7th RTD Framework Program

REALITY

Reliable and Variability Tolerant System-on-a-Chip Design in More-Moore Technologies

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Report on Variation-Aware Statistical Information Format

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Universita Di Bologna (UNIBO)	Contractor	Italy
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1. Disclaimer

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2. Acknowledgements

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3. Document revision history

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4. Preface

The scope and objectives of the REALITY project are:

- Development of design techniques, methodologies and methods for real-time guaranteed, energy-efficient, robust and adaptive SoCs, including both digital and analogue macro-blocks“

The Technical Challenges are:

- To deal with increased static variability and static fault rates of devices and interconnects.
- To overcome increased time-dependent dynamic variability and dynamic fault rates.
- To build reliable systems out of unreliable technology while maintaining design productivity.
- To deploy design techniques that allow technology scalable energy efficient SoC systems while guaranteeing real-time performance constraints.

Focus Areas of this project are:

- “Analysis techniques” for exploring the design space, and analysis of the system in terms of performance, power and reliability of manufactured instances across a wide spectrum of operating conditions.

- “Solution techniques” which are design time and/or runtime techniques to mitigate impact of reliability issues of integrated circuits, at component, circuit, architecture and system (application software) design.

The REALITY project has started its activities in January 2008 and is planned to be completed after 30 months. It is led by Dr. Miguel Miranda of IMEC. The Project Coordinator is Dr. Miguel Miranda. Five contractors (STM, ARM, KUL, UoG, UNIBO) participate in the project. The total budget is 2.899 k€.

5. Abstract

The goal of this WP is to develop advanced methodologies and techniques for Statistical Analysis all the way from the device level to the system level. The WP also targets developing and fully characterizing a limited standard cell library (50-100 cells) for synthesis based on restricted design rules for use in WP2, WP3, WP4, and WP5. Novel techniques to percolate variability all the way from the device level to the system level shall be developed to evaluate the impact that intrinsic variability will have on timing, energy, and yield of the complete SoC architecture, including a view on the impact of application-dependent activity. Commercial EDA solutions (e.g., fast circuit simulators, SSTA tools, power analysis tools, etc) shall be reused in the flow wherever possible in combination with Monte Carlo-based simulation techniques. Also considered in this WP is the strategic aspect of the standardization of the interfaces between different abstraction levels to enable the propagation of variability specific information throughout the design flow in order to guarantee the compatibility with existing electronic design simulation/verification tools.

This document is the deliverable D 2.4 comprising a description of an electronic information format for data under process variability. This is used to ease the link between levels of a variability aware design flow such as the one set in place in overall WP2. On top of that, there is an application interface to access the data, and an application layer for graphical representation.

6. List of Abbreviations

REALITY	Reliable and Variability tolerant System-on-a-chip Design in More-Moore Technologies
PDF	Probabilistic Density Function
RTL	Register Transfer Level
SoC	System on Chip
EDA	Electronic Design Automation
SSTA	Statistical Static Timing Analysis
IP	Intellectual Property (block)
WID	Within Die Variations
CDF	Cumulative Density Functions
CPU	Central Processing Unit
MOSFET	Metal Oxide Field Effect Transistor
SRAM	Static Random Access Memory

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10. Introduction

Key part to master the complexity and density of information of any variability aware design flow is a “Variability Aware Modelling information format” (VAM IF). Thus imec developed a format that considers connections between five levels of abstraction of modelling or simulation. It defines how variability information must be carried from the one level to the other.

The VAM IF is divided in 5 chapters or XML-files, corresponding to these levels of modelling.

- Chapter technology
- Chapter compact model
- Chapter cell
- Chapter digital
- Chapter system

11. The role of the information format in Reality

11.1. Overview

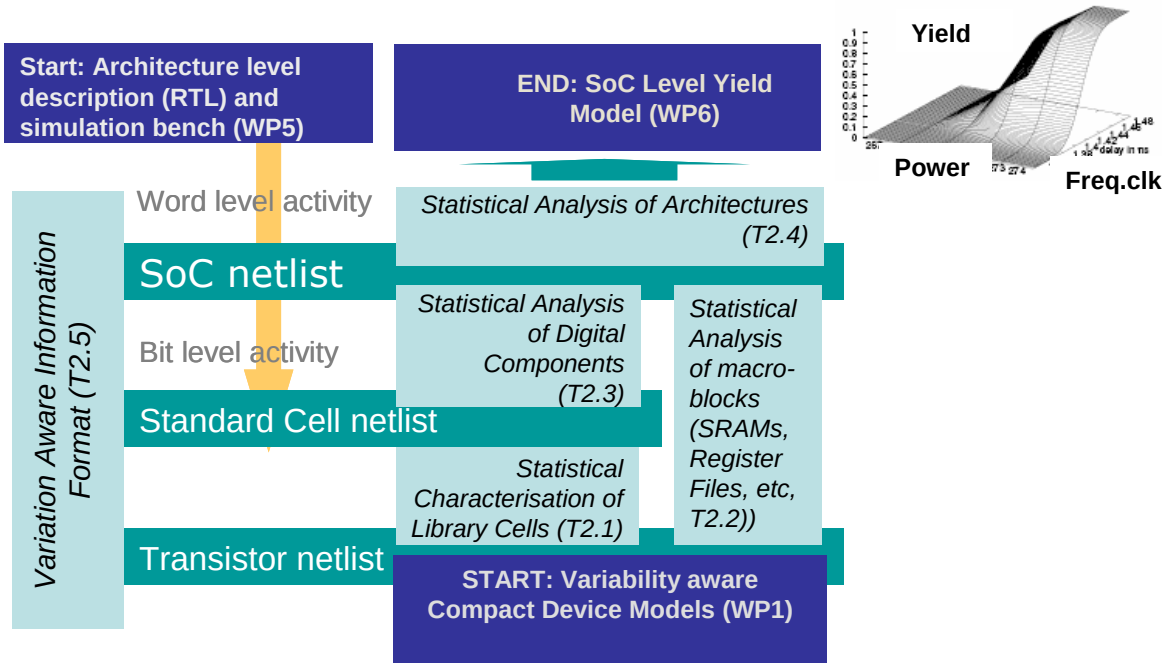


Figure 1 Work package overview.

As the Figure shows, the information format described in this deliverable plays an important role. It is positioned along and between every step of the flow, where it defines the format of information that flows between the steps. It serves as storage and retrieval system for this information.

11.2. Link to other work packages

The format accepts data from WP1 in form of injectors. These are additional circuit elements that model the variability of transistors. This can be done for several transistor types, but also differently degraded transistors.
The information format is also capable of storing and retrieving variability data on higher levels, such as the ones worked out in WP2, and integrated in WP5, like variable standard cells, macros, processor parts, or processors.
Its application layer allows to graphically publish the variability information in several formats. This is used heavily in almost all workpackages, especially WP6.

12. Application Layer Examples

The picture below shows several screen shots of the VAMIF browser application. The top-left screen shows the browser window itself on a digital chapter, highlighting a component-object (an ARM processor part).Objects can be browsed (cf Plot button top left of window).

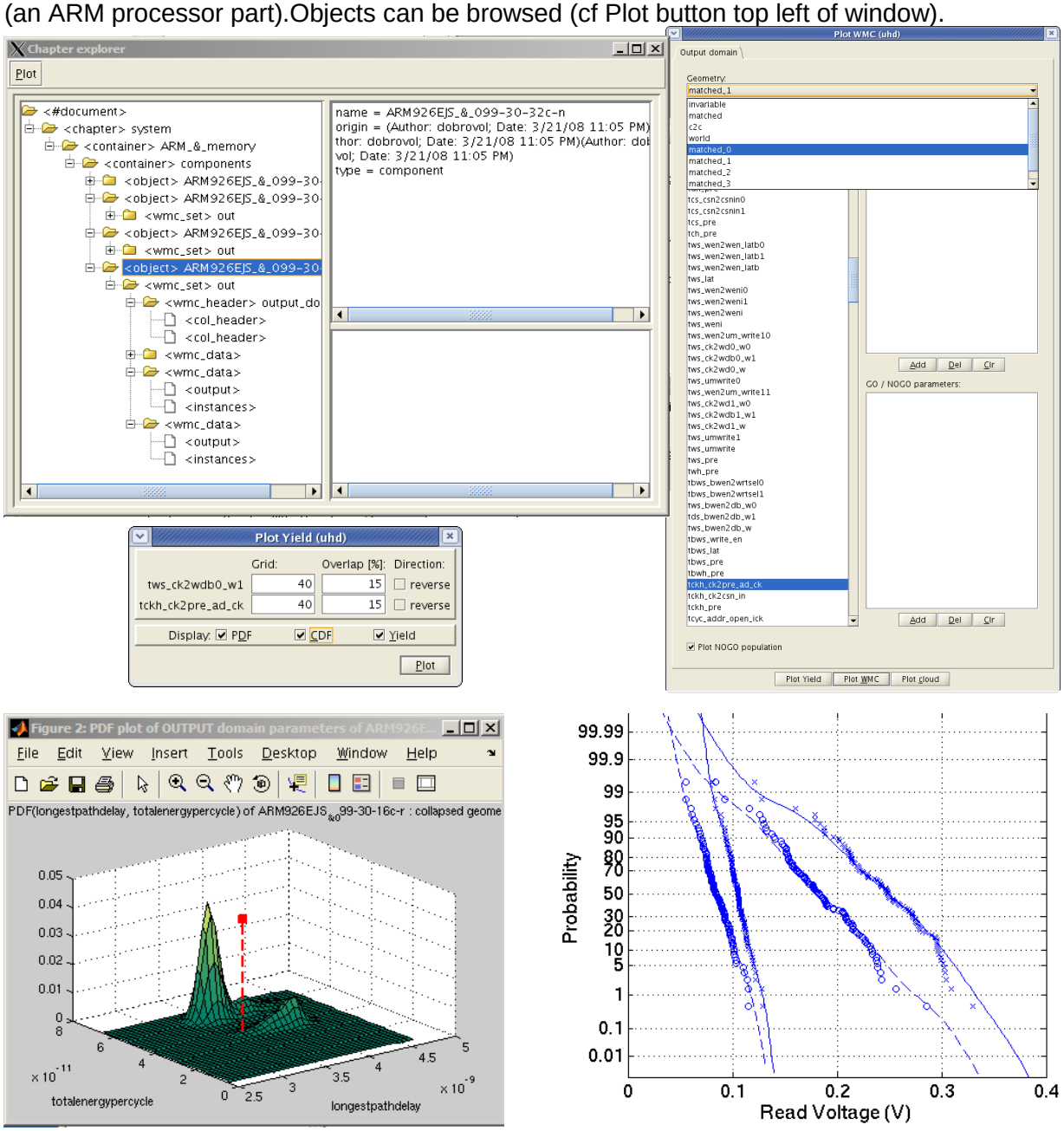


Figure 2 Vamif Application Layer Examples

To the right one finds an open plot window on a memory object. The Geometry selection box provides local (matched), global (c2c) and total (world) information and local sensitivity data (of the object to modifications in specific sub-blocks (matched_x)). The long list provides all metrics, which the user can choose to plot. There are about 500 parameters in this memory example. The user can plot pdfs, cdfs, and yield, all for 1 or 2 (compound) parameters.

The lower left plot shows an example 2-dimensional pdf of a processor part. The lower right plot shows a probit plot of the read-voltage distribution of two memories in two modes. Probit plots using this technique are used extensively to report in WP1, WP3, WP5, and WP6.

13. Chapters of the IF

13.1. General concepts

The information format is distributed over 5 “chapters” or XML-files, corresponding to the simulation levels of abstraction, having following filenames: *technology.xml* *compactmodel.xml* *cell.xml* *digital.xml* *system.xml*
These 5 files are in the same directory. This set of 5 files applies to one single design (i.e. identical mask set) with one single technology option, which is reflected in the directory name.
All data in the directory is assumed to be correlated. This is a direct consequence of the principle that VAMIF is a “virtual technology” (~platform)
Scripts, programs, tools using the VAMIF should be sufficiently instructed by only giving them the path to this directory. Scripts, programs, tools writing to a chapter should only *update* the chapter, thus leaving the unrelated data in the chapter untouched. It is forbidden that a scripts “resets” a chapter.

13.2. Chapter Technology

This chapter collects technology variability information.
The lowest level of abstraction, includes variability and reliability information from three complementary sources. Variability information is terms of dimensions or of concentrations.

- ⇒ the information that comes from the semiconductor fab, as measurement data sets.

  As a side effect, the VAM IF thus defines the variability data that are needed from the fab
- ⇒ from science and literature. *Large part of the work is to devise the formulas for reliability-related effects, with the possibility to model it for deep sub micron devices.*
- ⇒ *TCAD simulations*

This chapter is the input for the path from technology information to compact models that can handle variability and reliability effects.

In the most trivial form, i.e. if there is no variability information at all, this chapter is empty.

```
Chapter technology
```

note
Tools using VAMIF should always be able to handle empty or deliberately missing information, and treat that as the absence of variability and use the nominal (or “invariable”) value (which should be available from the non variability aware design flow).

13.3. Chapter compact model

Idea: this chapter contains all information necessary for adding *electrical domain* variability and reliability information to the classical compact model (Vth, β …), and other device models (R, C…) used in analog simulation and in (standard / non-standard) cell calibration. The intended users of (i.e. tools reading) this chapter are wrappers and scripts doing analog simulation, standard cell characterization, memory simulation, etc.

- Variability in this context always includes reliability, ageing and degradation effect, and wherever possible plain yield issues.
- The VAM concept considers the regular compact models as a black boxes. The compact model may as well be a physical or electrical model (i.e. a SPICE model with parameters as t_{ox}, concentrations or Vth), or predictive and even purely hypothetical. We strive to *“model and simulator independency”.*

In the most trivial form, i.e. if there is no variability information at all, this file and chapter may be empty. Or it may contain only a reference to the regular compact models.

```
Chapter compactmodel
```

```
chapter compactmodel
logbook
      entry 22sep2007 10:17 qwerty.exe scaling data
      entry 26sep2007 23:44 qwerty.exe scaling data

object name=mosfet                          // MOSFET with no variability at all modeled
      value name=mosfet_type nmosfet_hv
      value name=path psp1.mod

object mosfet
      value mosfet_type pmosfet
      value path psp6b.mod
      parameter delta_vth
      parameter delta_beta average 0.94 stddev 0.01
      value delta_w -1e-9
      value delta_l +23e-9
      value w0   1um
      value l0   1um
```

13.4. Chapter cell

Concept: this chapter contains all information necessary for adding variability and reliability information to the classical standard cell (i.e. to simulators using standard cells), plus the variability applying to the circuits parts coming from back annotated schematics.
The intended users (readers) of this chapter are wrappers and scripts doing digital simulation, and maybe, after translation to a proper format, SSTA.

User (tool writer) challenges are:

- ⇒ How to run a library or any more complex IP unattended through cell calibration, in a reasonable time.
- ⇒ How to generate the EMC population of .lib files?
- ⇒ (in the future) How to add non-static variability (temporal noise, jitter)?
- ⇒ How to capture similar information for non-standard cells (“Macros”, such as embedded memory, mixed signal blocks…)
- ⇒ Keep non-variability corners: calibrate the library for a given set of environmental parameters (VDD, T, age).

In the most trivial form, i.e. if there is no variability information at all, this chapter contains only a reference to the regular (“invariable”) standard cell library.

```
Chapter cell
logbook
      entry 22sep2007 10:11 makeit.exe create library
      entry 26oct2007 12:12 makeit.exe create library
```

13.5. Chapter digital

Idea: this chapter contains all information necessary for adding variability and reliability information to digital simulation, architecture.

The component-level information is variability of timing, static and dynamic power. Other information is timing and application information as the activity (stress history). The Chapter is used by a tool that can estimates parametric yield. Other information that might be needed is a list of blocks that are considered as [top-level] blocks that needs calibration.

In the most trivial form, i.e. if there is no variability information at all, this chapter contains one single top level digital block. Subsequent tools (DigiVAM) will take the list of top-level blocks and calibrate them.

13.6. Chapter system

Idea: this chapter contains remaining information necessary for adding variability and reliability information tot system level simulations and yield estimation. It must also contain the top level activity information, application specifics, and external factors as temperature, VDD, temperature, age, ..

System yield is written *into* this chapter, as a set of EMC tables with total power versus clock period. Display tools as “Vamifbrowser” will plot these into the “iso yield” format.

14. Syntax

14.1. XML and the VAM IF conventions

14.1.1. Files and chapters

The VAM IF chapters are in XML format.
Each chapter is a separate file, with filename identical to chapter name.
All chapter files are in the same directory.

This VAMIF directory, and each of its 5 files is design-project and technology option specific. If one wants to explore alternate technology options, library options, architecture opttions, one should do that in a separate directory, possibly while linking the chapters that do not differ.

It is assumed by default that all objects (and their parameters) inside the directory are correlated.

Scripts running under VAM should use VAMIF chapters as exclusive information source or pointers thereto. The only argument to such script is the VAMIF directory path.

14.1.2. Units and dimensions

Unless otherwise noted all units are Si. E.g. 5 um are represented as 5e-6.

It is a later[1] extension, to understand following postfixes, case sensitive:

T	*1e12	a	/1e15
G	*1e9	p	/1e12
M	*1e6	n	/1e9
k	*1000	u	/1e6
%	/100	m	/1e3

Time is expressed in seconds. It is a not explicitly supported later extension to understand following postfixes:

1hour	3600
1day	86400
1year	31557600

14.2. General syntax and use

XML implementations of different data information are described using the following syntactic elements (related to the corresponding XML implementation itself):

Convention: All keywords have only lower case alphabetic characters [a-z], digits [0-9] and _

`parameter`	The XML element named `parameter`
`description`	The attribute named `description`
double, string, …	datatypes of an attribute's or element's content
(`distribution`)	the reference to the XML element `distribution` described later
(…)?	the part of XML document that appears zero or one time

[1] If not implemented, a tool reading VAMIF should complain and flag such extensions.

(…)*	the part of XML document that appears zero or more times
(…)+	the part of XML document that appears one or more times
|	the choice among two or more alternatives

The description of XML implementations presented in this chapter is focused on the explanation of individual elements' and attributes' structure and meaning. The precise formal descriptions of our XML applications for different chapters of the information format (from syntactic point of view) are kept in the corresponding XML Schema documents.

14.3. Values, parameters, Emc_sets, objects and containers

In the VAMIF, there are 4 basic standalone elements allowable
The

- *Container*: a generic representation of a more complex structure, itself containing zero or more values, objects and other containers
- *Value*: in most cases similar to a double, but it may be also a string etc…
- *Parameter*: this is a value with a distribution attached to it.
- *Object*: this is a group of correlated parameters (may contain also values)

14.3.1. The value element

The `value` element

`name`=*string*	the name attribute	required
Double | *integer*| *string*	the value	required
`description`=*string*	the description or comment, provided by user or program	optional
`Origin`=*string*	the origin of the data, either provide by users or generated by program. Format: time (YYYYMMDD_hhmm) username description. *to avoid data explosion: origin should NOT be automatically added to values.*	optional

Example in xml:

```
<value name=tox>1e-9</value>
```

14.3.2. The `list` element

The `list` element

`name`=*string*	the name attribute	required
`type`=*string*	The type of list	optional
(Double|integer|string) *	1 or more values	required
`description`=*string*	the description or comment, provided by user or program	optional
`Origin`=*string*	the origin of the data.*to avoid data explosion: origin should NOT be automatically added to values.*	optional

Example in xml:

```
<list type=configuration_parameter name=bpw>4 8 32</list>
```

14.3.3. The `parameter` element

The `parameter` element serves the user to *enter* value with attached distribution. Parameters only can be part of the VAMIF `object` element. Before parameters are used, their distributions are internally converted in an object-specific emc_set, for which the parameters are columns. The `avg`, `stddev`, `geometry` and distribution elements shown hereafter only serve to *enter* data. The `parameter` element, where the user wants to enter the variability in a trivial way using a simple average and standard deviation, is given as

`name`=*string*	the name	required
`description`=*string*	the description	optional
`Origin`=*string*	if not added, origin is automatically generated	optional
`avg` *double*	the average or nominal value of that parameter	Required *
`Stddev` *double*	the standard deviation on that average, assuming thus a gaussian distribution. If absent, zero is assumed. This distribution will become “matched”, see further.	Required *

Example in xml:

```
<parameter name="delta_w" description="width variation" origin="P. Dobrovolny, 20-01-2007">
        <avg>10e-9</avg>
        <stddev>0.9e-9</stddev>
</parameter>
```

If the distribution needs to be more complex, the `parameter` element is generalized as

`name`=*string*	the name	required

description=*string*	the description	optional
Origin=*string*	the origin of the data if known	optional
avg *double*	the average or nominal value of that parameter	optional*
Stddev *double*	the standard deviation of that average	optional*
(geometry)	detailed description of a variability information	required

* if geometries are given, they supersede avg and stddev entries.

Variability information is entered in more elaborate way using geometries.

Example in XML:

```
<parameter name="tox" description="oxide thickness" origin="P. Dobrovolny, 20-01-2007">
        <avg>20.0e-9</avg>
        <stddev>1.4e-9</stddev>
        <geometry …>
        …
        </geometry>
        <geometry …>
        …
        </geometry>
</parameter>
```

Note on the use of parameters and emc_sets
In an object, two distinct ways of use of parameters and emc_sets are allowed

1. every object has al least (and often only) the emc_set name="out". Parameter names are the column headers of the set. This representation is used when VAM API's write objects as a whole in a chapter.
2. have exactly one parameter element for each parameter in the object. Parameters distributions may refer to emc_sets with names differing from "out", inside the same object. In fact parameter elements are converted first to smaller emc_sets internally, and then all are combined into the internal emc_set name="out". This method is likely used for manual inputting data in VAMIF.

14.3.4. The geometry element (correlation_geometry)

This element can only be part of a parameter, and has the following structure

type=*geo_enum*	the correlation_geometry for which the variability is considered (see description below)	required
avg *double*	the average value	optional
(gauss | poisson | delta | histogram | histogram_file | montecarlo | montecarlo_file | EMC | weibull | lognormal | min_typ_max)+	One or more distribution component (see descriptions further). Serve to "fill" a parameter distribution internally.	Optional, only used to fill in analytical distributions via VAMIF directly

Tools must anticipate handling the fact that the distributions given for each correlation_geometry may have different averages. E.g. in the creation of std cell or digital component delays, the resulting average for each

correlation_geometry is not a priori the same.
Key is the “invariable” correlation_geometry, which is a reference for each.

Proposed precedence policy:
-if a geometry and invariable is given in detail, that geometry is assumed correct.
-if a geometry is not given, it is assumed empty – hence copied from the invariable geometry
-if the invariable geometry itself is not given, take its value from the parameter avg if given, if not assume that invariable was zero..

Example:

```
<geometry type="w2w">
        <gauss …>
        …
        </gauss>
        <EMC …>
        …
        </EMC>

</geometry>
```

Correlation_geometries

Variability is considered at 5 orthogonal levels of geometrical correlation. It means that the `type attribute` takes value from the enumeration set *geo_enum* = {“invariable”, “matched”, “local_systematic”, “c2c”, “w2w”, “b2b”, <some others>}:

invariable	As a reference the case without variability is tracked, in order to keep a common reference for the next 5 basic geometries. The invariable distribution is internally represented as a EMC with a single entry. For most purposes “Invariable” is very much the same as the TT corner.
matched	Or Local Random variability on close scale, applied to identical components in identical geometrical environments; it is by definition uncorrelated with local layout or inter-device distance. This geometry closely appeals to the notion “matching” or “mismatch”. Specific for matched only, and optional, are attributes correlation_distance [default infinity] and correlation_exponent [default ½]. The use of this feature is not yet defined in detail yet.
local_systematic	Local systematic (reproducible, yet unpredictable or unpredicted[2]) variability on close scale due to components not being in identical layout / environments; seemingly random within a chip, reproducible from chip to chip.
c2c	Random from chip to chip, fixed within a chip, variability due to variability (which may be random or systematic) over a wafer
w2w	Random from wafer to wafer, within the same batch.
b2b	Random from batch to batch. A further refinement fab to fab (f2f) is not considered
Apart from these 1+5 basic geometries, we define following intuitively known shorthands and synonyms. (may become obsolete). These are not stored in VAMIF	

[2] Systematic variability that is actually predicted, thus found in back-annotation of net lists etc., is not represented in VAMIF and thus not in this number. Think of back-annotation from mask data due strains, proximity effects, OPC etc.

all na	Apply to all together: there is no geometrical distinction. In practice when writing such distribution, it goes into matched and the 4 other geometries are made invariable. When reading (picking) from the shorthand na or all, it should pick from all 5 geometries, and sum the values, referred to invariable.
intradie ocv (local)	Combines matched and local_systematic – when writing such distribution, VAMIF considers this to be equivalent to allocating all variability to matched (worst case) and making local_systematic empty.
Interdie (global)	Combines c2c, w2w and b2b – when writing such distribution, equivalent to c2c, where w2w and b2b become empty.

Note: we refrain from defining similar intuitive shorthands for "global", "random" and "systematic", "reproducible" , … as these terms are inconsistently used in literature.

Following non-basic geometries can be stored in VAMIF too. They have normally an information function only.	
userdef name=xxx	user defined geometries with a name attribute. May be used for anything, e.g. to explicitly name corners.
ocv	Is the combined effect of matched and local_systematic. How such geometry must be constructed is subject to a specific method.
world	Is the combined effect of all five basic correlation_geometries. How such geometry must be constructed is subject to a specific method.
measurement	In the case that a measurement set (of a large block, or of the system) corresponding to an object exists, it can be stored here for easy comparison using the VAMIFbrowser.

How to use the correlation_geometry information in a Monte Carlo (-like) wrapper?

- One starts from 5 independent population in the EMC set (actually 6 as invariable is a singular population too). We assume that the 5 geometries are truly orthogonal (they should be, by concept!)
- *When building walls from bricks,* bricks are picked in each of the 5 geometries, with picking strategies that may differ amongst geometries.
- The resulting "wall" populations (items at the next abstraction level) have again 5 geometrical kinds of variability, represented in an internal EMC set.

Distribution components, implemented in this version of VAMIF

A gauss element describes Gaussian distribution using the following parameters

fraction = *double*	The fraction of this gauss distribution in the total population for this geometry/parameter	optional*
average *double*		required
dtddev *double*		required
lower_limit *double*	Distribution is clipped bellow this value	optional
upper_limit *double*	Distribution is clipped beyond this value	optional

[1] Sum of fractions is not necessarily 1. In fact, as distributions are internally loaded into a EMC, renormalization to 1 is done automatically. Required if there are more than one distribution component

A `uniform` element describes a uniform distribution using the following parameters

`fraction` = *double*	The fraction of this `uniform` distribution in the total population for this geometry/parameter	optional
`nof_points` *double*	Number of points used to approximate the uniform distribution. Default=10.	optional
`min` *double*	Distribution is clipped bellow this value	required
`max` *double*	Distribution is clipped beyond this value	required

A `emc` element refers to Weighted Monte Carlo distribution, used to enter data.
It is distinct from the internal representation of the parameter in its object!

`fraction` = *double*	The fraction of this `emc` distribution in the total population for this geometry/parameter	Optional
`path` *string* `col_index` *integer*	path of an external ascii file, white space separated. 0th column is frequency. The column index, default [1].	optional
or `set_name` string	This refers to a emc_set with a different name than "out", inside the same object. Parameter names are headers of this `emc_set out`.	optional

Further distribution components, not yet implemented in this version

A `poisson` element describes Poisson distribution using the following parameters

`fraction` = *double*	The fraction of this `poisson` distribution in the total population for this geometry/parameter	optional
`average` *double*	Positive number	required
`factor` *double*	x-scale of distribution must be multiplied with this value	optional
`offset` *integer*	origin of distribution is increased with this value	optional

A `delta` element describes a simple variability specified by only one number

`fraction` = *double*	The fraction of this `delta` distribution in the total population for this geometry/parameter	optional
Double	a delta (single value) distribution	required

A `histogram` element retains histogram data as the set of number pairs

`fraction` = *double*	The fraction of this `histogram` distribution in the total population for this geometry/parameter	optional
(*double double*)+	a pair of numbers (thus in fact, this may also serve to input single column EMC)	required
`Filename` *string*		optional
`column_header` *string*		optional
`column_header` *string*		optional

A `montecarlo` element keeps a set of values from a montecarlo simulation

`fraction` = *double*	The fraction of this `montecarlo` distribution in the total population for this geometry/parameter	optional
(*double*)+		required
`path` *string*	if stored in a file	optional

Note this approach does not support correlation as the EMC does.

A `min_typ_max` describes simple variability specified by only three numbers.

`fraction` = *double*	The fraction of this `min_typ_max` distribution in the total population for this geometry/parameter	optional

`min` *double*		required
`typ` *double*		required
`max` *double*		required

Note: Yes indeed, this is strictly speaking not a distribution, but it is a route to introduce the classical corners into the VAM flow

A `weibull` element describes Weibull distribution parameters
A `lognormal` element describes lognormal distribution parameters

Example:

```
<gauss fraction="0.9">
        <average>20e-9</average>
        <stddev>1e-9</stddev>
</gauss>
```

14.3.5. The EMC (Exponent Monte Carlo) set `emc_set`

EMC represents by default the so-called "output domain" parameters, i.e. parameters that belong to the instantiations of the object for which the parameters are properties. E.g. the [output domain] parameters of a logic gate are delays, power, energy.

For use in RSM or binning/interpolation, "input domain parameters" are useful. These are essentially the output domain parameters of the objects used inside the object.
E.g. when creating a NAND from 4 MOSFETs, it *might* have
output domain parameters:
maxdelay avdelay maxenergy avenergy staticpower
input domain parameters:
M1!delta_vth M1!delta_beta M2!delta_vth M2!delta_beta M3!delta_vth M3!delta_beta M4!delta_vth M4!delta_beta
But preferable we use the "corrid"s of the input objects to decribe the input domain paramters. See further

The element `emc_set` represents a container to keep `emc_data` elements for existing geometries of a parameter or a correlated set of parameters

`emc_set`

`name`=*string*	the name (the object –specific "output domain" Emc_set is named "out")	required
`corrid`=*string*	Correlation id.: EMCs with the same corrid are correlated entry by entry. Suggestion to construct this unique number from machine time *time(0)* or otherwise.	Required except for matched
`description`=*string*	the description	optional
`origin`=*string*	the origin of the data if known	optional
`path`=*string*	the file (directory?) where EMC data are stored	optional[1]
(`emc_data`)+	one or more `emc_data` elements that keep (or point to) a numerical EMC data	required
`emc_header`	gathers `col_header` elements that identify parameters referring to the current EMC set	Optional

[1] If this attribute is omitted, the EMC data is stored directly in the VAM IF chapter

Example:

1) the `emc_set` with EMC data directly stored in a VAMIF chapter

```
<emc_set name="emc_set_1" origin="Author: …" >
        <EMC_header>
        …
        </EMC_header>
        <EMC_data …>          …
        </EMC_data>
        …
</emc_set>
```

2) the `emc_set` with EMC data stored in files


```
<Emc_set name="Emc_set2" origin="Author: … "pathname="set2.dat/">
        <EMC_header>
        …
        </EMC_header>
        <EMC_data … />
        <EMC_data … />
        …
</Emc_set>
```

The `emc_header` element

The `emc_header` element groups `col_header` elements that identify parameters referring to the EMC set

(`col_header`)*	zero or more `col_header` elements that identify parameters	optional

The `col_header` element keeps information that identify a parameter whose data are stored in corresponding column of a EMC data table

`index`=*integer*	the index of the column (starting from 0)	required
string	the name of the parameter	required

Some suggested, optional or mandatory column headers

- "entry" as such is not a column. It is the row number in the EMC table and e.g. also the returned value from PickInstanceIndex(). Row numbers start from 0.
- "ptoir" the *probability to occur in reality* is always column[0]
- "defunct", 1 if this instance is dysfunctional, otherwise 0.
- "outlier", 1 if this instance *contains* an outlier, otherwise 0.
- "corrid_####": the instances in the present object are created from objects with EMC tables with a corrid (unique correlation id) being the number #### . The data in the present column are the entries (row numbers) used from that other EMC.
- "simulation_reference": a text reference to the simulation testbench of results of the entry. Format depends on the actual script.

Example:

```
<emc_header>
        <col_header index="0">ptoir</col_header>
        <col_header index="2">dCoverC</col_header>
        <col_header index="1">dRoverR</col_header>
        …
</emc_header>
```

The `emc_data` element

The `emc_data` element keeps or points to a numerical EMC data of a parameter or a set of correlated parameters for a given geometry type. The EMC data stored inside XML file are formatted in a table where each row corresponds to one data set of a population – the first value of the row is the frequency (probability), the next values correspond to concrete values of correlated set of parameters. The same format rule is applied also for data stored in a file. Because generally it can not be guaranteed that the original shape of data table will be preserved (for instance it could be lost during some XML transformations), the attribute `cols` helps to reconstruct the original shape of table.

`type`=*string*	the type of `geometry` to which EMC data corresponds	required
`pathname`=*string*	The full pathname of a file where numerical EMC data are stored	optional[1]
`cols`=*integer*	The number of columns in the EMC data table	required
`rows`=*integer*	The number of rows in EMC data table that were generated by a simulation	required
(*double*)+	The numerical EMC data	Optional

[1] If this attribute is not present, the EMC data is stored directly in VAM IF chapter. Q: isn't this redundants wth the similar attribute in the emc_set?

Example:

1) the `emc_data` element with EMC data stored directly in a VAMIF chapter

```
<emc_data type="local_systematic" cols="2" rows="100">
        1.215176571174768E-9 1.5999999999999986E-10
        3.954639285187116E-9 2.2799999999999986E-10
        1.2365241012645407E-8 2.9599999999999986E-10
        3.714723692809837E-8 3.639999999999999E-10
        1.07220707000726E-7 4.3199999999999985E-10
        2.9734390324296495E-7 4.999999999999998E-10
        7.922598189953721E-7 5.679999999999999E-10
        …
</emc_data>
```

2) the `emc_set` element with EMC data stored in files


```
<emc_data type="w2w" cols="3" EMCs="100" pathname="D:\ic\Emc_set2\Emc_set2_w2w.dat/">
```

14.3.6. The `object` element

The `object` element contains a set of correlated [output domain] parameters and (optional) input domain parameters

`name`=*string*	the name of the object	required
`type`=*ObjectType_enum*	the type of the object [1]	Optional (obsolete?)
`description`=*string*	the description or comment, provided by user or program	optional
`origin`=*string*	the origin of the data. If not provided by user, the origin is automatically generated	required
`dir`=*string*	the directory where all data relevant to the object are stored[2]	optional
`emc_set name="out"`	the output domain EMC set	Required if no parameters are given
`(emc_set)*`	Other emc_sets, under which the input parameter domain EMC set	optional
`(parameter)*`	Output domain parameters	only if no emc_set name="out" is given

[1] Object type, if specified, gets a value from the enumeration set *ObjectType_enum* = {"cel", "component"}. Specifying the object type enables a user/developer to exploit specific programming interface closely related to the specified type of object.
[2] If this attribute is not present, all related EMC data are stored directly in VAM IF chapter. If a relative path is given, this path is relative to the VAMIF chapter itself, is a separate directory.

Example:

```
<object dir="…\NAND1" name="NAND1" origin="Author: …" type="cell">
        <Emc_set dir="…\NAND1" name="inp" origin="Author: …">
                <EMC_header>
                        <col_header index="2">  T2_NMOS_Vth</col_header>
                        <col_header index="4">  T4_PMOS_Vth</col_header>
                        <col_header index="1">  T1_NMOS_Vth</col_header>
                        <col_header index="3">  T3_PMOS_Vth</col_header>
                </EMC_header>
                <EMC_data type="matched" cols="5" EMCs="100" pathname="…\inp_matchd.dat"/>
                <EMC_data type="local" cols="5" EMCs="100" pathname="…\inp_local.dat"/>
                <EMC_data type="c2c" cols="5" EMCs="100" pathname="…\inp_c2c.dat"/>
                <EMC_data type="w2w" cols="5" EMCs="100" pathname="…\inp_w2w.dat"/>
                <EMC_data type="b2b" cols="5" EMCs="100" pathname="…\inp_b2b.dat"/>
        </Emc_set>
        <Emc_set dir="…\NAND1" name="out" origin="Author: …" >
                <EMC_header>
                        <col_header index="2">delay</col_header>
                        <col_header index="1">power</col_header>
                </EMC_header>
                <EMC_data type="matched" cols="3" EMCs="100" pathname="…\out_matchd.dat"/>
                <EMC_data type="local" cols="3" EMCs="100" pathname="…\out_local.dat"/>
                <EMC_data type="c2c" cols="3" EMCs="100" pathname="…\out_c2c.dat"/>
                <EMC_data type="w2w" cols="3" EMCs="100" pathname="…\out_w2w.dat"/>
                <EMC_data type="b2b" cols="3" EMCs="100" pathname="…\out_b2b.dat"/>
        </Emc_set>
        <instance_list type="matched">
                NAND1_1 NAND1_2 …
        </instance_list>
        <instance_list type="local">
                NAND1_1 NAND1_2 …
        </instance_list>
        <instance_list type="c2c">
                NAND1_1 NAND1_2 …
        </instance_list>
        <instance_list type="w2w">
                NAND1_1 NAND1_2 …
        </instance_list>
        <instance_list type="b2b">
                NAND1_1 NAND1_2 …
        </instance_list>
</object>
```


14.3.7. The `container` element

The `container` element is defined as

`name`=*string*	the name of the container	required
`type`=*string*	Following types are predefined (1) Type=`manufacturing` Type=`model` Type=`signature` Type=`configuration`	required
`description`=*string*	the description or comment, provided by user or program	optional
`origin`=*string*	the origin of the data, either provide by users or generated by program. Format: YYYYMMDD hh:mm username description	automatic
`(value)*`	Zero of more, user / case specific	optional
`(object)*`	Zero of more, user / case specific	optional
`(container)*`	Zero of more, user / case specific	optional

(1) at this moment we consider:
Containers of *type*

⇒ Manufacturing: this container holds information that describes the manufacturing process, design rules, …

⇒ Model: this container holds models

⇒ Signature: this container holds "signatures", i.e. condensed properties of unique instances of a distribution of cells.

⇒ Configuration: a user defined, tool specific, free format list of configuration data for tools.

In the remainder of this document, we often use following shorthand
`container xyz`
or even
`model xyz`
actually means:
`container type=model name=xyz [description=…] [origin=…]`
Which looks in XML as:
`<container name=xyz type=model description=… origin=… > … </container>`

This item may contain	value	list	paramet…	emc_set	object	container
chapter					x	x
object	x	x	x	x		
container	x	x			x	x

In summary:

- an *object* contains a single [output domain] EMC set *or* one or more parameters from which the EMC set is internally created, and optional "values". EMC sets and parameters do not exist outside an object, and there is exactly one output domain

EMC set present or created in every object. (Q: is this limitation acceptable? Yes, as: correlation is guaranteed by construction and correlation propagation enforced) (one keeps the possibility to import other EMC's values via the parameter EMC attribute)

- *container's* content is free. They may contain anything, including any other containers, values and objects, but not parameters
- of these the *configuration container* is just as well free, but is not assumed to contain anything other than values and other configuration containers. Configurations are intended to store user/local/machine/tool specific things and are not for documented use in the VAMIF sense.

14.4. User guide to the VAMIF API (Application Programming Interface)

This chapter should provide concise user guide for the developers involved in the development of all simulation/ modeling levels of the overall VAM flow. The more detailed and complete description of VAM IF API will be left to Appendix chapters.
As was already mentioned, the whole input/output communication of each simulation level is carried through appropriate VAMIF chapters. Tool (wrapper) writers use the standardized interface -"VAMIF API"- to access and process data stored in a VAMIF chapter and also write back simulated (or computed) data to another (probably higher level) VAMIF chapter. The general VAMIF API functionality should be preserved over different implementation platforms. Due the platform independency and nice Matlab interface the JAVA was choose to implement VAMIF API at first. For the documentation of VAM IF API implemented in JAVA see Appendix A.

14.4.1. Loading, parsing and (re)writing VAMIF chapters

This chapter will present how to load a chapter from a file, extract and write back relevant information and again save a chapter in a file.
To load, display and write a whole chapter the class `VamifChapter` supply the set of public interface methods. The following Matlab example demonstrate their typical usage:

Example 1

```
1 techChapter = VamifChapter('technology.xml');
2 techChapter.browse;
3 techChapter.write('technology.xml');
```


At the first line the VAMIF chapter stored in the the file `'techchap.xml'` is loaded into the variable `techChapter`. The Matlab variable `techChapter` is actually a JAVA object with possibility to apply certain set of methods (called interface) to it. The complete public interface of a JAVA object or class can be revealed by using the Matlab command `methods`. The line 2 and 3 shows two methods of the public interface of the class `VamifChapter` – the method `display` displays the content of a chapter on the standard output and the method `write` saves a chapter in a file specified by the first argument of the method (in our example it is the same file `'technology.xml'`). Because a VAMIF chapter is in fact an XML application, the data are stored in a tree structure with several types of nodes. To access any piece of information, we have to specify a node's tree path with possible set of node's attributes to avoid ambiguity. The following Matlab example shows the way how to access VAMIF objects and values form previously loaded technology chapter (see Example 1)

Example 2

```
1  deltaW = techChapter.getVamifElement('object(name=delta_w)');
2  thickness = techChapter.getVamifElement('/metal(name=metal1)/object(name=thickness)');
3  alfa = techChapter.getVamifElement('value(name=alfa)');
```

The argument of the method `getVamifElement` could be simply type of a node *bare name* (`parameter`, `object`, `value`, …) or a node *tree-path name* (see line 2: `/metal(name=metal1)/object(name=thickness)`) possibly combined with one or more pairs *node-attribute-name* = *node-attribute-value* (see line 1,2 and 3: `name`=`thickness`, `name`=`delta_w`,…).
The following example demonstrates the way how modified, newly computed or simulated objects or values or any other VAMIF elements could be added into a chapter.

Example 3

```
1  techChapter.addVamifObject(EMCSet);
2  techChapter.addVamifObject('interconnect_scaling(name=metal1)', dROverR);
```


The method `addVamifElement` can have one or two arguments: at the first line the method absorbs one argument `EMCSet` - a VAMIF element that should be added to a chapter. At the second line the first argument specifies a tree-path under which the object should be added and the second argument `dROverR` is again a VAMIF element that should be added to a chapter. If the tree-path argument is missing the VAMIF element is attached directly as a child node to an object on which the method was invoked (in our example the method was invoked on `techChapter` object, so the `EMCSet` object is added at the top level of `techChapter` while `dROverR` object is added in the path specified by the second argument).
Note: Chapters being updated must be integrally locked before loading. Writing that chapter clears the lock. Read-only access remains always possible. The locking system must be foolproof (locks expire automatically). Locking is a future extension, not immediately needed.

14.4.2. Creating new VAMIF elements

Until now we discussed the situation when VAMIF elements (`object`, `container`, `value` ...) were created based on loading and parsing their XML representation from a VAMIF chapter. But the user of a VAMIF chapter also has to be able to create new VAMIF elements based for instance on the measurements data, simulation data, data from FABs and so on. The next example shows creation a new `object` element based on some hypothetical variability data to demonstrate hierarchical way of such process.
The `object` element servers for keeping correlated variability data (`parameter` elements) together with related `value` elements. The Java class `VamifObject` represents he basic way how to construct an `object` VAMIF element. Nevertheless a user instead of creating `VamifObject` most likely will use the specialized variants (Java subclasses) of the `VamifObject` called `Rule`, `Cell`, `Component`, ... The following example demonstrates the creation of `Rule` element of type `mosfet` containing some `parameter` and `value` elements.

Example 4

```
% create the gauss distribution 'gauss'
vthMean = 0.5;
vthSigma = 0.01;
gauss = GaussDist(vthMean, vthSigma);
gauss.setFraction(0.90);

% create the EMC distribution 'EMC'
EMC = EMCDist('Emc_set');
EMC.setFraction(0.10);

% create the matched geometry
geo = Geometry('matched')
geo.addDistComponent(gauss);
geo.addDistComponent(EMC);

% create the parameter Vth
vth = Parameter('vth', vthMean, geo);
vth.setDesc('The vth parameter');

NMOSTypeName = 'nmos_pt_013';
NMOSRule = Rule(RuleName.MOSFET);
NMOSRule.setAttr('type', NMOSTypeName);
NMOSRule.addParam(vth);

```



```
25 delta_w = NumericValue('delta_w', 0.0);
26 NMOSRule.addValue(delta_w);
27 delta_l = NumericValue('delta_l', 0.0);
28 NMOSRule.addValue(delta_l);
29 w0 = NumericValue('w0', 0.0);
30 NMOSRule.addValue(w0);
31 l0 = NumericValue('l0', 0.0);
32 NMOSRule.addValue(l0);
19 compChapter.addVamifElement(NMOSRule);
```

This parameter `vth` comprises real variability data only for `'matched'` geometry. This geometry has two distribution components, a gauss distribution and a EMC distribution. The lines 1-5 displays the way how to construct the gauss distribution element `gauss` from mean and sigma, at the lines 7-9 the EMC distribution element `EMC` is created and `'matched'` type of geometry `geo` (containing previously created distribution objects `gauss` and `EMC`) is constructed at lines 11-14. The `parameter` element `vth` is created at lines 16-18. The `rule` element of `'mosfet'` type is constructed at lines 20-21, the line 22 sets the `name` attribute of the `rule` element and the `parameter` element `vth` is added to the `rule` at the line 23. At lines 25-32 a set of `value` elements – `delta_w, delta_l, w0 and l0` - are added to the `rule` element and finally the `rule` element is added to the chapter `compChapter`.
The similar approach can be utilized to create other types of VAMIF elements. The only requirement is that a VAMIF element stored in a chapter has a counterpart Java class implemented in the VAMIF API.

14.4.3. Read and write data from `object` element

The `object` element represents a set of correlated variability data together with some other non-variable information attached to it. For detail explanation of its structure see chapter 5.3. This chapter demonstrates how to retrieve numerical data from `object` element, how to use this data in a computation and produce newly computed `object` elements.

Example 5

```
1  % retrieve (non-variable) values
2  % from NMOSRule and PMOSRule elements
3  % ------------------------------------
4  nmos_delta_w = NMOSRule.getValue('delta_w');
5  nmos_delta_l = NMOSRule.getValue('delta_l');
6  nmos_w0 = NMOSRule.getValue('w0');
7  nmos_l0 = NMOSRule.getValue('l0');
8  pmos_delta_w = PMOSRule.getValue('delta_w');
9  pmos_delta_l = PMOSRule.getValue('delta_l');
10 pmos_w0 = PMOSRule.getValue('w0');
11 pmos_l0 = PMOSRule.getValue('l0');
12
13 % create new VAMIF cell object
14 % ----------------------------
15 cellName = 'NAND2';
16 cell = Cell(cellName);
17 cell.setDir('design1/cells/NAND1');
18
19 % define input domain  cell's parameters
20 % --------------------------------------
21 cell.addInpParam('T1_vth');
```



```
cell.addInpParam('T2_vth');
cell.addInpParam('T3_vth');
cell.addInpParam('T4_vth');

% define output domain cell's parameters
% ---------------------------------------
cell.addOutParam('power');
cell.addOutParam('delay');

% set gamma as a common value for all parameters involved in the computation
% ---------------------------------------------------------------------------
VamifObject.setGamma(0.2);

% run Exponent Monte Carlo simulation over all geometries
% -------------------------------------------------------
geometry = {'matched', 'local', 'c2c', 'w2w', 'b2b'};
nofMCSamples = 100;
for j=1:length(geometry)
  geo = geometry{j};
```

```
  for i=1:nofMCSamples

    % randomly pick Vth for each cell's transistor and apply Pelgrom rule
    % -------------------------------------------------------------------
    idx = NMOSRule.pickInstanceIdx(geo);
    T1_prob = NMOSRule.getInstanceProb(geo, idx);
    T1_vth0 = NMOSRule.getOutParamInstanceVal(geo, idx, 'Vth');
    T1_vth = pelgromRule(T1_vth0, nmos_delat_w, nmos_delta_l, nmos_w0, nmos_w0);
    idx = NMOSRule.pickInstanceIdx(geo);
    T2_prob = NMOSRule.getInstanceProb(geo, idx);
    T2_vth0 = NMOSRule.getOutParamInstanceVal(geo, idx, 'Vth');
    T2_vth = pelgromRule(T2_vth0, nmos_delat_w, nmos_delta_l, nmos_w0, nmos_w0);
    idx = PMOSRule.pickInstanceIdx(geo);
    T3_prob = PMOSRule.getInstanceProb(geo, idx);
    T3_vth0 = PMOSRule.getOutParamInstanceVal(geo, idx, 'Vth');
    T3_vth = pelgromRule(T3_vth0, nmos_delat_w, nmos_delta_l, nmos_w0, nmos_w0);
    idx = PMOSRule.pickInstanceIdx(geo);
    T4_prob = PMOSRule.getInstanceProb(geo, idx);
    T4_vth0 = PMOSRule.getOutParamInstanceVal(geo, idx, 'Vth');
    T4_vth = pelgromRule(T4_vth0, nmos_delat_w, nmos_delta_l, nmos_w0, nmos_w0);

    % now an analog simulation comes to determine 'delay'
    % and 'power' for the current instance of the cell
    cellNetlist = modifyNetlist(cell, T1_vth, T2_vth, T3_vth, T4_vth) ;
    [delay, power] = analogSimulation(cellNetlist);

    % store simulation results in the cell object
    % -------------------------------------------
    instanceName = [cellName, '_', int2str(i)];
    prob = T1_prob * T2_prob * T3_prob * T4_prob ;
    inpParams = [T1_vth, T2_vth, T3_vth, T4_vth] ;
```



```
72      outParams = [delay power];
73      cell.addSample(geoType, instanceName, prob, Vth, inpParams, outParams);
74    end
75 end
```

The example shows the code that enables characterizing the variability of the cell NAND2. in terms of delay and power. The input variability is represented by the variability of V_{th} of cell's transistors. We assume that the VAMIF elements NMOSRule and PMOSRule have been already loaded or created (see the code in the previous chapter).
At lines 1-11 non-variable numerical parameters used for evaluation of Pelgrom rule – `delta_w, delta_l, w0, l0` – are retrieved from NMOSRule and PMOSRule elements. Lines 13-17 displays the creation of the new cell VAMIF element with corresponding cell name `NAND2` and root directory where simulated results are stored. At the lines 19-29 the parameters of input and output domain are defined. The method `VamifObject.setGamma` at the line 33 sets the *Gamma* value. This method sets the *Gamma* value for all parameters involved in a computation. The set Gamma value remains valid till the next calling of the method `VamifObject.setGamma`. The *Gamma* is the exponent used to sample a EMC distribution. Gamma is a number between 0 and 1, where 0 corresponds to classic MC sampling, 1 corresponds to Entry Sampling and values in between are Weighted Monte Carlo sampling[3].
The outer loop over all types of variabilities contains the inner "Monte Carlo" loop. The method `pickInstanceIdx` randomly picks an index from an existing EMC distribution set. In case when a distribution of a particular variability type is not a EMC distribution, it is numerically converted to a EMC distribution. Then the method `getInstanceProb` and `getOutParamInstanceVal` return probability and concrete value of the output parameter corresponding to the randomly picked index. Retrieved V_{th} values are subject of Pelgrom rule – in this code represented by function call `pelgromRule`. Resulting V_{th} values are then used to modify original (non-variable) cell netlist to create its random instance which is then characterized by an analog simulation (lines 62-65).
The results of the cell characterization - values of `delay` and `power` - are then stored in the output domain of the cell object using the method `addSample`. After finishing the inner and outer loop the cell object `NAND2` should be complete characterize in its output domain (together with input data stored in its input domain).

[3] if you do not know which gamma to choose, set gamma to 1 if you pick only one brick to build a wall, and go down to 0.2…0 if your need many independently picked bricks to build a wall. Note thus that gamma may vary significantly amongst geometries. Matched and Local_systemtic typically have values 0 … 0.5; c2c, w2w and b2b have values around 0.5 … 1.

15. Underlying models for variability mechanisms

This chapter contains the descriptions of variability and reliability mechanisms.

Conventions for denominating distributions used in this chapter:
Vth, W, T: means the nominal, average or invariable value
ΔVth, ΔW, ΔT: static shifts away from the above value
If a parameter is called “delta_vth”, it means that it is referred to a certain “vth” in a relative fashion. The invariable geometry of a “delta_something” is exactly zero.
If the parameter would be called “vth” as such, the members of the EMCs are not relative.
σVth, σW, σT: “distribution” of the parameter.
In case of a Gaussian distribution “σ” means standard deviation, but in VAM we use the symbol σ in a generalized way, implying 5 corerlation_geometries etc.
Each of the 5 correlation_geometry distributions *may* be explicited as σ_MVth, σ_LVth, σ_CVth, σ_WVth, σ_BVth.
Refrain from using algebra on σs that is valid for true Gaussians only.

15.1. MOSFET static variability

Part of chapter “compact model”

15.1.1. model

Most variability parameters and several degradation mechanisms are at some point during the modeling flow condensed into a ΔVth and other netlist components.
For that purpose every MOSFET is a SPICE netlist is reparsed as:

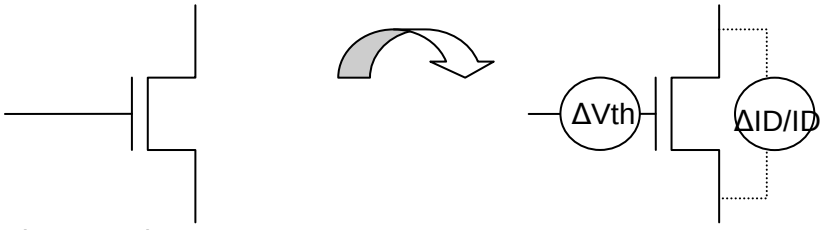


Figure 3 Injector concept.

The ΔVth in this scheme is series voltage source added to the netlist; the $\Delta I_D/I_D$ (Δbeta) Is a current dependent current source added to the netlist.

Note that in the VAMIF approach, the MOSFET, or any transistor, itself is a blackbox. Its *modelcard* is NOT changed. This allows using any compact model, macro, subcircuit, with minimal invasion in the existing simulation flow

Pelgrom’s rule for W and L scaling *applies to the* `matching` *geometry only.* See further

$\sigma(\Delta Vth)_{ref}$ and $\sigma\left(\frac{\Delta I_D}{I_D}\right)_{ref}$ are the variability for the nominal transistor size,

15.1.2. Object and parameters

`object type=mosfet name=<mosfet_type>`	should correspond to the model name in SPICE ("modelcard" such as nmosfet, mypmos, nmos_hv etc.) Default: this object applies to all transistors. One may also have multiple mosfet_type entries in this container.
`value compact_model_path`	path to compact model of this mosfet_type [optional].
`parameter delta_vth`	basic ΔVth variability – note that the Pelgrom rules apply to the "matched geometry" fraction only; for other geometries the distribution is taken as such. Note also that the invariable `delta_vth` is 0
`parameter delta_beta`	basic $\Delta I_D/I_D$ or Δbeta variability - note that the Pelgrom rules apply to the "matched geometry" fraction only! Note also that the invariable `delta_beta` is 0.
`value delta_w`	*default = 0*
`value delta_l`	*default = 0*
`value wref`	*default = 1um,* the reference MOSFET for which the ΔVth and Δbeta data are valid.
`value lref`	*default = 1um,* idem
Not yet documented, but eventually coming:	
`parameter r_sd`	modeling SD leakage variability
`parameter r_gate`	modeling gate leakage (GS, GD)
`parameter r_sat`	modeling saturation impedance variability
If documented, the *unpredicted* part of strain can be modeled	
`value strainfactor`	if given, additional Δbeta variability may be added starting from overlay variability (`parameter alignment` in `rule litho`): Δbeta=strainfactor*alignment

ΔVth and Δbeta in this approach are assumed to already include the variability effects of dopant and interface state fluctuations, CD variations, LER variations and layer thickness variations, and more. If one chooses to include the propagate one or more of DF, ISF, CDV, LER or LTV separately, make sure that their effect is taken out of the ΔVth and Δbeta parameters.

In such case, one could e.g. implement CD variations and LER by directly impacting the L and W parameters of the MOSFET modelcard.

Our preference and baseline however is that ΔVth and Δbeta do include all mentioned effects.

In a typical case, for each correlation_geometry, there is a EMC table representing the mentioned parameters, in a correlated fashion, e.g.:

ptoir	delta_vth	delta_beta	r_sd	r_gate
0.00013	+0.00239	-0.0445		
0.00044	-0.00097	-0.0067		
0.000012	-0.00566	+0.0125		
…	…	…		

15.1.3. Scaling with W, L and others

Pelgrom's rule for W and L scaling *applies to the* `matched` *correlation_geometry only*

$$\sigma(\Delta Vth) = \sigma(\Delta Vth_{ref}) * \frac{\sqrt{(W_{ref} + \Delta W) * (L_{ref} + \Delta L)}}{\sqrt{(W + \Delta W) * (L + \Delta L)}}$$

And a similar law applies to ΔID/ID:

$$\sigma\left(\frac{\Delta I_D}{I_D}\right) = \sigma\left(\frac{\Delta I_D}{I_D}\right)_{ref} * \frac{\sqrt{(W_{ref} + \Delta W) * (L_{ref} + \Delta L)}}{\sqrt{(W + \Delta W) * (L + \Delta L)}}$$

having nominal design size W_{ref} and L_{ref}. Often the nominal size is 1um.
For all other geometries, $\sigma(\Delta Vth)$ and $\sigma(\Delta\beta)$ are independent of W and L!

At this moment we assume that there is no significant scaling of $\sigma(\Delta Vth)$ and $\sigma(\Delta\beta)$ with temperature and VDS.

15.2. Template format for the description of a variability or reliability mechanism

This paragraph describes how a reliability/variability model must be setup in order to be implementable in VAMIF/VAM.
Essentially such description consists of 4 parts.

1. analytical or algorithmical model (say, C-code), containing *design values* and *technology parameters,* which describes (a) network element(s) for insertion in a SPICE netlist.

Example: in TDDB a extra resistor R (or alike) obeys: Δ(1/**R**) = Δ(t) * "slope" * exp(A * max(abs(VGS), abs(VDS)) Where this formula contains design values t, VGS, VDS (i.e. known by the designer or simulator, technology value A (a technology dependent constant), and the parameter "slope"

2. statistical distribution of the parameters in that model

In a general case, all parameters are represented in a emc_set in a VAMIF "object". In the most elaborate case, statistics for all correlation_geometries exist, directly or indirectly derived from measurements. Minimally only geometry "matched" (="all") must exist. If there is not variability, the EMC may contain just one entry or line. The values are added to the object separately. Also the reference state (the conditions where the EMC measurements are taken) is given as values.
It is thus silently assumed that the EMC set refers to one single reference case for [W_{ref}, L_{ref}, t_{ref}, T_{ref}, V_{ref}, …], and that the object thus contains also the relevant W_{ref}, L_{ref}, etc.
It is mandatory that the model contains exclusively "values" known by the designer (or designer tools), and "parameters" coming from measurements and likely subject to a distribution. Key is also: how to obtain such measurement data and transform them in a good set of parameters.

3. scaling rules allowing to translate the effect to a different case that is not in the measured set (i.e. in the set that is represented in the EMC tables). E.g. the case described in the EMC applies to W_{ref}, L_{ref} and VGS_{ref}; now what would it transform to for a case W, L, VGS?

Examples in the following paragraphs

4. scaling the cumulative effect of multiple different stress conditions

Examples in next paragraphs
We consider worst case degradation conditions captured in a single degradation corner

These 4 items are each time a sub-paragraph in the real models here below

15.3. Hot carrier degradation

15.3.1. Analytical model

We propose to follow the approach as Chittoor Parthasarathy[4] compiled in his PhD.
The degradation [relating to created interface states, hence to saturation current, gm, weak inversion slope and Vth] is expressed as:

$$\Delta D(t) = \left(\frac{I_D}{W*H} * \left(\frac{I_B}{I_D} \right)^m * t \right)^n$$

Where ΔD is proportional to the "damage" in terms of interface states, n is about ½, m is about 3 [depends on V_{GD}] and H is a technology constant.
We assume that we can calibrate the formula with a reference measurement, thus:

$$\frac{\Delta V_{th}(t)}{\Delta V_{th\,REF}(t_{REF})} \; or \; \frac{\frac{\Delta gm(t)}{gm}}{\frac{\Delta gm_{REF}(t_{REF})}{gm}} = \frac{\Delta D(t)}{\Delta D_{REF}(t)} = \frac{\left(\frac{I_D}{W*H} * \left(\frac{I_B}{I_D} \right)^m * t \right)^n}{\left(\frac{I_{DREF}}{W_{REF}*H} * \left(\frac{I_{BREF}}{I_{DREF}} \right)^m * t_{REF} \right)^n}$$

which opens the perspective for straightforward implementation in the VAM IF, as ΔV_{TH} and $\Delta g_m/g_m$ can be modeled with analog net list element. The variability thereof is then easily brought in via variability on these parameters themselves.
We *silently assume* that we can interchange $\Delta g_m/g_m$ and $\Delta I_D/I_D$, thus:

$$\frac{\Delta V_{th}(t)}{\Delta V_{th\,REF}(t_{REF})} \; or \; \frac{\frac{\Delta I_D(t)}{I_D}}{\frac{\Delta I_{D\,REF}(t_{REF})}{I_D}} = \frac{\left(\frac{I_D}{W} * \left(\frac{I_B}{I_D} \right)^m * t \right)^n}{\left(\frac{I_{DREF}}{W_{REF}} * \left(\frac{I_{BREF}}{I_{DREF}} \right)^m * t_{REF} \right)^n}$$

The degradation under bias conditions that have been different during different time spans t_1, t_2, … is straightforward extension:

$$\frac{\Delta V_{th}(t)}{\Delta V_{th\,REF}(t_{REF})} \; or \; \frac{\frac{\Delta I_D(t)}{I_D}}{\frac{\Delta I_{D\,REF}(t_{REF})}{I_D}} = \frac{\left(\frac{I_{D1}}{W} * \left(\frac{I_{B1}}{I_{D1}} \right)^m * t_1 + \frac{I_{D2}}{W} * \left(\frac{I_{B2}}{I_{D2}} \right)^m * t_2 + \ldots \right)^n}{\left(\frac{I_{DREF}}{W_{REF}} * \left(\frac{I_{BREF}}{I_{DREF}} \right)^m * t_{REF} \right)^n}$$

[4] C. Parthasarathy, "Etude de la fiabilité de technologies CMOS avancées: applications a la simulation de la fiabilité de conception de circuit numeriques et analogiques", PHD thesis, 9 Oct 2006, chapter 4.2. With acknowledgements for Guido Groeseneken.

This formula is usable as such when I_B or I_B/I_D is known by the simulator. Often this is not the case.
In order to tackle that situation, we include in the rule Parthasarathy's (with some pragmatic simplification) approach to calculate I_B/I_D:

$$I_B = \frac{A_i}{B_i} * E_m * l_c * I_D * \exp(-\frac{B_i}{E_m})$$

Where

$$E_m = \frac{V_{DS} - V_{DSAT}}{l_c} \qquad \text{and} \qquad V_{DSAT} \cong V_{GS} - V_{TH}$$

Hence

$$\frac{I_B}{I_D} = \frac{A_i}{B_i} * (V_{DS} - V_{GS} + V_{TH}) * \exp(-\frac{B_i * l_c}{V_{DS} - V_{GS} + V_{TH}})$$

for $V_{DS}>V_{GS}-V_{TH}$, (for an NMOSFET). Otherwise I_B is just zero.

And we reduce to two technology constants A and V_B:

$$\frac{I_B}{I_D} = A * (V_{DS} - V_{GS} + V_{THref}) * \exp(-\frac{V_B}{V_{DS} - V_{GS} + V_{THref}})$$

$$\log\left(\frac{\left(\frac{I_B}{I_D}\right)}{A * (V_{DS} - V_{GS} + V_{THref})}\right) = -\frac{V_B}{V_{DS} - V_{GS} + V_{THref}}$$

A and V_B are approximately constant for a given type of MOSFET in a given technology. A is not of importance as it is eliminated in the HCD formula. V_B must be obtained from a I_B/I_D calibration measurement plotted as follows. Temperature dependence is neglected.

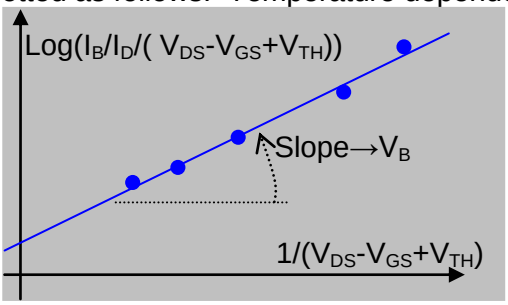


Figure 4 Hot Carrier Degradation slope.

Although conceived for NMOS, the overall HCD formula might be applied to PMOS. In that case, $V_{DS}>V_{GS}-V_{TH}$! In a PMOS the absolute value of V_{TH} decreases due to HCD, and the g_m decreases. Typically one chooses to neglect the effect of HCD in PMOS.

15.3.2. Parameters (and EMC table)

object type=hcd name=<mosfet_name>	the transistor type to which this applies. Default: all transistor types.
parameter delta_vth_ref parameter delta_beta_ref value t_ref value id_ref value ib_ref // if not	// $\sigma(\Delta V_{THref}(t_{REF}))$ // $\sigma\left(\frac{\Delta I_{Dref}(t_{REF})}{I_D}\right)$ in seconds!

	given, the I_B/I_D estimation formula is used	
value w_ref		
value n	optional, default 0.5	
value m	optional, default 3	
value vb	// used only for estimating I_B/I_D , see formula. *Good default wanted – in absence, without any guarantee, use 1V.*	
value vth_ref	// used only for estimating I_B/I_D // default: use the MOSFET's Vth, something like 0.5V	

15.3.3. scaling rules for design parameters

$$\frac{\Delta V_{th}(t)}{\Delta V_{th\,REF}(t_{REF})} \text{ or } \frac{\frac{\Delta I_D(t)}{I_D}}{\frac{\Delta I_{D\,REF}(t_{REF})}{I_D}} = \frac{\left(\frac{I_D}{W} * \left(\frac{I_B}{I_D}\right)^m * t\right)^n}{\left(\frac{I_{DREF}}{W_{REF}} * \left(\frac{I_{BREF}}{I_{DREF}}\right)^m * t_{REF}\right)^n}$$

Allows to scale for different W. L is not explicit in this formula, ID/IB depends on L, it is. One must of course know ID and IB either from the simulations or from

$$\log\left(\frac{\left(\frac{I_B}{I_D}\right)}{A*\left(V_{DS}-V_{GS}+V_{THref}\right)}\right) = -\frac{V_B}{V_{DS}-V_{GS}+V_{THref}} \text{ (see above)}$$

15.3.4. Scaling rules for dynamic stress conditions

$$\frac{\Delta V_{th}(t)}{\Delta V_{th\,REF}(t_{REF})} \text{ or } \frac{\frac{\Delta I_D(t)}{I_D}}{\frac{\Delta I_{D\,REF}(t_{REF})}{I_D}} = \frac{\left(\frac{I_{D1}}{W}*\left(\frac{I_{B1}}{I_{D1}}\right)^m * t_1 + \frac{I_{D2}}{W}*\left(\frac{I_{B2}}{I_{D2}}\right)^m * t_2 + \ldots\right)^n}{\left(\frac{I_{DREF}}{W_{REF}}*\left(\frac{I_{BREF}}{I_{DREF}}\right)^m * t_{REF}\right)^n}$$ indicates that the stress histories can be added before taking the result to the power n.

15.4. Manufacturing yield

This item describes hard defects that occur in manufacturing and that are *not* modeled via any variability and reliability rules in VAMIF. This is often described as functional yield in contrast to parametric yield.

Formula: $yield = \left(yield_{1m^2}\right)^{area[m^2]}$

Where $yield_{1m^2} = \exp\left(-defect\_density\right)$ Poisson: probability to have no defect in 1 m^2

In `chapter system`:

```
Container system_properties
     value chipsize nnn          in m2!  (Si units)
     value chipdiagonal nnn      in m  (Si units)  // optional
```

In `chapter technology`:

```
object name=manufacturing_yield
     parameter defect_density average=ddd  defects per m2! (Si units)
     parameter defect_size …     optional
```

Defect_density given as such only as an average and no distribution assumes that the statistics are pure poisson irrespective of geometry

This is an exception to the prescribed use of `parameter`. In fact one can *imagine* that the above is a shorthand for:

```
Container type=rule name=manufacturing_yield
      parameter defects_density
            average ddd stddev ddd
            geometry na
                  distribution poisson average ddd
      [parameter defect_size … ]
```

Parameter (hence distribution) `defect_size` is not documented at the moment. In the future this distribution may be used for finer assessment of impact of manufacturing defects on subcircuit size.

15.5. Interconnect R and C variability

As these are device electrical parameters, this is part of chapter “compact_model”

For an interconnect resistance

$$\frac{R}{R_{av}} = \frac{R_{av} + \Delta R}{R_{av}}$$

Where R_{av} is the average [nominal, design][5] resistance of a resistor or interconnect, R is the actual value, ΔR is the difference between the two.
This ratio is subject to a distribution, in shorthand[6]

$$\sigma\left(\frac{R}{R_{av}}\right)=\sigma\left(\frac{R_{av}+\Delta R}{R_{av}}\right)$$

For a particular resistor or interconnect in a certain layer, use following Pelgrom-like relation for the `matched` geometry only:

$$\sigma\left(\frac{\Delta R}{R}\right)=\sigma\left(\frac{\Delta R}{R}\right)_o * \frac{\sqrt{(W_0+\Delta W)*(L_0)}}{\sqrt{(W+\Delta W)*(L)}}$$

(W are design widths, W+ΔW are effective/electrical widths)

Similarly

$$\frac{C}{C_{av}}=\frac{C_{av}+\Delta C}{C_{av}}$$

Where C_{av} is and average [nominal, design][7] inter-interconnect capacitance, C is the actual value, ΔC is the difference between the two.
This ratio is subject to a distribution, in shorthand

$$\sigma\left(\frac{C}{C_{av}}\right)=\sigma\left(\frac{C_{av}+\Delta C}{C_{av}}\right)$$

For a particular later capacitance *within* a layer, use following Pelgrom-like relation for the `matched` geometry only:

$$\sigma\left(\frac{\Delta C}{C}\right)=\sigma\left(\frac{\Delta C}{C}\right)_o * \frac{\sqrt{(S_0+\Delta S)*(L_0)}}{\sqrt{(S+\Delta S)*(L)}}$$

L is the wire length, S+ΔS are effective/electrical spacings
Within the same layer, ΔS=- ΔW

For capacitances between interconnects on *different* layers, the key layer name is the dielectric name.

$$\sigma\left(\frac{\Delta C}{C}\right)=\sigma\left(\frac{\Delta C}{C}\right)_o * \frac{\sqrt{(W_0+\Delta W)*(L_0)}}{\sqrt{(W+\Delta W)*(L)}}$$

An in more elaborate form:

$$\sigma\left(\frac{\Delta C}{C}\right)=\sqrt{\sigma^2\left(\frac{\Delta C}{C}\right)_o+\eta\cdot\sigma^2\left(\frac{\Delta C}{C}\right)_{overlay}} * \frac{\sqrt{(W_0+\Delta W)*(L_0)}}{\sqrt{(W+\Delta W)*(L)}}$$

L is the effective wire length, the length over which the line segments overlap
W+ΔW are effective overlap width

"overlay": $\sigma\left(\frac{\Delta C}{C}\right)$ has a fraction due normal C and to overlay variability. The overlay part may be significantly larger than the classic C variability. The additional fraction of "overlay" is defined by the device-specific value η (eta).

η (eta) must be obtained by the designer or by back annotation.

[5] all three mean the same: it is the value that the simulation tool assumes in the non-variability-aware simulation flow, and to which VAMIF is assumed to add variability.
[6] Shorthand σ stands for any distribution, including multiple geometrical correlations. It implies the same information as in reserved keyword `parameter`.
[7] All three mean the same: it is the value that the simulation tool assumes, and to which VAMIF is assumed to add variability.

Typically:

- If one of the layers overlaps completely the other, over the full length, as in matched capacitor design, eta is zero.
- A wire or plate that orthogonally crosses: eta is zero.
- If the capacitor is partly overlapping for both metals, eta is maximal, 1.
- For two wires of same width on top of each other, eta is small, in the order of 0.0 to 0.2.

Default eta is 0.

Object type=interconnect_rc name =<layername>	Layername default: if not indicated, applies to all interconnect layers – must comply to interconnect name used in backend_definition in chapter technology. It means also that multiple versions of this rule may exist for the various metals.
parameter delta_rr .	basic $\sigma\left(\frac{\Delta R}{R}\right)_o$ variability – note that the Pelgrom rules apply to the "matched distribution" fraction only
value l0 value w0	*Both default = minimum width (!) in that layer*
value delta_w	*default = 0.* defines electrical width wrt design width. Note that delta_w equals also –ΔS (?). includes the LER effect (how?)
value sheet_r	*sheet resistance R□ for large squares. Optional, only given if known,*
value s0	*default = minimum spacing in that layer (for C)*

How should software tools proceed when they have only a backannotated R, but no clue on W and L of line segments?
We propose: estimate L as: L = R/ R□*(W_0+ΔW), i.e. we assume that the wire has minimum width, which is a reasonable worst case. L should not drop below minimum.

<<<Similar approach for C to be explicated???>>>

Alternative approach to import a few critical resisters / capacitors in VACCinate:
-think of resistor naming as `R_METAL1_W2u somenode othernode bwp*500hm`
-or code in in extra comment line in spice netlist
-or in separate table with the resistor name as entry
-Q: how about length parameterization

Proposition to define C from inside a spice netlist for VACCinate lateral `c_metal1_l200u_s2u line1 line2 50fF` vertical `c_diel2_l200u_w2u_eta0.1 line2 vdd 40fF` Any simple capacitor is perhaps subdivided in many individual capacitors. Is that worth the effort?

`Object` `type=vertical_capacitor` `name =<dielectriclayername>`	Layername default: if not indicated, applies to all dielectric layers – must comply to interconnect name used in `backend_definition` in chapter technology.
`parameter delta_cc_zero .` `parameter delta_cc_overlay .`	$\sigma\left(\frac{\Delta C}{C}\right)_o$ and $\sigma\left(\frac{\Delta C}{C}\right)_{overlay}$ variability – note that the Pelgrom rules apply to the "matched distribution" fraction only
`value l0` `value w0`	
`value delta_w`	*default = 0.* defines electrical width wrt design width. includes the LER effect (how?)

`Object` `type=via` `name =<layername>`	Layername default: applies to all via and contact layers – must comply to via layer used in `backend_definition` in chapter technology.
`parameter delta_rr` `value r`	basic $\sigma\left(\frac{\Delta R}{R}\right)_o$ variability *nominal r of the via (optional data)*

A point tool will translate chapter technology to chapter compact model, and do:

σ(deltaR/R) = alfa * (σthickness/thickness) + beta * σ(LER) / w + gamma*(effect of barrier layer thickness horizontal) + delta*(effect of barrier layer thickness vertical) alfa and beta are constants that need separate calculation. In the absence of any better value, we use the default 1. thickness is the average of `thickness` found in the `backend_definition` σthickness is the distribution thereof the value w = $w_{electrical}$ = w_{design}+delta_$w_{electrical}$. σ(delta_w) is the distribution of delta_$w_{electrical}$, which is derived from delta_$w_{physical}$ see below. (both σthickness and σ(delta_$w_{physical}$) are subject to 5 types of geometry if available from fab.)

delta_$w_{electrical}$ = f(LER, technology things) + f(delta_$w_{physical}$) default rule is: delta_$w_{electrical}$ = delta_$w_{physical}$ delta_$w_{physical}$ is found in the `backend_definition` LER is found in `rule litho`

15.6. Litho variability

Part of chapter technology.

The 4 elementary litho `parameters` are:

- ⇒ Δdose/dose , as derived from variability on a dose in [mJ/cm2]
- ⇒ Focus [nm]
- ⇒ Aligment [nm], overlay error
- ⇒ LER [nm], accompanied by the correlation length along edge

This litho LER may translate to the LER-effect in interconnects?>

The two first have a rather well documented impact on printing accuracy, as:

CD = f(dose, focus)

A good, simple first order formula exists:

CD = a* Δdose/dose + b*focus^2 [8]

This may be the basis to for a rule estimating linewidth and spacing variations for interconnects and MOSFET W and L.

These a en b are functions of local layout geometry,

- ⇒ Hence, a end b are parameters with only local_systematic variability
- ⇒ Eventually, OPC-like tools may predict these, thus yielding a and b per polygon piece.

We assume that this is not the case, hence:

For the moment we propose the following approach:

- ⇒ a and b are defined as parameters (local_systematic only[9]) representing the “general layout style” used in the design. For a so called litho-friendly (RDR) layout style, a and b are lower and have smaller distributions than for a spaghetti style layout.

[8] Staf Verhaegen, IMEC, 22-jul-07

[9] Although a and b are represented as local_systematic, tools should apply it to all geometries of delta_dose and focus in the formula CD = a* Δdose/dose + b*focus.

object name=litho	
parameter a	(local_systematic only) // reflects layout style
parameter b	(local_systematic only) // reflects layout style
parameter delta_dose	Δdose/dose, average is 0
parameter focus	in [m] average is 0
parameter alignment	in [m] average is 0 (overlay alignment error)
parameter ler	in [m] line edge roughness
value ler_length	[m] correlation length of LER

typical values for 65nm (no guarantee on these values!)
1sigma(focus)=50nm
1sigma(Δdose/dose)=2%
1sigma(alignment)=10nm
1sigma(LER)=2nm, averaged
1sigma(CD) due to dose = 4%, for long parallel lines (matched)
1sigma(CD) due to focus = 4%, for long parallel lines (matched)

15.7. TDDB on MOSFETs

15.7.1. Piece-wise approximation model

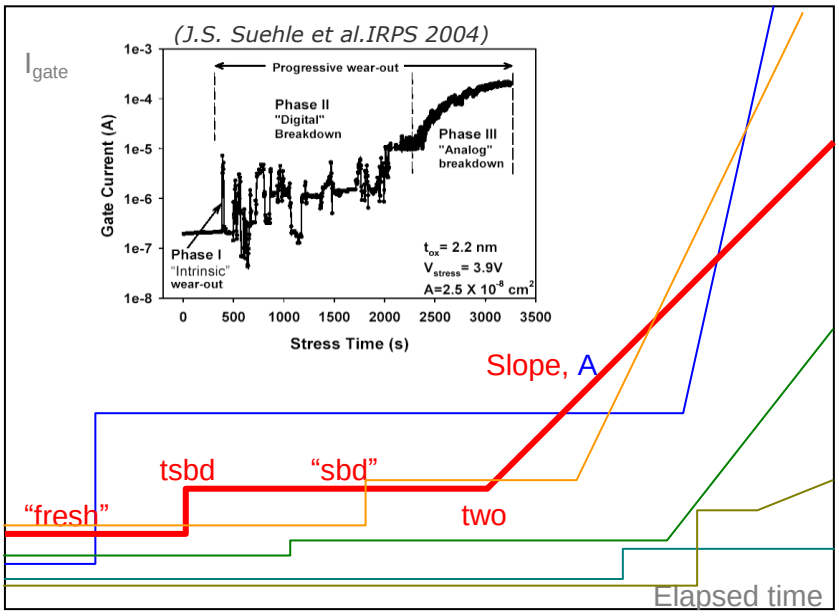


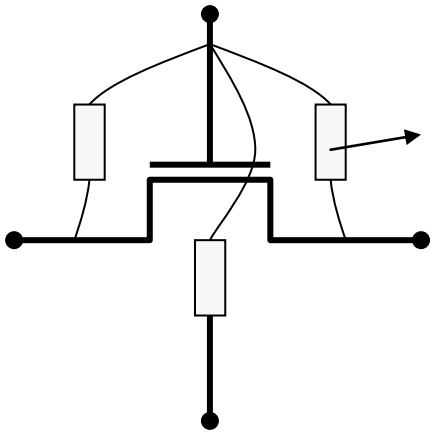
Figure 5 MOSFET soft and hard breakdown.

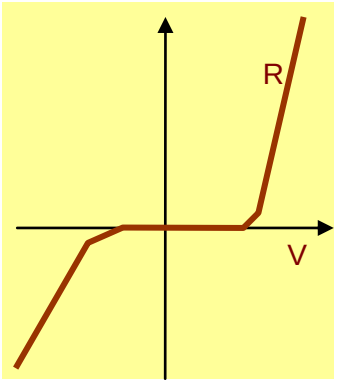
- soft breakdown (sbd) happens after a time tsbd. After that the initial "fresh" I/V characteristic changes to a "sbd" I/V characteristic. This I/V characteristic is strongly non-linear, and is characterized by.
- ware-out (wo) happens after a time two, after which the device goes in "hard breakdown" (hbd). The I/V behavior becomes that of a simple time dependent, progressively decreasing resistance R, obeying:
  - $\Delta(1/R) = \Delta(t) * slope * \exp(A * \max(abs(V_{GS}), abs(V_{DS}))$

- Asymptotically R evolutes to zero! The observed current limitation is due to external series resistances to the gate.

How is this injected (VACCinate) a Spice net list?

In *fresh state* and in *soft breakdown*, gate leakage is a time dependent nonlinear resistance between G, S, D and B, as shown below.



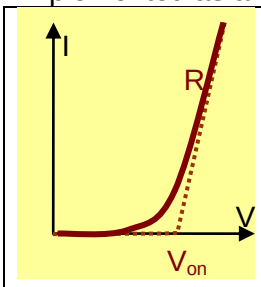


In *hard breakdown* the resistance is linear, and obeys.
Δ(1/R) = Δ(t) * slope * exp(A * max(abs(VGS), abs(VDS))

Herein slope is a "parameter" and, there is one technology specific "value" A, which has unit [V]

Figure 6 MOSFET soft and hard breakdown injection.

We simplify the SBD model further: we disregard the small asymmetry between inversion and accumulation, and we completely disregard the leakage to Bulk. The model will be implemented as a Verilog-A model, which is identical in both quadrants.



The proposed model[10] for Fresh and SBD, for one quadrant is:

$$I = I_0 \cdot \left(\exp\left(\frac{V - I \cdot R}{\eta \frac{kT}{q}} \right) - 1 \right)$$

with 3 parameters that must be fitted to each measurement curve.
R fits to the IV curve for high I. η ("eta") and I_0 determine the low current behavior. Physically the "ideality factor" η must be larger dan 1.
One can revert to a simple, piece-wise linear approximation, using R and a V_{on} (dotted line in figure) in case the analog simulator can not handle the full model. V_{on} is then calculated from the formula, where V_{on}=2R.I(V_{on})

Figure 7 Simplified MOSFET soft and hard breakdown injection.

15.7.2. EMC table of parameters

This table contains a populations of measured devices (or created devices). Some parameters are given, duplicated for G-S and G-D.
These are for a given [technology, NMOS/PMOS, tox,] W, L, T, t, …, example:

ptoir	Tsbd	two	slope_s	slope_d	rfresh	rsbd_s	rsbd_d	etafresh	etasbd_s	etasbd_d	i0fresh	i0sbd_s	i0sbd_d
1	2022	23456	23.3	22.1	1.23e9	3.4e7	3.4e7	3,7	1.3	1.3	1.23e-19	3.4e-7	3.4e-7
1	678	10987	24.5	23.7	9.88e8	1.1e7	1.1e7	3.5	1.6	1.6	9.88e-18	1.1e-7	1.1e-7
1	13900	19765	21.7	19.0	7.88e8	2.9e7	2.9e7	3.2	1.5	1.5	7.88e-18	2.9e-7	2.9e-7

[10] R. Fernández, J. Martín-Martínez, R. Rodríguez, M.Nafría, and X. H. Aymerich, "Gate Oxide Wear-Out and Breakdown Effects on the Performance of Analog and Digital Circuits", IEEE Transactions on ED, Vol. 55-4, p.997 (2008)

In this table separate values for source and drain are given. We might consider to simply further and make these identical.

15.7.3. Rules for scaling W, L, T, t…

Should tell us “what is the effect on elapsed time” when stress condition V, T etc change. (attention: the measurement conditions after stress do not change)

A Pelgrom rule applies to R, only for Matched

15.7.4. Rules for scaling to multiple sequential stress conditions

Approach: each stress condition on its own creates an “elapsed time”. The different stress conditions just accumulate those times.

15.8. NBTI of MOSFETs

15.8.1. Algorithmical model

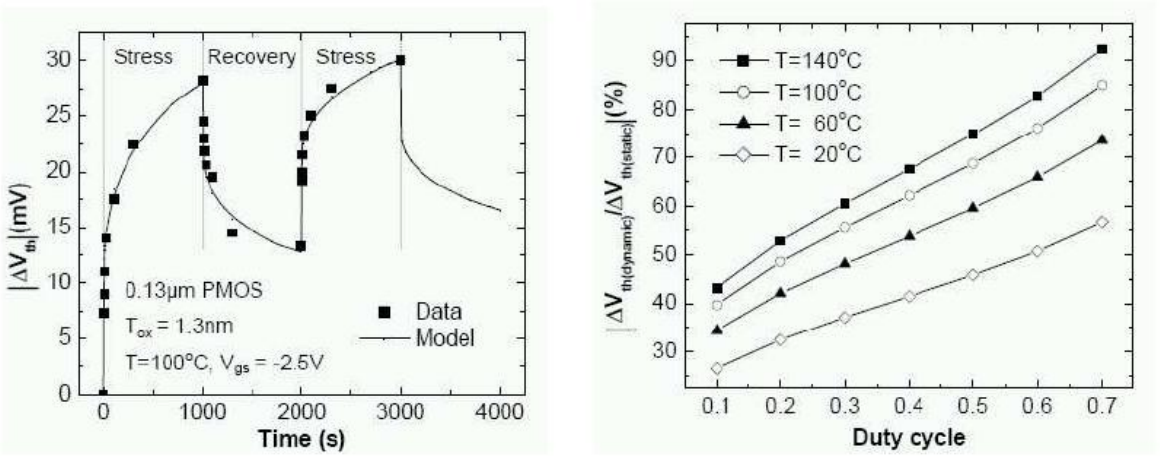
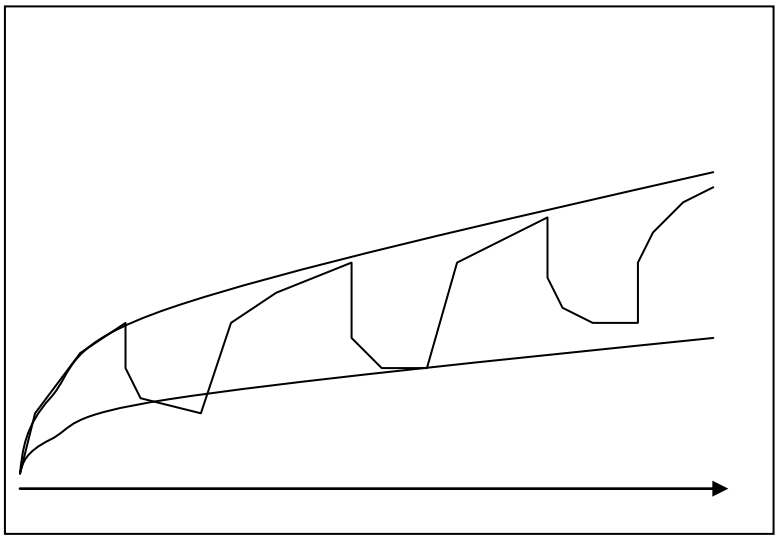


Figure 8 Healing property of NBTI (negative-bias temperature instability) and effectiveness of duty-cycle in controlling Vth shift[11]

[11] Vattikonda R., Wang W., Cao Y., “Modeling and Minimization of PMOS NBTI Effect for Robust Nanometer Design”, DAC 2006

Function



NBTI creates an upper and lower boundary between which the transistor will move. The actual value at evaluation time is not known (pick randomly???)

$$\Delta Vth_{\min} = f(time, duty\_cycle, toggle\_rate, VGS, VDS, ID, some\_parameters)$$

$$\Delta Vth_{\max} = f'(time, duty\_cycle, toggle\_rate, VGS, VDS, ID, some\_parameters)$$

We to derive these relations from Cao's model[12], summarized in this table:

TABLE I
SUMMARY OF THE PREDICTIVE MODEL

$\lvert\Delta V_{th}\rvert$ under NBTI			
Static	$A\left((1+\delta)t_{ox}+\sqrt{C(t-t_0)}\right)^{2n}$		
Dynamic	Stress	$\left(K_v(t-t_0)^{0.5}+\sqrt[2n]{\Delta V_{th0}}\right)^{2n}$	
	Recovery	$\Delta V_{th0}\left(1-\frac{2\xi_1 t_e+\sqrt{\xi_2 C(t-t_0)}}{2t_{ox}+\sqrt{Ct}}\right)$	
K_v	$\left(\frac{qt_{ox}}{\epsilon_{ox}}\right)^3 K^2 C_{ox}(V_{gs}-V_{th})\sqrt{C}\exp\left(\frac{2E_{ox}}{E_o}\right)$		
C	$T_o^{-1}\cdot\exp(-E_a/kT)$		
t_e	t_{ox}		$t-t_0 \geq t_1$
	$t_{ox}\sqrt{\frac{t-t_0}{t_1}}-\frac{\sqrt{\xi_2 C(t-t_0)}}{2\xi_1}$		*otherwise*
E_a (eV)	0.49	E_0 (V/nm)	0.335
δ	0.5	K $(s^{-0.25}\cdot C^{-0.5}\cdot nm^{-2})$	8×10^4
ξ_1	0.9	ξ_2	0.5
T_o	10^{-8}		

15.8.2. EMC table and parameters

NBTI/PBTI in combination with radon doping fluctuations and other sources of intrinsic device variability just interface state fluctuations and contribute in statistical manner to the variation parameters at circuit level ΔVth and Δbeta (see Section 15.1.2 and REALITY deliverable D1.2), hence their table representation follows that one of variability injectors in general.

ΔVth and Δbeta in this approach are assumed to already include the variability

[12] Sarvesh Bhardwaj, Wenping Wang, Rakesh Vattikonda, Yu Cao, Sarma Vrudhula, "Predictive Modeling of the NBTI Effect for Reliable Design", CICC 2006, p. 189

effects of dopant and interface state fluctuations, CD variations, LER variations and layer thickness variations, and more.

In a typical case, for each correlation_geometry, there is a EMC table representing the mentioned parameters, in a correlated fashion, e.g.:

ptoir	delta_vth	delta_beta	r_sd	r_gate
0.00013	+0.00239	-0.0445		
0.00044	-0.00097	-0.0067		
0.000012	-0.00566	+0.0125		
…	…	…		

15.8.3. Scaling rules for circuit and use

As statistical parameter, we consider the combined impact of NBTI/PBTI induced interface states with the other sources of intrinsic variations to apply the matched geometry only via variability injectors. Different amount of trap concentrations will capture the effect of the changing stress conditions, e.g., elapsed time, voltage, T etc. For that reason and similar to the time-zero matched geometry, a variability a Pelgrom rule will apply in this case.

15.8.4. Scaling rule for mulitple stress conditions

We do not consider multiple stress conditions yet. Instead we consider a corner like analysis approach that assumes all devices of the circuit to be subject to the same stress factors. Hence, all devices hence share the same VMIF compact model chapter. Yet we accommodate for different “flavours” of stressed circuits with all devices subject to the same degradation by accommodating a different VAMIF compact model chapter for each degraded circuit.

15.9. MOSFET hysteresis

Some types of MOSFETs suffer from hysteresis. Such are: SOI with floating body, MOSFETs as used in EEPROM and certain high-k gate MOSFETs. Also NBTI is a kind of hysteresis that is not modeled separately.
The hysteresis is modeled as a voltage source in series with the gate. Modelling details not available

15.10. Variability of MOSFET temporal noise

Temporal noise *as such* is not part of the VAM(IF). It is assumed to be sufficiently covered in the normal design flow. Yet *variability* of MOSFET noise is represented here. Temporal noise sources are:

15.10.1. MOSFET white noise

Also known as (thermal ~, Johnson ~) noise
(No model for distribution)
No report has been found that thermal noise variability is significantly higher beyond the noise level itself, thus not modeled at the moment.

15.10.2. MOSFET 1/f noise

Also known as “flicker noise” (fn)

We assume following model for spectral noise density of a MOSFET's equivalent gate noise $S_{V_{Geq}} = \frac{KF}{W.L.f}$ where KF is a technology constant, often given explicitly or indirectly in the SPICE model.
We propose to represent the variability in a dimensionless prefactor, which is 1 on average, and which applies to the gate voltage domain.

$$S_{V_{Geq}} = fn\_prefactor^2 \times \frac{KF}{W.L.f}$$

The Gaussian, instantaneous/temporal, distribution of the gate voltage offset itself is separately obtained by integration of S:

$$V_{G\_RMS} = fn\_prefactor \times \sqrt{\frac{KF}{W.L}} \times \sqrt{\int_{f_{low}}^{f_{high}} \frac{1}{f} \cdot \partial f}$$

$$V_{G\_RMS} = fn\_prefactor \times \sqrt{\frac{KF}{W.L}} \times \sqrt{\log(4\frac{f_{high}}{f_{low}})}$$

Where f_{high} corresponds to the bandwidth of the circuit node and f_{low} is somewhere between the age of the circuit or the time since turning to accumulation (TBD).
Smaller MOSFETS suffer from ever larger 1/f noise, just as they suffer from ever larger V_{th} variability. Note that the factor W.L (electrical W and L!, as for V_{th}) in the formula represents a Pelgrom rule. This Pelgrom rule (in contrast to the MOSFET Vth variability Pelgrom rule) applies to all geometrical correlations.

15.10.3. MOSFET RTS noise

To model RTS, we need:
(1) The number of states per reference W*L area.
(2) The distribution[13] of Vth-equivalent amplitudes for a given state for such given W*L
- ⇒ In strong inversion
- ⇒ In weak inversion[14]

The effective V_G equivalent amplitude is inversely proportional with W*L, so these amplitudes must be given for a reference W and L. If not given Wref and Lref are assumed 1um.
(3) To every individual RTS state belongs a set of emission & capture time constants, or described as an overall time constant $\frac{1}{\tau_{RTS}} = \frac{1}{\tau_e} + \frac{1}{\tau_c}$ and a duty cycle. τ_{RTS} and τ_c are approximately inversely proportional to inversion charge thus drain current density. τ_e is less dependent of the current. The RTS is most effective when τ_c and τ_c are equal, at a current I_{50}.

The distributions of weak inversion amplitudes is very long tailed; the time constant distribution covers multiple decades (Ms to ns).

The detailed description is subtle, yet for the purpose of estimating noise margin, one may suffice with a correlated set of following parameters:
- ⇒ Amplitude in strong inversion

[13] K. Abe & al, "Analysis of source follower random telegraph signal using nMOS and pMOS array TEG " IEEE IISW 2007, proceedings p. 62
[14] E. Simoen, B. Dierickx, "Critical examination of the relationship between random telegraph signals (RTS) and low-frequency (LF) noise in small-area Si MOSTs", 12th International Conference on Noise in Physical Systems and 1/f Fluctuations, St.Louis, Missouri, USA, 16-20 Aug., 1993

⇒ Amplitude in weak inversion (it may be tricky to “invent” a value in case measurements are not available in the other mode. It does not hurt to give as default value zero then))

⇒ Reference drain current $I_{50\%}$ at which the duty cycle is 50% (and $\tau_e = \tau_c = 2^* \tau_{RTS}$) for the reference W and L.

⇒ The actual time constant τ_{RTS} at $I_{50\%}$.

How to use noise in a digital design flow?
A possible approach for using this information for the digital design flow would be to adjust Monte-Carlo-wise the noise margin.
Start from a default noise margin, and add to the margin the amplitude derived from the instantaneous range of eq gate voltages due to 1/f and RTS. How to do this in practice and check if this corresponds to reality is an open research topic.

We assume that if both RTS and 1/f are described, that they are cumulative. *This is not obvious as RTS and 1/f are emanations of the same phenomenon: 1/f can be described as the superposition of many smaller RTSs.*

Object type=mosfet_noise name=<mosfet_type>	If name not given, applies to all MOSFETs
Value kf	Optional, rather build on the mechanism present in the existing SPICE models if available
Parameter fn_prefactor	Voltage domain prefactor to flicker noise. Average value being 1
Parameter rts_states	number of RTS states in area Wref*Lref
Value w_ref	Effective (electrical) W
Value l_ref	Effective (electrical) L
Parameter i_50 Parameter tau_rts	$I_{50\%}$, tau_{RTS} and the amplitudes must be a correlated set of values.
Parameter amplitude_si	In case that either amplitude_si (strong inversion) or amplitude_wi (weak inversion) are lacking, 0 is a good default.
Parameter amplitude_wi	

16. Other underlying models

16.1. Activity, stress history on circuit parts (cells) and their inputs

Is part of several chapters. E.g. in `chapter cell` as it has to be used in the calibration of standard cells and memories for reliability effects.
In order to calibrate cells for activity on their nodes, one needs a representation of "stress history". This is preliminary and needs huge refinements.

The age of a device is represented in `chapter system` as

`Container name=system_properties` `value age nnn`	in seconds! Si units the number of seconds of calendar lifetime of the device

The most basic way to represent "activity" information is as:

`Container` `type=activity` `[value component name]` `[value input name ]` `value stress_case name` `value togglerate nnn` `value dutycycle nnn`	default cell name: applies to all cells default input: applies to all inputs of cell case: one of: typical, worstcase, standby, … as a scenario togglerate: the effective number of 0-1 transitions per second dutycycle: the effective ratio between input high time and the total time

This approach is certainly too simplistic. One should represent such information per individual cell, and for each cell a number of cases. And discriminations per input, even on power supply tuning or stdby modes. Likely, if too numerous, it will be in a separate file (is there a standard…?)
Another shortcoming is that it does not represent correlation between inputs, not that it represents the recovery time, which is of use in degradation mechanisms that have some recovery or hysteresis.

16.2. Backend definition

In: `Chapter technology`.
This information is used to define backend variability, including LER, thickness variations…

```
Container
type=backend_definition  //with dielectrics and metals from bottom to top
      Container
      Type=dielectric
      Name=STI
            Parameter thickness
            Value permittivity
            Parameter via_resistance
      Container
      Type=interconnect
      Name=metal1
            parameter thickness
            parameter delta_w  // where W_physical = W_design + ΔW
            value min_width          //design value
```



```
                value min_spacing          //design value
                parameter LER              //NOTE is not the same as distribution on
width!
                [value spacing_permittivity] //in case the spacing permittivity is different
from lower/upper dielectric
                value resistivity
                value resistivity_offset  // effect of the encapsulation layers etc. formula
TBD
```

16.3. Temperature gradient

temperature gradient as such is not considered as a variability, but a system level input to the simulation flow. In that sense it is a “predicted systematic variability”. External tools might yield sub circuit specific local temperatures based on system operating mode.
How to enter this in the VAM context is not obvious. Possibilities are:

- neglect and work with an average die temperature (given in chapter system)
- back annotated local temperature per subcircuit, eventually percolating down to each transistor. Input should come from external tools, data format unknown.
- clever back annotation, using similar concepts as scenarios for power estimation and historic stress conditions. I propose to piggyback such developments, both for the method to propagate the information, as to the activity/scenario method.

16.4. Standard cell libraries

(Part of chapter cell)
Standard cell libraries are referred to:

Spectre/Spice netlists represent the original variability free library.
We also make a clear separation between representation of .lib and of methods to create a .lib

Creation of .lib
in this example STDCELL_ROOT_DIR represents the root directory of the standard cell characterization project (e.g. file:///einstein/scratch2/marchal/characterization) and LIB_NAME is a name of a library under characterization (e.g. PT130).
The library may be represented by a collection of .gds files, one for each standard cell. Using an LVS tool (e.g. CALIBRE) this library is converted to a collection of Spectre netlists (the directory STDCELL_ROOT_DIR/run/svbd) .

Representation of .lib
See below

Standardcell_library
The variability aware library e.g. is produced by SignalStormLC tool (Cadence) which perform characterization of standard cell with applied compact model variability. The output is the .alf library, subsequently converted to the .lib compatible format.

the variable aware .lib library is represented as

- ⇒ For each of the 5 geometries, and as reference one “invariable” library, which is more or less the same as the “typical-typical” library.
- ⇒ one large library file that includes all variable instances of all characterized standard cells (e.g. for the cell INVBD2 cell there are several corresponding variable instances INVBD2_v1, INVBD2_v2 …, INVBD2_v*max*).

Note on cell interpolation:

- Instances of the same cells in .lib files must be interpolatable: i.e. one can make a sensible linear combinations of instances of the same cell, by simply making linear combinations of the numbers on the same position in these cells. *Concept to be proven!*

Geometrical correlation is introduced in the .lib files

container type=cell_library name=<name of library>	The .lib or vital "library name". If there are multiple libraries used, multiple containers are there.
Value root <root directory>	If empty, neglect
Value gds_dir <pathname>	GDS is given in case Spectre or Spice netlist do not exist yet and tool can handle that
Value spectre_dir <pathname> Value spice_dir <pathname>	Only one is required
Container Name=Cells temperature =<…> vdd =<…>	Attributes temperature and VDD are modes at which the library is calibrated. There can thus be multiple copies of this container applying to the same library.
Value dotlib_dir <pathname>	This directory on itself contains 6 subdirectories named invariable, matched, local_systematic, c2c, w2w and b2b. The files therein are the libraries, (one or more files per directory)
object type=cell name=<cellname> Parameter instantiation Parameter defunct (0 or 1)[15] Parameter outlier (0 or 1)[16]	*Instantiation* is the name of an instance in the EMC population of cells. Used to retrieve a certain instantiation from the .lib.
[*(Parameter *inputparameters*)]	Optional "Input domain parameters": parameters of underlying blocks (e.g. Vths inside std cells). These values describe the used input parameter. Can be used for binning or RSM if ever one wants to do that. These parameters have geometry obviously corresponding to the

[15] Defunct==1 mandatory parameter, means that this instantiation is a non-functional part. How to handle in the .lib and tools using the .lib remains to be discussed. Minimal approach is to give the non-functional part very large (1 second) delays in the .lib.

[16] Outlier==1 means that the cell contains one or more transistors that were labeled as "outlier" themselves.

	dotlib geometry. Alternate and preferred: use the "corrid_###" concept.
[Value nominalload [Value inputslope [Parameter nominaldelay[17] [Parameter zeroloaddelay [Parameter nominalenergy [Parameter zeroloadenergy [Parameter staticpower [Parameter nominalsetup [Parameter zeroloadsetup [Parameter nominalhold [Parameter zeroloadhold	These 5 (9 for sequential cells) correlated "output domain" parameters, are optional. They yield help at the next level of propagating variability. Currently implemented using liberty parser and timing engine of Synopsys Design Compiler.

Defunct standard cells
Due to variability, it is likely that some instances of cells will not yield a correct functionality. Classic calibration software (as SignalStorm) may crash or yield not usable results.
Yet, such cells must be represented in VAMIF as realistic as possible:

- Such cell instances should have an entry and an instantiation
- They parameter "defunct" is set to 1
- A .lib entry must exists. Minimally it must mimic the actual faulty operation by a very long delay, >>1ms
- Preferably, the .lib entry models the static and dynamic power correctly.
- Normally not possible with .lib, but useful and not required, would be to change the functionality of the cell.

16.5. Representation of non-standard cells: embedded memories

16.5.1. The MemoryVAM configuration contained

Container type=configuration name=memoryvam	
Process 1 –related options:	
list donuts fast_donut l2memory	This is the list of *the* donuts to be processed by MemoryVAM. The actual donut information is inside, and referred to by, configuration container <donut_name> donut, within this configuration
value mode1.name vdd list mode1.domain 1.0 1.1 1.2	Optional. Enumerate modes starting from one, and supply

[17] nominaldelay: the maximum delay for any input to any output, where all input see the given input slope, and all outputs are loaded nominally, eg. the max in the .lib table. zeroloaddelay: the maximum delay for any input to any output, for zero load. Energy: dynamic energy, per operation; staticpower: DC [leakage] power.

`value mode1.command ".param vdd_sv=%s"` `Value mode2.name temperature` `list mode2.domain 273 300 400` `value mode2.command ".temp '%s-273'"` `Value mode3.name corner` `list mode3.domain "NN FF SS SF"` `value mode3.command ".LIB '/path/to/your/lib' %s"` `Value mode4.name Margin_control_signal` `list mode4.domain 00 01 10 11` `value mode4.command ".inc mcs%s.inc"` (…)	Mode<n>.name, Mode<n>.domain, Mode<n>.command. *.name should not contain spaces. *NOTE: Some modes you can apply without changing your netlist, such as simple parameter settings (eg: ".param vdd=%s" overrides original value for vdd), while others require you to change the netlist, for example in ".LIB '/path/to/your/lib' %s", while most likely not work if you keep your original .LIB statement. Also NOTE: do not supply multiple .TEMP statements! Remove your original .TEMP statement if you are using .TEMP in a mode or work with ".TEMP placeholder" in the netlist and with ".PARAM placeholder=%s" in the mode command instead.* Mode names must not contain spaces or special characters! These names will be found back later as attribute names of the donut *objects*. *Do not forget that one can always reduce to a trivial configuration space, i.e. the donut is specific for one specific memory, hence these lists have only one value or are simply omitted* Modes can be overwritten by particular donuts (NOT YET IMPLEMENTED).
`Value n_matched 100` `Value n_local_systematic 100` `Value n_c2c 100` `Value n_w2w 100`	Number of samples to go for. Specify 0 for any geometry you do not want to simulate.

`Value n_b2b 100`	N_matched also applies to the Islands, see below. Specifying a number >0 for a geometry that is not supplied in the compact model chapter causes an error.
`Value gamma_matched 0` `Value gamma_local_systematic 0` `Value gamma_c2c 0.9` `Value gamma_w2w 1` `Value gamma_b2b 0.8`	Gammas (EMC statistics) used for each geometry. You can omit gamma values and MemoryVam tries to find an optimized gamma for you.
`list CORNERS NN FF SS SF …` `Value CORNER_LIB '/path/to/your/lib'`	Will create simulation decks using CORNER_LIB with the .LIB suffices given in CORNERS There is no CORNER Geometry Type (yet). Therefore, at the moment, new object in a new cell.xml file in a new directory corners/ is created and the w2w Geometry is used. The user can browse this chapter and combine corner figures and cloud figures using the MATLAB Figure editor functions. (NOTE: STATUS is EXPERIMENTAL. Known limitation: If you use MODES (see above, the behaviour of CORNERS is undefined)
`Value dest_directory <dir>`	Working directory for MemoryVam. If omitted, <xml_directory>/.mvam will be used. The directory is created if it does not exist.
`Value pass_to_vaxc_<option> <value>` `(…)`	Optional low level control of vaccinate. Normally not required for MemoryVAM users. <option>=<value> is processed by vaccinate, not by MemoryVam. Refer to VACCinate user guide for more information and list of supported options.
`Value pass_to_vaxc_gamma_autoreduce 30` `Value pass_to_vaxc_gamma_autoreduce_step 0.9`	Automatically reduce too high gamma values to a small enough number using at most gamma_autoreduce iterations and adapting GAMMA -> GAMMA * STEP. If, after all

	iterations, Gamma is still too high, MVAM continues with a warning. DEFAULT: 30 iterations, step factor 0.9. To turn off Gamma autoreduction based on probability, set gamma_autoreduce to 0 (not recommendend). To make the reduction in finer steps, use higher numbers for step, such as 0.95 or 0.99 but then make sure to use higher number of iterations. The default settings are safe together with starting values for gamma of 1.0 NOTE: Do not worry about messages like
	`Warning: Divide by zero.` `> In pick_matrix>analyze_probabilities at 328` `In pick_matrix at 179` `In vaccinate at 242` `In mvam at 146`
	These happen when gamma is so high that the resulting probabilities would be smaller than the resolution of a double float. In this case mvam reduces gamma automatically.
Simulator –related options:	
`Value simulator_executable <executable>`	MemoryVAM runs the simulator <executable> for you with the vaccinated donut file name as only parameter from the directory of the vaccinated donut file. You can add command line options here, MemoryVAM always adds the testbench-wrapper as last parameter. Example: “hspice64 –mt 8 –i “ or “hspice_sub –l” NOTE: you can also specify a wrapper script that takes as $1 parameter the testbench-wrapper to be simulated.
`Value unimportant_measures <regexp_string>`	By default, MemoryVAM considers a “failed” of any .MEAS statement as a

	functional failing of the donut variant. You can specify a regular expression for exceptions here. Example: "^chk|dummy|stability$" Will ignore "failed" measurements when computing yield for all measures beginning with "chk", the measure "dummy" and all measure ending with "stability".
Process 2 –related options:	
`Value N 100`	Memories are created in a Monte Carlo Fashion from donut statistics. Specify here how many memory samples you want. 100, 200, 5000 are good settings for low, medium, and high accuracy.
`List memory_cells M1109 M4563 S6542`	Not USED. Every donut produces one memory in this version. The actual memory cells to be processed. The actual cell information is in the container memory_cell, including which donut is used in that cell.

16.5.2. Donuts of memories

Memories as such cannot be calibrated as a whole. In VAM, MemoryVAM calibrates a memory through its “donut”. See also MemoryVAM Users manual.

Container type=donut name=<donut name>	This container contains configuration information for one particular donut
Value testbench <path>	Test bench = path to file name which contains instantiation of your donut.
Value circuit <circuit name>	Needed for VACCination to know where to start injecting. If your circuit resides at toplevel, specify: top__level__ (in total four underscores)
Value island_table <path>	Path to the island table. Example: /my/project/island.csv. See below on format of this file. Without island specification, process two cannot run and process one can run with limited functionality only.
Value vsr_table <path>	Path to the “Variability scaling rule table”. Example: /my/project/vsr.csv. Without this file, See below on format and meaning of this file.
Value vsr_table <path>	Path to the “constraint table”. Example: /my/project/constraints.csv. See below on format of this file.

16.5.3. Memory cells

These are represented at the same level as standard cells and standard cell libraries. Memory cell variability is coded as a population of .lib cells. There may be one or more memory libraries, represented as following container. (see als MemroyVAM container)

container type=memory name=<name_of_memory>	The .lib or vital "library name". If there are multiple libraries used, multiple such containers exist.
Value root <root directory>	If empty, neglect
Value gds_dir <pathname>	Only for reference
value donut <name>	the donut underlying this memory
*(object type=memory name=<name> Temperature=60 Vdd=1.1 <configurationparameters>=<…>	All modes and configuration parameters are attributes to the memoryobject
Value dotlib_dir <pathname>	This directory on itself contains 6 subdirectories named invariable, matched, local_systematic, c2c, w2w and b2b. The files therein are the libraries, one single file per directory.
Parameter instantiation Parameter defunct (0 or 1) Parameter outlier (0 or 1)]	Instantiation is the name of an instance in the EMC population of cells. Used to retrieve a certain instantiation from the .lib.
[*(Parameter *corrid_###*)]	See the "corrid_###" concept.
Parameter <*>	.

16.6. Top level components hierarchy

System yield analysis works with top level components. In the most trivial case there is only one single toplevel component. In the more elaborate case, there may be a hierarchy of toplevel components, which is represented as containers of toplevel components.
Toplevel component names correspond with their RTL name and with the names in backannotated netlist container.

Container type=toplevel_components Value rtl_path <string>	
Value component <component_name1> Value component <component_name2> container toplevel_component Value component <component_name3> Value component <component_name4>	

Do not confuse this container with the following! The top level description may contain multiple instances of the same component.

16.7. Backannotated netlists of components

System component library, i.e. all cells that are use in yield analysis. Each of the cells is described by VHDL or Verilog, and [may be] backannotated using .SPEF and .SDC file

Custom cells (used in Macro's) and Standard cells do not belong here.

Container type=netlist name=…	
Vdd=… Temperature=…	Attributes . The temperature/supply set for which this library is evaluated. There may thus be multiple instances if this container.
Value root <root directory> Value spef_dir <path> Value sdc_dir <path> Value verilog_dir Value vhdl_dir Value sdf_dir Value vcd_dir	If empty, neglect Is absent, one neglects backannotation If not given, one uses a default [tbd if VAMIF must provide a default] At least one per cell is needed Optional. Coding of populations of components xxxx_v1 etc. if needed.,. maybe sfd s are not recorded
Container type=components	This information allows EMC sampling components For each component there is 1 entry.
Object Type=component name=<componentname> Parameter longestdelay Parameter staticpower Parameter dynamicenergy Parameter instantiation Parameter defunct (0 or 1) Parameter outlier (0 or 1)	Instantiation is the name of an instance in the EMC population of components. The longest delay for the actually used set of vectors. Not exactly the same as critical path delay.

The effect of output load on delay and dynamic power is accounted for by the fact that output interconnect C is lumped into the component itself.

16.8. Variability aware yield prediction

The variability aware yield prediction tool consumes information from the digital chapter and produces results written into the system chapter.

The input is represented by three main parts:
1) The description of system

- the [possibly hierarchical] list of top level components, implying also the connectivity, which is by default assumed to correspond to a parallel organization.

2) The PTOIR versus (dynamic energy, static power, max delay) in EMC format, for each component
   - the component variabilities, from the backannotated netlist
3) The activity of each block (at this moment it's only one number - derived from previous (logic?) simulation - representing the number of activations of the block per unit of time; it's application dependent); future extensions assumes the bit level vector trace (vector of bits) representation [see `activity`]
4) The timing and energy constraints enabling yield calculation

The output is
1) Multi-dimensional representation of (parametric including functional) variability cloud the user parameter space (clock frequency, power, <other parameters as T, VDD…>)
2) This will happen for each geometry separately, and for all geometries aggregated.

Converting to iso-yield curves is done in a rendering tool such as the "VAMIF-browser" (browse). If the rendering tool can do the aggregation itself, no separate parameter is required.

`object` `type=systemyield`	
`Vdd=1.8` `Temperature=21` `Age=82000000`	Attributes, multiple instances of the same object may exist
`Value <other> <some value>` `Parameter totalpower` `Parameter cycletime` `Parameter aggregated_totalpower` `Parameter aggregated_cycletime`	All are aggregated in geometry "all (matched)

16.9. Example of a configuration container

See the MemoryVAM configuration container

17. Specific fast models for Top-Down

The following models are specific for the so-called “Quick&Dirty” VAM. They contain the reduced set representation of libraries and other objects.
At yield estimation level and at compact model abstraction level, one assumes that the scripts are already fast and do not need a Q&D version.

17.1. Q&D standard cell representation

Applies to the “average” Stdcell, or on each individual (if specific name is given TBD).
This information is either extracted as an average form .lib, or synthesized separately and eventually brought back into a .lib by scaling.

Object Type=qd_standardcell	
[Value cellname <name>] Value nominalload Value inputslope Parameter nominaldelay[18] Parameter zeroloaddelay Parameter nominalenergy Parameter zeroloadenergy Parameter staticpower	Nominalload [F] = load capacitor for which nominal delay and energy are obtained. This q&d model assumes that any other load condition is linearly interpolated Inputslope [V/s] = assumed worst case input slope [default zero]

17.2. Q&D area

In some applications of VAM, it is necessary to have an estimation of the area of a circuit part (standard cell, digital block):

- To estimate the functional yield, using the manufacturing yield object
- To estimate the average distance between circuit part inside, to assess the interpolation of variability between matched and c2c geometries, using correlation length and correlation exponent.

[18] nominaldelay: the maximum delay for any input to any output, where all input see the given inputslope, and all outputs are loaded nominally, eg. the max in the .lib table. zeroloaddelay: the maximum delay for any input to any output, for zero load. Energy: dynamic energy, per operation; staticpower: DC [leakage] power.

Container type=qd_area	
Value mosfet_over_node_factor	how much area does a MOSFET (in a stdcell) take on average compared to node number [e.g.22nm] squared
Value stdcell_routing_efficiency	Ratio between actual routed stdcell density and minimum packed stdcells
Value stdcell_over_mosfet	

17.3. Ion ioff

Elementary MOSFET parameters for quick and dirty analog/digital behavior

Container Type=Qd_ion_ioff Name=<Mosfettype> Ion (for a minimum MOSFET) Ioff (for a minimum MOSFET) Cgate (for a minimum MOSFET)	

17.4. Critical path distribution

Part of chapter digital.

This feature is not used in a full VAM flow, as the detail of each path is known as such and is thus not a variability “parameter”. This parameter is of use in early, fast, empirical path-finding.
[critical] path length is expressed in units of execution time, without further correlations added. [If this distribution is part of a larger set which contains also parameters as VDD and T, we have inherited automatically that correlation.]

object type=critical_path_distribution parameter critical_path	required

18. References

References appear in text.

Appendix A

The documentation of VAM IF API implemented in JAVA

