the OPD. Note that the thing removed must be matched to **T1**. The production is shown in **Fig 19**.

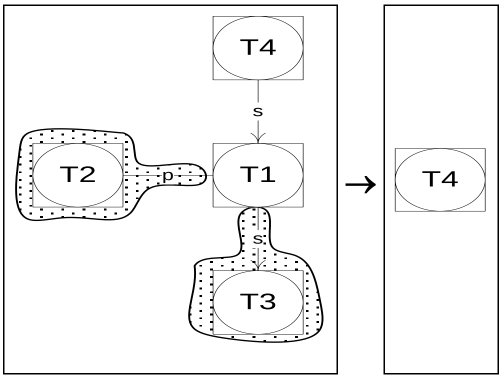


Fig 19 Thing Removal production

4.2.3. Illegal Constructs

Illegal constructs are OPM constructs that create invalid or contradictory semantics in the model. If one of these constructs is found in the OPD, or is created by the abstraction algorithm, the OPD becomes invalid.

Below we show a number of illegal OPM constructs, which can occur in the local context of the abstraction algorithm. Next to each construct is a brief explanation on the rationale behind the illegality of the construct.

Illegal Construct 1 – Part Consumption and Aggregate Instrument: The consumption link in **Fig 20** between **P** and **O2**, that signifies change to **O1**, contradicts the instrument link between **O1** and **P**, which signifies no change to **O1**.

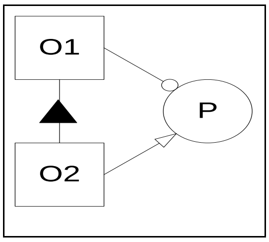


Fig 20 Part Consumption and Aggregate Instrument illegal construct

Illegal Construct 2 – Exhibitor Effect and Attribute Result:

The effect link between **P1** and **O** in **Fig 21** is less specific than the fact that **O** is created by an attribute of **P1**.

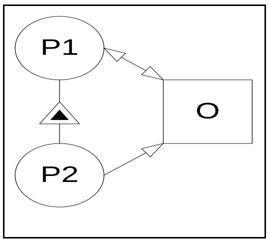
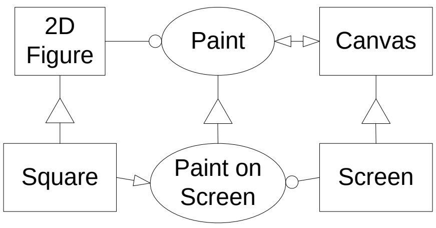


Fig 21 Exhibitor Effect and Attribute Result illegal construct

4.2.4. Generalization and Classification Abstraction

The generalization-specialization relation can link two objects or two processes. When two processes are related with a generalization-specialization link, the abstraction process must validate that the “signature” or "API"[1] of the source of the relation is maintained in the target of the relation. The signature of a process consists of all incoming and outgoing procedural links, including the object types that are at the ends of these links. An example of an OPD that is invalid because the signature of a process is not inherited correctly is shown in **Fig 22**.



[1] API – An application programming interface (API) is a source code interface that an operating system or library provides to support requests for services to be made of it by computer programs

Fig 22 Invalid signature example

Process **Paint** requires **2D Figure** and affects **Canvas**. **Paint on Screen** is a **Paint**, therefore it must conform to the same signature as **Paint**, meaning that it must require an object of type **2D Figure** and must affect an object of type **Canvas**. Since this is not the case, this OPD is invalid.

The signature of the process must be maintained, but may be expanded by creating new links in addition to the links that already exist in the original signature.

The signature validation relies on the *type* of a thing. Each modeled thing in OPM has at least one type[2], and the OPM generalization or classification relations create a type hierarchy. For each thing:

- Each modeled thing is always of a primitive type. A modeled process named $<pname>$ is of type $<pname>\_ptype$. A modeled object named $<oname>$ is of type $<oname>\_otype$. The primitive type of a thing is denoted as $T(<thing\_name>)$.

Using the OPM generalization-specialization relation, we can model the fact that one thing specializes another thing, inheriting its features (i.e., attributes and operations), relations and states[3]. This means that the specialized thing becomes of the type of the general entity. This creates the *Type Closure* of a thing, denoted by $TC(<thing\_name>)$, such that:

- $TC(<thing1>) = \left[\bigcup_{<thing1> \triangleright\!\triangleright <thing2>} TC(<thing2>) \right] \cup T(<thing1>)$, where $<thing1> \triangleright\!\triangleright <thing2>$ denotes that **thing1** is a **thing2**, as modeled in OPM using the generalization-specialization relation.
- If **thing1** is an instance of **thing2**, then $TC(<thing1>) = TC(<thing2>) \cup T(<thing1>)$.

For example, suppose **P1** and **P2** are two processes. From the definition above, process **P1** is of type *P1_ptype* and **P2** is of *P2_ptype*. Furthermore, suppose that **P1**

[2] The word type rather than class has been selected since class is used in most languages to define objects, and this might confuse the reader.

[3] The Generalization-Specialization relation in OPM is usually called inheritance in modern object oriented languages.

and **P2** are connected with a Generalization-Specialization link, where **P1** is the source of the link and **P2** is the target of the link. Then **P2** is also of type *P1_ptype*. Using the above definitions, the *signature consistency validation* verifies that all processes that are part of a generalization-specialization relation have the same signature. The algorithm checks each procedural link of the parent in the relation, and searches for a matching link in the child of the relation. When such link is found, it verifies that the type closure of the connected element in the child's relation matches at least one element in the type closure of the connected element in the parent's relation. The algorithm succeeds if all of the links in the parent are valid.

4.2.5. OPD Abstraction and Validation Algorithm

As stated above, the OPD Abstraction and Validation algorithm tries to abstract the OPD as much as possible, while continuously checking that the syntax and semantics of the OPD remain valid.

The first step of the algorithm is the signature consistency validation. This must be done before the abstraction of the OPD since the abstraction may change and remove the links in the graph invalidating the API.

The second step of the algorithm is the core of the abstraction process. The algorithm runs on all of the things ordered by their modeling height descending. The result of each iteration can be: (1) removal of the processed **thing**, if all of the outgoing links from the thing were removed by the abstraction productions; (2) marking the **thing** as processed if the algorithm could not remove it but did not find any illegal construct after all abstraction productions, or (3) finding an illegal construct in the context of the processed **thing**.

The abstraction process is done in three steps. The first step is to abstract all of the states of the **thing** (if it has any). This is done in order to transfer all the links to the **thing** being abstracted. For example, suppose an **object** is consumed by a **process** only when it is in a specific **state**. The abstraction process would cause the model to show that the **process** consumes the **object**, regardless of its current **state**. As expected, some information is lost, but the "strongest" consequence of the link, namely that the **process** consumes the **object,** is maintained.

The algorithm then tries to transfer all the links that originate from the current **thing** to its parent, using procedural abstraction productions. Note that because there are many (116 to be exact) abstraction productions, specifying them all in the algorithm would make it unreadable, so they have all been called *Procedural Abstraction*. Their classification is refined in [2] using link types as the basis for classification. The purpose of this step is to remove as much information as possible from the **thing** being abstracted, up to the point that it is not the source of any procedural link. As in the state abstraction process, this may cause some information loss. For example, suppose object **O1** consists of object **O2** and **O3**, and **P1** is a process that consumes **O3**. When object **O3** is abstracted, the consumption link to **P1** is transferred so it starts at **O1** while also being changed to an effect link (since this is the defined semantic of consumption of an aggregate). After this abstraction, the model is still correct, but less informative.

A description of the algorithm in pseudo code follows.

- Input: OPD
- Algorithm:

1. Validate all Process signatures by applying the **Error! Reference source not found.** algorithm. If validation fails, stop and return failure on signature validation.
2. While OPD contains things that have not been processed:
   - 2.1. Of all the things in the current OPD select **thing** with *max*(*height*(thing)) and no outgoing structural links.
   - 2.2. Transform all *Temporary Links* that start at **thing** to *Regular Links*.
   - 2.3. Apply *State Change Abstraction* productions to **thing** if applicable, as many times as possible.
   - 2.4. Apply *State-Specified Link Abstraction* productions to **thing** if applicable, as many times as possible.
   - 2.5. Apply *Procedural Abstraction* productions to **thing** if applicable, as many times as possible.
   - 2.6. Check *Illegal Constructs* on **thing**. If at least one *illegal construct* exists, stop and return failure on **thing**.
   - 2.7. Apply *Thing Removal* production to **thing** if applicable. If the production is not applicable, mark **thing** as processed.
3. Transform all *temporary links* in the OPD to *regular links*.
4. End.

The best way to understand the algorithm is through an example, where we validate SD1 of the ABS Ford system model example provided by OPCAT [7] (the OPM modeling tool) shown in Fig 23 ABS Ford System Model SD1**Fig 23**.

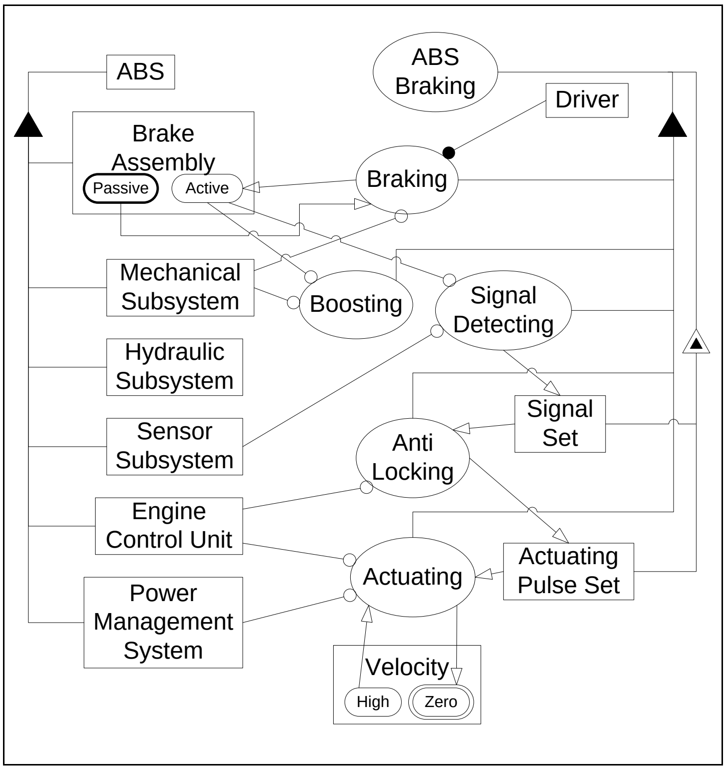


Fig 23 ABS Ford System Model SD1

The algorithm selects a thing with the highest height to start the abstraction. For example, suppose **Brake Assembly** is selected first. The first production that can be applied is *State-Change Abstraction*, as shown in **Fig 24**.

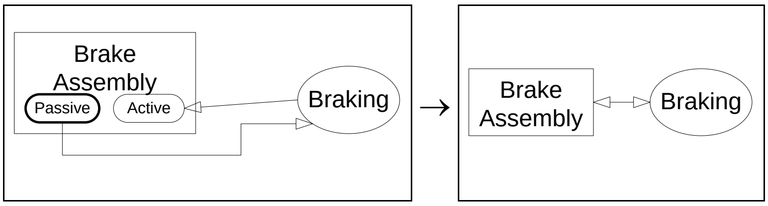


Fig 24 State change abstraction on Brake Assembly

State-Specified Link Abstraction is then applied, as shown in **Fig 25**.

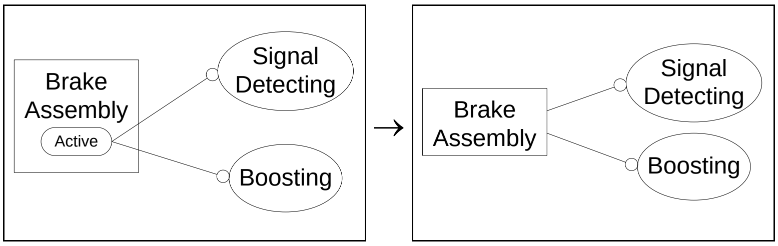


Fig 25 State-Specified Link abstraction on **Brake Assembly**

The next step in the algorithm is *Procedural Abstraction*. In this step, the procedural links that connect **Brake Assembly** to all other things in the diagram are migrated as temporary links to its structural parent, which is **ABS**. The result of this is shown in **Fig 26**.

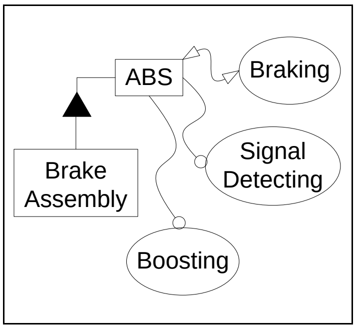


Fig 26 Example diagram after initial abstraction of **Brake Assembly**

No *illegal constructs* were detected on **Brake Assembly**, so the next step is *Thing Removal*, which removes **Brake Assembly** from the diagram with the result show in **Fig 27**.

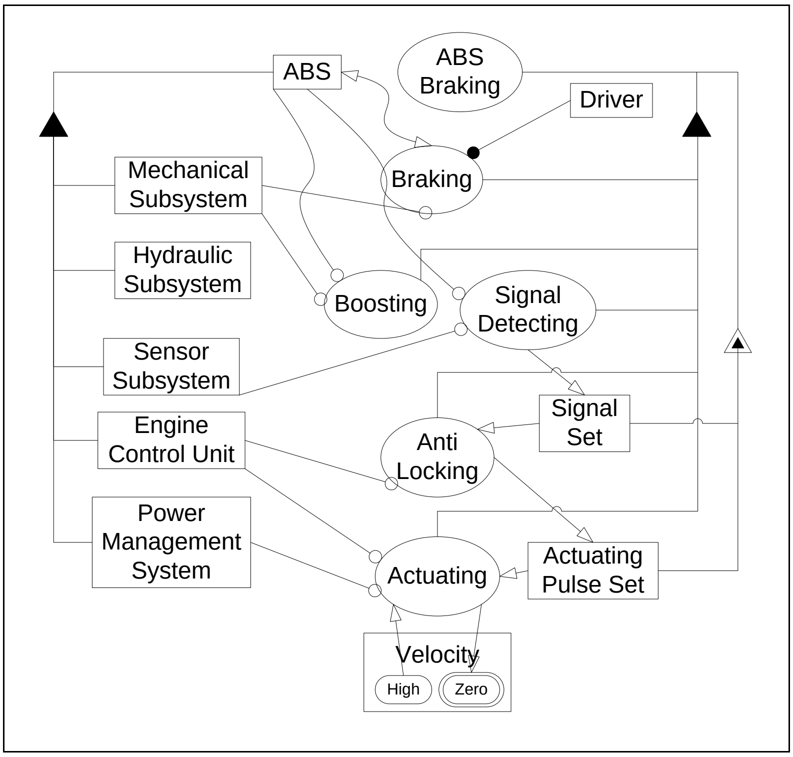


Fig 27 OPD diagram after first round of the abstraction algorithm

Since at each round of the algorithm a **thing** is removed or marked as processed, and there is a limited number of **things** in the OPD, the algorithm will finish either when there is no **thing** in the OPD not marked as processed, or if there were illegal constructs found in the way.

The final result of the algorithm after a number of rounds is shown in **Fig 28**.

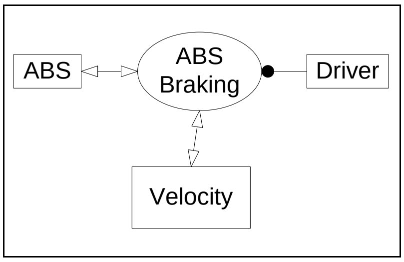


Fig 28 Final abstraction of the example diagram

Even though the algorithm validated the OPD and found it syntactically and semantically correct, the final result of the algorithm provides the modeler with the most simplified version of the system, which she or he must examine to see if the abstract system model reflects the modeler's intent.

5. Conclusions

In this research we have formally defined the syntax of an OPD and a method for the creation and verification of OPDs. This formalization provides OPM with a solid software engineering foundation, as the syntactic and some of the semantic correctness of models and diagrams can be verified. This formal verification is critical as we wish to create robust and verifiable systems.

A formal and exact definition of the syntax and the semantics of OPM opens the way for such desirable features as validation and automatic testing of systems at design time. This formalism also supports system lifecycle management. As a system is changed, these changes can be done in the system model and can be compared semantically to the original model to detect what of the model were affected by the change. This can greatly reduce the amount of testing needed when new versions of a system are produced.

5. References

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