Towards a Formal Specification of Multi-Paradigm Modelling

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***Abstract*—The notion of a programming paradigm is used to classify programming languages and their accompanying workflows based on their salient features. Similarly, the notion of a *modelling paradigm* can be used to characterise the plethora of modelling approaches used to engineer complex Cyber-Physical Systems. Modelling paradigms encompass formalisms, abstractions, workflows and supporting tools and tool chains A precise definition of this modelling paradigm notion is lacking however. A precise definition will increase insight, will allow for formal reasoning about the consistency of the framework and may serve as the basis for the construction of design (modelling, simulation, verification, synthesis, ...) environments. In this paper, we present a formal framework aimed at capturing this notion, as a first step towards a comprehensive formalisation of multi-paradigm modelling. Our formalisation is illustrated by CookieCAD, a simple Computer Aided Design paradigm used in the development of cookie stencils.**

I. Introduction

Modern General-Purpose Programming Languages (GPLs) are traditionally classified according to their supporting paradigm(s). For example, Eiffel is object-oriented and supports the contract-based-design paradigm, Prolog is declarative, and Lisp is functional. The paradigm characterises the underlying syntactic and semantic structures and principles that govern these GPLs' execution: object orientation is imperative in nature and imposes viewing the world in terms of classes and communicating objects; the declarative style relies on term substitution and rewriting. But this has a concrete consequence for users: a statement in Eiffel has very few commonalities with a Prolog sentence. A programming paradigm directly translates into different concepts encoded in the GPL's language syntax definition (known as a metamodel in the Model-Driven Engineering world). Very naturally, the idea of combining several paradigms at the level of GPLs led to more expressive, powerful programming languages such as Java (which is imperative, object-oriented, concurrent, and real-time and, since recently, somehow functional) or Maude (which is declarative, object-oriented and also concurrent and real-time). What is a *paradigm* then? In a philosophical attempt, Kuhn [1] defines it as an open-ended contribution that frames the thinking of an object study with concepts, results and procedures that structures future achievements. Although far from the concerns in the discipline of Computer Science, this definition nevertheless highlights the emergence of a *structure* that captures the object of discourse, and the notion of *procedure* that guides achievements.

Multi-Paradigm Modelling (MPM) has been recognised lately as a powerful paradigm that may be helpful in designing, reasoning about, communicating on Cyber-Physical Systems (CPS), because such systems integrate several components that are themselves already complex: in a CPS for example, a physical part interacts with software and humans through networks to achieve difficult tasks such as medical monitoring, autonomous cars, robotics in manufactures, etc. CPS are notoriously complex because they mix cross-disciplinary models, which in turn produce inter-domain interactions, in applications that are often safety-critical.

In this paper, we intend to propose a formal framework aimed at capturing the notion of *paradigm*, as a first step towards a formal framework for MPM (with obvious application in CPS). Beyond the mathematical specification, this formal framework aims at facilitating the communication between experts for helping them better grasp the core of how their CPS are built, but also at facilitating a formal comparison of systems based on their core MPM components. Ultimately, this formal framework would support (meta-)tool building that would help practitioners reason about CPS and figure out which tools are the most appropriate to handle their task(s).

After further motivating our work in Section II, we sketch a proposal for a formal framework addressing the notion of paradigm in Section III. We then present a small Case Study that illustrates this notion on a simple, yet realistic CPS application in Section IV. We then conclude in Section VI with Related Work and closing remarks.

II. Motivation

For developing a Cps, project managers and engineers need to figure out what core properties the future system has, and select the most appropriate development languages, software lifecycles and "interfaces" to make the different views and components of their system communicate appropriately. For example, when a manager knows that system/software requirements are likely to change frequently during the project's course, selecting an Agile development process may likely help handle evolution and change. If the system's behaviour requires that operations are triggered when data become available, similar to reactive systems, relying on Data Flow languages may help handle the most critical part of the software behaviour.

Mpm requires to *model everything explicitly*, with *the most appropriate formalisms*, *at the most appropriate abstraction level* [2]. This suggest that a *paradigm* is a placeholder for describing the properties of each of the dimensions described above: the *formalisms*, the *abstraction levels*, and the *processes* that enable interactions between all the basic modelling activities. Ultimately, Mpm aims at providing the tool machinery and support for helping managers and engineers select, organise and manage the three dimensions above. We aim at clarifying the formal foundations of Mpm to help design these tools. This paper represents a first step where we ignore the abstraction dimension for now and focus on the others, but we motivate here why those dimensions are necessary and how they integrate together.

Formalisms/Languages. The first dimension relate to what is otherwise known as *Modellng Languages Engineering*, i.e. the explicit modelling of the key components of (modelling) languages: concrete and abstract (i.e. metamodels) syntaxes, as well as semantics, together with the usual activities around: analysis, simulation, execution, debugging, etc. that should be supported by tools that may be largely synthesized from high-level specifications of these languages and their usage. These multiple languages are organised in a repository that we call the *Modelverse* intended to be dynamically evolving over time.

Abstraction / Viewpoints. Since Mpm integrate multiple users all with different concerns, an infrastructure should be provided for relating models at different abstraction levels, while ensuring that certain language-related properties still hold to ensure a consistent manipulation.

Processes. Many workflows govern the various Mpm activities for engineering languages in a concern-consistent way, but also to support lifecycles and development processes by connecting models in tool chains to achieve larger workflows. To capture this dimension, we rely on a structure called Ftg+Pm [3] tightly connected to the Modelverse: the Modelverse may be queried to obtain any modelling artefact (related to languages of course, but also the processes themselves), providing a snapshot at the current time of the relevant artefacts that may be helpful (e.g. for the general tasks described above), or providing a partial projection of the full Modelverse to be reasoned over. Processes play their full role: they may be *descriptive*, allowing to check that engineers follow the appropriate activities towards project completion; *proscriptive* by putting limits and constraints on what engineers may consider as valid activities; and *prescriptive* by enacting the specific tasks to follow. This Ftg+Pm also enables reasoning over shared parts of, and relationships between languages to give meaning to various models aimed at being used together: for example, finding the highest language (in terms of a mathematical order over the formalisms supported by these languages) to which all relevant models may be mapped, enabling easier reasoning, analysis or (co-)execution.

All three dimensions have at their core the use of *model transformation*: for achieving the various activities for engineering languages (cf. [4]), for specifying the multiview relationships between models, or for performing the various activities in their defining processes. Furthermore, they may also provide the basic manipulations necessary for querying, extracting and projecting the Modelverse.

TABLE I: Properties of two paradigms: Object Orientation (OO[5]) and Computer-Aided Design (CAD[6])

ι_1: Object Orientation (OO)	
OO_1	Possess the concepts of Object and Class
OO_2	Objects possess a state and a set of capabilities / operations
OO_3	Possess an inheritance mechanism
OO_4	Inheritance allows to reuse operations
ι_2: Computer-Aided Design (CAD)	
CAD_1	Comprises concepts of (2D/3D) points and lines
CAD_2	Shapes are defined by lines
CAD_3	Supports transformation of shapes into (2D/3D) products

III. Formalisation

Our formal framework defines a *paradigm* as a *label* or *name* ι denoting a set of properties $\pi \in \Pi$. We define a *paradigmatic structure* $\mathsf{PS} \in \mathbb{PS}$ as a candidate structure that *qualifies*, or *embodies*, or *follows* the paradigm ι if PS satisfies π. PS describes a set of workflows that capture various activities seen to be desirable for realising ι. Table I shows, for illustrative purposes, some relevant properties for two possible paradigms.

Since every aspects of the paradigmatic structure needs to be explicitly modelled, we first introduce the two established notions to manipulate languages explicitly, namely metamodels and models on the one hand, and transformation specification and execution on the other.

A *metamodel* $\mathsf{MM} \in \mathcal{M}$ specifies the *abstract syntax* of a language L. MM is expressed in a specific language called meta-metamodel. A *model* $\mathsf{M} \in \mathbb{M}$ is a particular instance of L, also specified using a language that may be visual / diagrammatic, textual or hybrid (and normally different from the meta-metamodel). When M is a valid instance of MM, M is said to *conform to* MM and noted $\mathsf{M} \rhd \mathsf{MM}$.

A *transformation specification* $\mathsf{T} \in \mathbb{T}$ is a triple $\mathsf{T} = ((\mathsf{MM}^{\mathsf{i}}_{\mathsf{s}})_{\mathsf{i} \in [1..n]}, (\mathsf{MM}^{\mathsf{j}}_{\mathsf{t}})_{\mathsf{j} \in [1..m]}, \mathsf{spec})$, where $(\mathsf{MM}^{\mathsf{i}}_{\mathsf{s}})_{\mathsf{i} \in [1..n]}$ and $(\mathsf{MM}^{\mathsf{j}}_{\mathsf{t}})_{\mathsf{j} \in [1..m]}$ are indexed sets of source and target languages, respectively, and constitute the transformation's *signature*;

while spec is a well-formed transformation definition written in a transformation language. A *transformation execution* $\mathsf{TE}_\mathsf{T} \in \mathbb{TE}$ is a general computation performed on (a) language instance(s) that conform(s) to the source language(s) of the transformation $\mathsf{T} \in \mathbb{T}$.

As an example, the javac compiler is a transformation $\mathsf{T}_{compil} = (\mathsf{MM}_\mathsf{Java}, \mathsf{MM}_\mathsf{BC}, \mathsf{javac})$ that outputs byte code (BC) from any (valid, conforming) Java program $\mathsf{J} \rhd \mathsf{MM}_\mathsf{Java}$. Note that javac is itself specified as a Java program (i.e. $\mathsf{javac} \rhd \mathsf{MM}_\mathsf{Java}$).

A. Templates

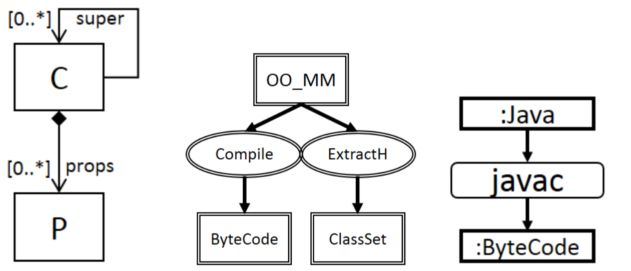
Templates are plain metamodels and transformations, specified with the usual meta-metamodel(s) and transformation languages. A key difference however is that they are not complete, in the sense that they require a regular metamodel (or transformations) to be matched. Templates are used as placeholders for enforcing transformation signatures, expressing high-level properties for metamodels and transformations (specifications), or capturing the necessary steps in a transformation. Suppose we want to formally specify property OO_3 for inheritance in Table I. Figure 1a presents a minimal template defining the basic placeholders: to even allow discussing about super- and sub-classes, one need at least distinguishing between Class and Objects, and defining a partial order (super) between classes. The inheritance property then states that any object of a subclass has access to the state defined by its class, but also to the state defined by its superclass. Note that using a MOF-like meta-metamodel for expressing the template provides navigational notation for free: the property would start with something like $\mathsf{c1}, \mathsf{c2} : \mathsf{Class}$ such that $\mathsf{c2} \in \mathsf{c1.super}$.

Using templates requires a powerful, customisable matching process. For metamodels, contributions on model typing [7], a posteriori typing [8], and metamodel morphisms [9], [10] may be appropriate; for transformations, the rich literature on reuse [11] provides some guidelines on how to realise that. Hence, matching Fig. 1a's template into the Java metamodel [12] would match ClassDeclaration to C and the extends clause to super. We simply capture this important relationship in the following: for a template metamodel $\mathsf{TMM} \in \mathcal{M}$ and a regular metamodel $\mathsf{MM} \in \mathcal{M}$, we note $\mathsf{TMM} \rightsquigarrow \mathsf{MM}$ when TMM is appropriately matched by MM.

B. Workflow

Transformations typically support the realisation of activities that are essential to (the engineering of) languages, typically for parsing and/or pretty printing, defining their semantics (translationally or operationnaly), analysing relevant properties, debugging, and of course executing, simulating, animating, etc. [4]. These activities, and others essential for a paradigm, are typically captured through a workflow.

In our framework, workflows describe precisely the set of activities captured by a candidate paradigmatic structure. A workflow is composed of two elements: a *Formalism Transformation Graph* (FTG) describes explicitly the links between



(a) Template for expressing inheritance. (b) FTG for compilation / hierarchy extraction. (c) Compiling PM.

Fig. 1: Examples for (a) Templates, (b) FTG, and (c) PM.

formalisms / languages, stating which possible transformations may be used; and a *Process Model* describes how language instances are combined together towards achieving a particular activity. Combining both elements results in a FTG+PM, as already described in [3], [13], [14].

Instead of directly manipulating (meta-)models and/or transformations, our framework relies on *names* that allow to retrieve the corresponding artefacts from a repository (eventually centralised as a Modelverse). This linking is captured by the following definition.

Definition 1 (Naming)**.** *The* naming functions *associate names to their actual item:*

$$\begin{aligned} model &: \mathsf{MName} \nrightarrow \mathbb{M} \\ mmodel &: \mathsf{MMName} \nrightarrow \mathcal{M} \\ tmm &: \mathsf{TMMName} \nrightarrow \mathcal{M} \\ trans &: \mathsf{TName} \nrightarrow \mathbb{T} \\ tt &: \mathsf{TTName} \nrightarrow \mathbb{T} \end{aligned}$$

All functions are partial, returning an undefined item (noted $\perp$) when the repository stores no item with the asked name. Template names for metamodels (TMMName) and transformations (TTName) are in a separate namespace than those for regular ones. The repository is ultimately responsible to retrieve appropriate items: for example, querying the repo with the template of Fig. 1a would eventually allow the selection of the Java metamodel if inheritance is required.

To accomodate with templates, we introduce *extended* FTGs, defined as a (name-restricted) mapping of (template) transformations (names) into a signature.

Definition 2. *(Extended) Formalism Transformation Graph (xFTG) An* Extended Formalism Transformation Graph $\mathsf{FTG} \in \mathbb{FTG}(TR, MM)$ *is a function* $\mathsf{FTG}\colon TR \to \langle MM \rangle \times \langle MM \rangle \times \mathbb{B}$.

We parameterise $\mathbb{FTG}$ with two sets of names $TR \subseteq (\mathsf{TName} \cup \mathsf{TTName})$ for regular or template transformations, and $MM \subseteq (\mathsf{MMName} \cup \mathsf{TMMName})$ for regular or template metamodels. Let $tr \mapsto (\langle mm_1, \ldots, mm_n \rangle, \langle mm'_1, \ldots, mm'_m \rangle, b)$ be such a mapping in $\mathbb{FTG}(TR, MM)$: when b is set to true, tr refers to an *automatic* transformation (and human guided otherwise); and mm_is (resp. mm'_js) names are the *source* (resp. *target*) of tr.

Figure 1b pictures a simple FTG using two template, automatic transformations (names) (represented with double-rounded, white items) called $\mathsf{Compile}, \mathsf{ExtractH} \in \mathsf{TTransName}$ that respectively compile and extract the class hierarchy of a template metamodel $\mathsf{OO\_MM} \in \mathsf{TMMName}$.

As its name indicates, a PM describes a process, i.e., a set of activities that are combined together towards achieving a particular goal. Instead of reinventing a Domain-Specific Language for this well-studied domain, we simply specialise one standard and well-known language that covers our needs, namely UML's Activity Diagrams.

Definition 3 (Process Model (PM))**.** *A process model $\mathsf{P} \in \mathbb{PM}$ is an instance of a* UML *Activity Diagram where*

- ActionNode*s are labelled by transformation instance names typed by their conforming transformation specifications, and may be* hierarchical *and may contain input or output* Pin*s; and*
- ObjectNode*s are labelled by language instance names typed by their conforming languages; and*
- ControlNode*s include* Decision/Merge*,* Fork/Join *and* Init/Final*s nodes.*

Figure 1c pictures a compilation process between one ObjectNode representing a Java program : Java producing a ByteCode instance : ByteCode through the ActionNode javac.

The following definition simply puts things together: a workflow is composed of an FTG together with a *well-formed* PM.

Definition 4 (Workflow)**.** *A* workflow $\mathsf{W} \in \mathbb{W}(TR, MM)$ *is a pair* $\mathsf{W} = (\mathsf{FTG}, \mathsf{P})$ *where* $\mathsf{FTG} \in \mathbb{FTG}(TR, MM)$ *and* $\mathsf{P} \in \mathbb{PM}$*, such that* P *is well-formed (noted* $\mathsf{P} \blacktriangleright \mathsf{FTG}$*) wrt.* FTG*, i.e., for each* ActionNode *inside* P *with name tr,*

- *there exists a transformation name* $\mathsf{t} \in \mathcal{D}\mathsf{om}(\mathsf{FTG})$ *that refers to a transformation specification* T *(i.e.* $trans(\mathsf{t}) = \mathsf{T}$ *or* $tt(\mathsf{t}) = \mathsf{T}$*) such that tr conforms to* T *(i.e.* $tr_{\mathsf{T}} \in \mathbb{TE}$*)*
- *for each source or target* mm_i *of* t *(i.e.* $\mathsf{FTG} = (\langle \ldots, mm_i, \ldots \rangle, \langle \ldots \rangle, b)$ *or* $\mathsf{FTG} = (\langle \ldots \rangle, \langle \ldots, mm_i, \ldots \rangle, b)$*) at rank* i *refering to a (template) metamodel* $\mathsf{MM_i}$ *(i.e.* $mmodel(mm_i) = \mathsf{MM_i}$ *or* $tmmodel(mm_i) = \mathsf{MM_i}$*), there exists a* Pin *at rank* i *connected (as input or output) to an input* ObjectNode *carrying a model name* mname *that refers to a model conforming to a metamodel* MM' *(i.e.* $model(\mathsf{mname}) \rhd \mathsf{MM}'$*, such that either* MM *is the source/target i-metamodel of* T *(i.e.* $\mathsf{MM} = \mathsf{MM}'$*), or it matches it (i.e.,* $\mathsf{MM} \rightsquigarrow \mathsf{MM}$*).*

When clear from context, or unnecessarily detailed, we simply note the set of workflows $\mathbb{W}$, without any indication of languages or transformations (sets).

For instance, the PM in Fig. 1c is well-formed wrt. the FTG in Fig. 1b: as established earlier, : Java refers to a Java model, whose metamodel matches OO_MM and javac is an appropriate match for Compile; furthermore, no transformation (execution) are exhibited for matching ExtractH.

Our definition for xFTGs relies solely on *names*: we heavily rely on the repository (Modelverse) capabilities in order to first retrieve the appropriate items (metamodels, models and transformations) as well as checking that matching between them is appropriately achieved. This was abstracted away in Def. 1, but requires a proper formalisation in the future.

Similar to the original [3], [13], [14], our definition does not impose a particular topology on the PM as long as transformations are well-formed. However, the original definition simply rely on a name-matching typing, similar to what is depicted in Fig. 1c, leverage UML-like Object/Class instanciation. In contrast, we introduced a relaxed matching mechanism based on metamodel/transformation matching relying on the $\rightsquigarrow$ relationship.

C. Paradigm

Properties characterising a paradigm (as briefly described in Table I) may span over all the previous elements: for example, expressing the inheritance formally would require to have at disposal the (template) metamodel of Fig. 1a, but also access to its semantic domain to check that the state of a superclass becomes available to all objects of any subclass. Similarly, properties over transformations may restrict or constraint its applicability (e.g., ExtractH would have to define preconditions for object-oriented metamodels allowing multiple inheritance, and have a postcondition on the datastructure of its output). Properties may also characterise the topology, the usage and the matching process in an FTG or its corresponding PM (by, for example, ensuring frequent loops for the Agile paradigm).

We first collect all previous elements in a single mathematical structure called *paradigmatic structure* on which properties may hold.

Definition 5 (Paradigmatic Structure)**.** *A* paradigmatic structure $\mathsf{PS} \in \mathbb{PS}$ *is a pair* $\mathsf{PS} = (MM, W)$ *where* $MM \in \wp(\mathcal{M})$ *is a set of metamodels and* $W \in \wp(\mathbb{W})$ *is a set of workflows.*

Following the mantra of modelling "at the most appropriate level of abstraction", it becomes impossible at the abstraction level of this presentation to formally (i.e., intensionally) define the nature of such a large class of properties. We therefore provide an extensional definition: we note $\mathcal{P}(S)$ the set of all possible properties expressible over a structure S.

Definition 6 (Paradigmatic Properties)**.** *A* paradigmatic property *is a tuple* $\pi = (\pi_{\mathsf{MM}}, \pi_{\mathsf{W}}, \pi_{\mathsf{PS}}) \in \Pi$ *where*

- $\pi_{\mathsf{MM}} \in \mathcal{P}(\mathcal{M})$ *is a set of properties over metamodels (and their semantics);*
- $\pi_{\mathsf{W}} \in \mathcal{P}(\mathbb{W})$ *is a set of properties over workflows (and their matching procedure);*
- $\pi_{\mathsf{PS}} \in \mathcal{P}(\mathbb{PS})$ *is a set of properties spanning over all components of paradigmatic structures).*

Paradigmatic properties may be expressed through *pattern languages*, e.g., for ensuring the presence of certain concepts, or through *dedicated logics*, e.g., for ensuring semantic prop-

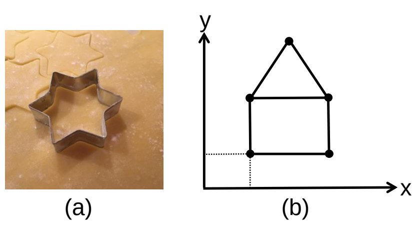


Fig. 2: CookieCAD: (a) Real-life cookie cutter. (b) House-like shape with line-sharing. (c) Invalid shape (due to overlaps).

erties. Finally, we associate a *name* to a set of properties for referring to a specific paradigm.

Definition 7. *Paradigm Let* ParadigmName *be a set of (paradigm) names, that we associate to properties through a function* $\iota \in [\mathsf{IntentN} \rightarrow \Pi]$.

For paradigm $\in$ ParadigmName *such that* $\iota(\mathsf{paradigm}) = (\pi_{\mathsf{MM}}(\mathsf{p}), \pi_{\mathsf{W}}(\mathsf{p}), \pi_{\mathsf{PS}}(\mathsf{p}))$*, we say that* $\mathsf{PS} = (MM, W) \in \mathbb{PS}$ embodies *(alternatively,* follows*,* qualifies as*)* paradigm *iff*

- *the properties* $\pi_{\mathsf{MM}}(\mathsf{p})$ *hold on* MM*;*
- *the properties* $\pi_{\mathsf{W}}(\mathsf{p})$ *hold on* W*; and*
- *the properties* $\pi_{\mathsf{PS}}(\mathsf{p}))$ *hold on* PS.

Notice that it may be interesting to introduce namespaces for paradigm names, since it is likely that similar denominations would be used for slightly different sets of properties: for example, one may define object orientation in the context of single or multiple inheritance, the latter requiring to take care of conflicting properties (as it is with the renaming mechanism in Eiffel).

IV. Case Study: CookieCAD

Computer-Aided Design (CAD) [6] promotes the use of computer systems to assist the creation, modification, analysis and optimisation of a design. A design may describe any physical, 3D object, e.g., engines or planes for analysing heat and fluid transfers, bridges and wind mills to estimate the dynamic response of the mechanical structure to various environmental variations. CAD is often paired with Computer-Aided Manufacturing (CAM) to help plan, manage and control the operations around the process of bringing 3D designs to life. Historically, techniques and tools heavily rely on geometry, solid and surface mathematical formalisms. This particular set of processes operated over a selected bunch of formalisms and languages makes CAD a paradigm on its own.

We propose to illustrate our formal framework with a simplified variant of CAD named CookieCAD(CCAD): it helps design simple cookie cutters, as illustrated in Fig. 2(a). A cookie cutter adopts a simple shape (triangle, rectangle, star, etc.) represented by 2D geometric lines (noted L) which are specified based on the definition of two points in no particular order (noted P) placed in a cartesian plan (using x-/y- coordinates). In order to be manufacturable, points shall not be placed too close to each other (the exact distance tolerance depends on the machinery used), and shall represent closed

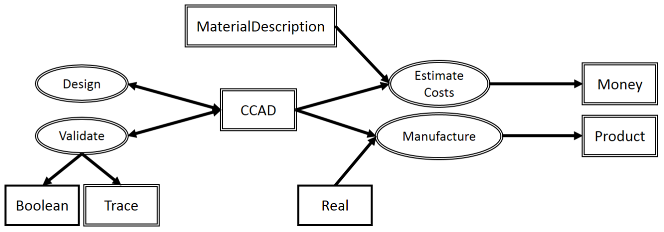


Fig. 3: $\mathsf{FTG}_{\mathsf{CCAD}}$: an xFTG for CCAD activities.

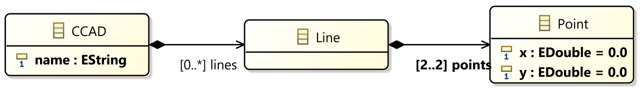


Fig. 4: Template metamodel CCAD in $\mathsf{FTG}_{\mathsf{CCAD}}$ (cf. Fig. 3).

polygons that may share some lines (as illustrated in Fig. 2(b) for a house-like cutter, with the triangular roof placed over the rectangular base). Consequently, lines shall not cross each others as illustrated in Fig. 2(c), which results in an *invalid* cookie cutter. At manufacturing time, such a design shall be associated with a width to build a 3D physical objects: the precision of the machine may finally discard some of the designs presented on Fig. 2(a) if it is not able to cut or fold metal pieces that size.

Figure 3 depicts a possible, simplified xFTG for CCAD named $\mathsf{FTG}_{\mathsf{CCAD}}$. It includes four transformations templates represented as double-rounded ellipses named Design, Validate, EstimateCosts and Manufacture. As an example, a repository would have to retrieve a transformation corresponding to the following signature: $\mathsf{Validate} \mapsto (\langle \mathsf{CCAD} \rangle, \langle \mathsf{CCAD}, \mathsf{Boolean}, \mathsf{Trace} \rangle, \top)$, meaning that Validate is automatic and takes as source a CCAD model and produces back the source CCAD (notice the double arrow from/to CCAD), and a boolean value, indicating whether the source model is valid or not, in which case a Trace model is produced. The target CCAD model may be discarded by some tools, but nothing prevents a repository to select transformations that may additionnally decorate the target with information from the trace model to help CCAD designers grasp their errors' origins more easily, or keep traces and models cleanly separated, since both behaviours match Validate's signature. All transformation and metamodel names in Fig. 3 are templates (meaning they belong to TMMName or TTName) except Boolean and Real, which is used as a source parameterising the width of the cookie cutter design in order to produce the physical 3D cutter.

These template transformations make a central use of the CCAD language that would handle the visual representation, design, validation, debugging, etc. of a cookie cutters designs, based on a template metamodel depicted in Fig. 4: a CCAD model is defined by a set of lines delimited by exactly two points, in no particular order, having real coordinates on a 2D plan. The semantics of such a metamodel captures all points in an Euclidian plan between any pair of points defining a line.

Figures 5a depicts a candidate, well-formed PMs named $\mathsf{PM}_{\mathsf{Full}}$. It arranges three transformations from $\mathsf{FTG}_{\mathsf{CCAD}}$ in a sequential fashion: starting from scratch, a designer starts iteratively create a design, then manufacture it once it has been validated. This workflow does not prohibit manufacturing of expensive designs, since EstimateCosts is left out. Enforcing such a scenario requires specifying properties specifically targeting $\mathsf{PM}_{\mathsf{Full}}$'s topology, asking at least EstimateCosts's presence in the PM in order to break $\mathsf{PM}_{\mathsf{Full}}$ well-formedness. Refering to Tab. I, CAD_1 and CAD_2 are easily recognised as property patterns over a metamodel manipulating CAD designs; while CAD_3 specifies a property characterising the existence of a transformation that produces a final, real-life 3D product. Fig. 5b shows possible patterns for capturing them in a MOF-like syntax. Assuming one has explicit and appropriate languages for expressing all properties required, this would built a set of paradigmatic properties $\pi_{\mathsf{CAD}} \in \Pi$ that would constitute part of our CAD paradigm (i.e. $\mathsf{CAD} \mapsto \pi_{\mathsf{CAD}}$ in the sense of Def. 7).

We have built a paradigmatic structure $\mathsf{PS}_{\mathsf{CCAD}} = (MM, \{\mathsf{W}_{\mathsf{CCAD}}\}) \in \mathbb{PS}$ with only one workflow $\mathsf{W}_{\mathsf{CCAD}} = (\mathsf{FTG}_{\mathsf{CCAD}}, \mathsf{PM}_{\mathsf{Full}}) \in \mathbb{W}(TR, MM)$ relying on transformation TR and metamodel names MM as described in Fig. 3. *Now, does* $\mathsf{PS}_{\mathsf{CCAD}}$ *qualify as a* CAD *(simplified) paradigm?*

Properties CAD_1 and CAD_2 are easily checked on the CCAD metamodel by matching the classes from the template properties to their corresponding class (namely, L and P to Line and Point, then references and b to x and y, and finally S to CCAD itself). Property CAD_2 may be matched to the transformation template Manufacture, with a template Product yet to be retrieved from the repository.

V. Related Work

MPM seems to have originated from the Modelling and Simulation community. As early as 1996, the Esprit Basic Research Working Group #8467 formulated a series of simulation policy guidelines [15] proposing a request to build ”a multi-paradigm methodology to express model knowledge using a blend of different abstract representations rather than inventing some new super-paradigm”. In [16], an MPM and Simulation methodology is proposed, with a specific focus on formalisms and languages. Later on, MPM became a well-recognised research field and a large body of research was produced and published in a dedicated MPM Workshop at the MoDELS conference. The COST Action IC1404 on MPM4CPS surveyed some existing languages and tools, and described through an ontology the languages and techniques for modelling CPS (http://mpm4cps.eu). This preliminary work triggered the effort presented in this paper. To the best of our through ontologies started during the COST Action IC1404, knowledge, there has been no clear attempt to formally describe the notion of MPM.

VI. Conclusion

To deal with the complexity arising from CPSs, the MPM approach was recently recognised as a potential candidate for helping project managers and engineers appropriately characterise the many paradigms involved in the CPS models.

This paper motivated the need of MPM for CPS and identified three important dimensions in MPM (formalisms / languages; abstractions / viewpoints; and processes) and proposes, as a first step, a partial formalisation of two of them to capture the notion of paradigm: after defining the core characterising properties of a paradigm, we offer a procedure to check that a structure comprising two of the three previous dimensions satisfy these properties. We illustrated that with a (simplified) CAD tool.

Many directions still need to be explored: first, upscaling to multiple paradigms and specifying how they relate to each others (through abstractions/multiviews) and characterising such relationships; then validating the approach on more realistic CPS settings.

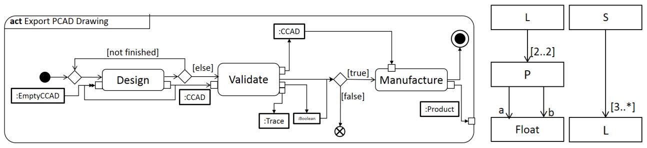


Fig. 5: (Left) Candidate PM for manufacturing CCAD designs. (Right) Pattern properties for CAD_1 and CAD_2.

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