DISENTANGLING CROSSCUTTING IN AOSD: FORMALIZATION BASED ON A CROSSCUTTING PATTERN*

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Abstract. Crosscutting is usually described in terms of scattering and tangling. However, the distinction between these concepts is vague, which could lead to ambiguous statements. Sometimes, precise definitions are required, *e.g.*, for the formal identification of crosscutting concerns. We propose a conceptual framework for formalizing these concepts based on a crosscutting pattern that shows the mapping between elements at two levels, *e.g.*, concerns and representations of concerns. The definitions of the concepts are formalized in terms of linear algebra, and visualized with matrices and matrix operations. In this way, crosscutting can be clearly distinguished from scattering and tangling. The usability of dependency matrices is illustrated in the analysis of crosscutting across several refinement levels, which can be formalized through the cascading of the crosscutting pattern.

1. INTRODUCTION

One of the key principles in Aspect-Oriented Software Development (AOSD) is Separation of Concerns (SOC). A concern can be defined very generally as a thing in an engineering process about which it cares [7]. Related with this principle is the problem of crosscutting concerns. Crosscutting is usually described in terms of scattering and tangling, *e.g.*, crosscutting is the scattering and tangling of concerns arising due to poor support for their modularization. However, the distinction between these concepts is vague, sometimes leading to ambiguous statements and confusion, as stated in [11]:

.. the term "crosscutting concerns" is often misused in two ways: To talk about a single concern, and to talk about concerns rather than representations of concerns. Consider "synchronization is a crosscutting concern": we don't know that synchronization is crosscutting unless we know what it crosscuts. And there may be representations of the

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2.2. Concepts based on Crosscutting Pattern

As we can see in Figure 1, there is a mapping from source elements to target elements. Moreover, this mapping from source to target has a multiplicity. In case of 1:many mappings we have scattering, defined as follows: *Scattering occurs when, in a mapping between source and target, a source element is related to multiple target elements.* The correspondence between two given domains, Source and Target, is defined as follows: For element $s \in \text{Source}$, $f(s) = \{t \in \text{Target} / \text{element } t \text{ is related to } s\}$. We can define scattering as: An element $s \in \text{Source}$ is scattered if and only if $\text{card}(f(s)) > 1$, where card is the cardinality.

Similarly, we can focus on the relation between target elements and source elements. This relation (here also called mapping) is the reverse of the mapping above. In case of 1:many mappings from target to source we have tangling, defined as follows: *Tangling occurs when, in a mapping between source and target, a target element is related to multiple source elements.* In other words, an element $t \in \text{Target}$ is tangled if and only if $\text{card}(f^{-1}(t)) > 1$, where f^{-1} is the inverse application.

There is a specific combination of scattering and tangling which we call crosscutting, defined as follows: *Crosscutting occurs when, in a mapping between source and target, a source element is scattered over target elements and where in at least one of these target elements, some other source elements are tangled.* In other words, crosscutting can be defined as follows. For element $s1, s2 \in \text{Source}$, $s1$ crosscuts $s2$ (with $s1$ different from $s2$) if and only if $\text{card}(f(s1)) > 1$ and $\exists t \in f(s1): \text{card}(f^{-1}(t)) > 1$ and $s2 \in f^{-1}(t)$. We do not require that the second source element is scattered. In that sense, our definition is not symmetric as definition in [13] (see Section 6).

3. MATRIX REPRESENTATION

In terms of linear algebra, the relation or mapping between source elements and target elements can be represented in a matrix that we called dependency matrix. *A dependency matrix (source $\times$ target) represents the dependency relation between source elements and target elements (inter-level relationship).* In the rows, we have the source elements, and in the columns, we have the target elements. In this matrix, a cell with 1 denotes that the source element (in the row) is *mapped* to the target element (in the column). Reciprocally this means that the target element *depends* on the source element. Scattering and tangling can easily be visualized in this matrix. In Table 1, we can see an example of dependency matrix where S denotes a scattered source element - a grey row; NS denotes a non-scattered source element; T denotes a tangled target element - a grey column; NT denotes a non-tangled target element.

dependency matrix						
		target				
		t[1]	t[2]	t[3]	t[4]	
source	s[1]	1	1	0	1	S
	s[2]	0	0	1	0	NS
	s[3]	0	0	1	0	NS
		NT	NT	T	NT	

crosscutting matrix				
		source		
		s[1]	s[2]	s[3]
source	s[1]	0	0	0
	s[2]	0	0	0
	s[3]	0	0	0

Table 1. Example dependency and crosscutting matrix with tangling, scattering and no crosscutting

We define a new auxiliary concept *crosscutpoint* used in the context of dependency diagrams, to denote a matrix cell involved in both tangling and scattering. If there are one or more

crosscutpoints then we say we have crosscutting.

Crosscutting between source elements for a given mapping to target elements can be represented in a crosscutting matrix. A *crosscutting matrix* (source x source) represents the crosscutting relation between source elements, for a given source to target mapping (represented in a dependency matrix). In the crosscutting matrix, a cell with 1 denotes that the source element in the row is crosscutting the source element in the column. In Section 3.1 we explain how this crosscutting matrix can be derived from the dependency matrix. In Table 1, we can observe the crosscutting matrix for dependency matrix shown in the same table. In this example, we have one scattered source element s[1] and one tangled target element t[3]. However, t[3] is not involved in the scattering of s[1]. We apply our definition of crosscutting and arrive to the crosscutting matrix. In this case, there is no crosscutting.

Another example mapping is shown in Table 2. Here, we have one scattered source element s[1] and one tangled target element t[3]. Moreover, there is one crosscutpoint at matrix cell [1,3] (dark grey cell). Again applying our definition, we arrive to the crosscutting matrix. Source element s[1] is crosscutting s[3] (because s[1] is scattered over [t[1], t[3], t[4]] and s[3] is in the tangled one of these elements, namely t[3]). The reverse is not true: the crosscutting relation is not symmetric. This illustrates our proposition about crosscutting not being symmetric: s[1] is crosscutting s[3], but s[3] is not crosscutting s[1] because s[3] is not scattered (scattering is a necessary condition for crosscutting).

dependency matrix					
		target			
		t[1]	t[2]	t[3]	t[4]
Source	s[1]	1	0	1	1
	s[2]	0	1	0	0
	s[3]	0	0	1	0
		NT	NT	T	NT
		S	NS	NS	

crosscutting matrix				
		source		
		s[1]	s[2]	s[3]
source	s[1]	0	0	1
	s[2]	0	0	0
	s[3]	0	0	0

Table 2. Example dependency and crosscutting matrix with tangling, scattering and one crosscutting

3.1. Constructing crosscutting matrices

We now describe how to derive the crosscutting matrix from the dependency matrix. We use the example detailed in Table 2 of Section 3 to show the construction of crosscutting matrix. Based on the dependency matrix, we define some auxiliary matrices: the *scattering matrix* (source x target), and the *tangling matrix* (target x source). For our example in Table 2, these matrices are shown in Table 3.

scattering matrix					
		target			
		t[1]	t[2]	t[3]	t[4]
Source	s[1]	1	0	1	1
	s[2]	0	0	0	0
	s[3]	0	0	0	0

tangling matrix				
		source		
		s[1]	s[2]	s[3]
target	t[1]	0	0	0
	t[2]	0	0	0
	t[3]	1	0	1
	t[4]	0	0	0

Table 3. Scattering and tangling matrices for dependency matrix in Table 2

These two matrices are defined as follows:

- In the scattering matrix a row contains only dependency relations from source to target elements if the source element in this row is scattered (mapped onto multiple target elements); otherwise the row contains just zero's (no scattering).

- In the tangling matrix a row contains only dependency relations from target to source elements if the target element in this row is tangled (mapped onto multiple source elements); otherwise the row contains just zero's (no tangling).

We now define the crosscutting product matrix, showing the frequency of crosscutting relations. *A crosscutting product matrix (source x source) represents the frequency of crosscutting relations between source elements, for a given source to target mapping.* The crosscutting product matrix is not necessarily symmetric. The *crosscutting product matrix* $ccpm$ can be obtained through the matrix multiplication of the scattering matrix sm and the tangling matrix tm : $ccpm = sm \cdot tm$ where $ccpm[i][k] = sm[i][j] \cdot tm[j][k]$.

In this crosscutting product matrix, the cells denote the frequency of crosscutting. This can be used for quantification of crosscutting (crosscutting metrics). In this example, there are no cells in the crosscutting product matrix larger than 1. A cell on the diagonal which contains 1 denotes a crosscutting relation with itself, which we disregard here. In the crosscutting matrix, we put the diagonal cells to 0. Obviously, this is because we assume that a source element can not crosscut itself.

crosscutting product matrix				
source	source			
		s[1]	s[2]	s[3]
	s[1]	1	0	1
	s[2]	0	0	0
	s[3]	0	0	0

crosscutting matrix				
source	source			
		s[1]	s[2]	s[3]
	s[1]	0	0	1
	s[2]	0	0	0
	s[3]	0	0	0

Table 4. Crosscutting product matrix and crosscutting matrix for dependency matrix in Table 2

In the crosscutting matrix, a matrix cell denotes the occurrence of crosscutting; it abstracts from the frequency of crosscutting. The *crosscutting matrix* ccm can be derived from the crosscutting product matrix $ccpm$ using a simple conversion: $ccm[i][k] = \text{if } (ccpm[i][k] > 0) \wedge (i \neq k) \text{ then } 1 \text{ else } 0$. The crosscutting product matrix and the crosscutting matrix for the example are given in Table 4. For convenience, these formulas can be calculated automatically by means of simple mathematic tools. By filling in the cells of the dependency matrix, the other matrices are calculated automatically.

4. CASCADING OF CROSSCUTTING PATTERNS

Usually we encounter a number of consecutive levels or phases in software development. In MDA [14], we have transformations from Platform Independent Models, Platform Specific Models to Implementation Models. From the perspective of software life cycle phases, we could distinguish Domain Analysis, Concern Modelling, Requirement Analysis, Architectural Design, Detailed Design, and Implementation.

Figure 2. Two Cascaded Crosscutting Patterns

We consider here the cascading of two crosscutting patterns: the target of the first pattern serves as source for the second one. We call the first target our intermediate level, and the second target just target (Figure 2). Each of these mappings can be described with a dependency matrix. We describe

how to combine two consecutive dependency matrices, in an operation we call cascading. Cascading is an operation on two dependency matrices resulting in a new dependency matrix, which represents the dependency relation between source elements of the first matrix and

target elements of the second matrix.

For cascading, it is essential to define the transitivity of dependency relations. Transitivity is defined as follows. Assume we have a source, an intermediate, and a target level. There is a dependency relation between an element in the source and an element in the target if there is some element at the intermediate level that has a dependence relation with this source element and a dependency relation with this target element. In other words, the transitivity dependency relation R for source s , intermediate level u and target t , and $\text{card}(u)$ is the number of elements in u : $\exists k \in (1..u): (s[i] R u[k]) \wedge (u[k] R t[m]) \Rightarrow (s[i] R t[m])$

Cascading may also be generalized to n -levels through function composition [5].

As an example, we explain the cascading of two dependency matrices: one for concerns $\times$ requirements and one for requirements $\times$ modules. The two dependency matrices are shown in Table 5.

dependency matrix 1					dependency matrix 2					
concern	requirement				requirement	module				
	r[1]	r[2]	r[3]	r[4]		m[1]	m[2]	m[3]	m[4]	m[5]
c[1]	1	0	0	1	r[1]	1	0	0	0	1
c[2]	0	1	0	0	r[2]	0	1	0	0	0
c[3]	0	0	1	1	r[3]	0	1	1	0	0
					r[4]	0	0	0	1	1

Table 5. Dependency matrices of two cascaded patterns

The first dependency matrix relates concerns with requirements. The second dependency matrix relates requirements with modules. The resulting dependency matrix relates concerns with modules (see Table 6). This matrix can be used to derive the crosscutting matrix for concern $\times$ concern with respect to modules.

resulting dependency matrix						crosscutting matrix			
concern	module					concern	concern		
	m[1]	m[2]	m[3]	m[4]	m[5]		c[1]	c[2]	c[3]
c[1]	1	0	0	1	2	c[1]	0	0	1
c[2]	0	1	0	0	0	c[2]	0	0	0
c[3]	0	1	1	1	1	c[3]	1	1	0

Table 6. The resulting dependency matrix and crosscutting matrix based on cascading of the matrices in Table 5

From this description, it is clear that cascading can be used for *traceability* analysis across multiple levels, e.g. from concerns to implementation elements, via requirements, architecture and design (c.f.[5]).

5. CASE STUDY

In this section, we show the application of our approach in a case study. This case has been used for some workshops, e.g. [8]. The case study implements a Conference Review System (CRS) [6]. For space reasons, we have used a simplification of this system. The general purpose of the system is to assist a conference's program committee to perform the review of papers and registration of participants of such conference.

There are four different user types in the system: PcChair, PcMembers, Authors and Participants. A PcChair is the main responsible of the review process. He has access to every paper and every review in the system. A PcMember takes over the reviews of the papers. A PcMember can see information of the papers but not reviews by other PcMembers. An Author

can submit papers to the system. An Author can see only information about his own submission. A Participant must register in order to attend the conference. The register process is completely separated from the login process. However, once a user has registered he will need log whenever he accesses the system. This login process checks the role of the user in the system. The use case model of the conference review system is shown in Figure 3. The complete requirements' analysis can be seen in [6].

Figure 3. Use case model of the Conference Review System

performed, from coarse to fine grain. Here, we take the elements in the use case model (each package) shown in Figure 3 and the set of actors which take part in system as decomposition of requirements (coarse grain).

(a) dependency matrix (concerns x requirements)		Requirements							
concerns		Register Process	Info Papers	Load Papers	Review Process	Conf. Manag.	Login & Roles	Actors	
	PS	0	0	1	0	0	0	0	NS
	PQ	0	1	0	0	0	0	0	NS
	Reg	1	0	0	0	0	0	0	NS
	C	0	0	0	0	1	0	0	NS
	R	0	0	0	1	0	0	0	NS
	IRS	1	1	1	1	1	0	0	S
	L	0	1	1	1	1	1	0	S
	UT	0	0	0	0	0	0	1	NS
		T	T	T	T	T	NT	NT	

(b) crosscutting matrix (concerns x concerns)		concerns							
concerns		PS	PQ	Reg	C	R	IRS	L	UT
	PS	0	0	0	0	0	0	0	0
	PQ	0	0	0	0	0	0	0	0
	Reg	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0
	R	0	0	0	0	0	0	0	0
	IRS	1	1	1	1	1	0	1	0
	L	1	1	0	1	1	1	0	0
	UT	0	0	0	0	0	0	0	0

Table 7. (a) Dependency matrix concerns x reqs and (b) crosscutting matrix for the Conference Review System

In Table 7a we show the dependency matrix with mappings between concerns and requirements and in Table 7b the crosscutting matrix obtained from the former. Other decompositions of both concerns and requirements would be possible and consequently, the dependency matrix would be different. For example, we could use a finer grain decomposition of requirements such as each use case and each actor, thus increasing the size of tables. Anyway, the approach with a finer grain decomposition would be similar to the coarse grain decomposition shown in Table 7.

As we can see in Table 7b, the Login concern crosscuts every concern where the user must authenticate and system must check the role of such user. Similarly, the Information Retrieval/Supply concern crosscuts the concerns which need an access to the correspondence information to perform their actions.

Once we have identified the crosscutting concerns with respect to the requirements domain,

we can observe how the concerns are related to the design of the system.

Figure 4. Class diagram of Conference Review System

(*infoRegister* and *login*, *passwd* attributes of Participant class). These requirements are tangled in such class with the own functionality of Participant class (User Type).

		classes								
		Paper	Review	Conference	PcChair	PcMember	Author	Participant	Logger	Registry
Requirements	Register Process	0	0	0	0	0	0	1	0	1
	Info Papers	1	0	0	0	0	0	0	0	0
	Load Papers	1	0	0	0	0	0	0	0	0
	Review Process	0	1	0	0	0	0	0	0	0
	Conf. Manag	0	0	1	0	0	0	0	0	0
	Login& Roles	0	0	0	0	0	0	1	1	0
	Actors	0	0	0	1	1	1	1	0	0
		T	NT	NT	NT	NT	NT	T	NT	NT

Table 8. Dependency matrix requirements x design

with respect to the design -there are some additional crosscutting concerns (compared with Table 7b). The Registration concern (Reg) crosscuts the concerns Information Retrieval/Supply (IRS), Login (L) and User Types (UT). Similarly, the concern UT crosscuts the concerns Reg, IRS and L. As we showed in dependency matrix obtained by means of the cascading operation (see Table 9a), these concerns are scattered in several design modules and in at least one of these modules other concern is tangled.

Obviously, this conclusion about crosscutting depends very much on the decomposition at each level and the dependencies between elements at these levels. There are many alternatives, which could aim at avoiding crosscutting by using another modularization (e.g. aspect-oriented techniques such as [3]). Here, we showed how to analyse crosscutting across

We show in Figure 4 a simple UML class diagram representing the static structure of the design.

Now, we take the requirements as represented in the use case model as source elements, and the classes in the class diagram of the design as target elements.

We can build the dependency matrix shown in Table 8 to show the trace dependencies between requirements and design elements. As we can see in Table 8, the trace dependencies between Requirements and classes are direct mappings except for *Register Process* and *Login&Roles* because of information added in the *Participant* class for such register and login purposes respectively

We apply the cascading operation (defined in Section 4) between the dependency matrix concerns x requirements (Table 7a) and the dependency matrix requirements x design (Table 8) to obtain mappings between concerns and design elements. This derived dependency matrix concerns x design is shown in Table 9a. Finally, applying our definition of crosscutting to derived dependency matrix, we obtain the crosscutting matrix shown in Table 9b.

From this matrix we can observe that -

several phases in the software life cycle.

Cascaded dependency matrix										
		classes								
		Paper	Review	Conference	Pc Chair	Pc Member	Author	Participant	Logger	Registry
concerns	PS	1	0	0	0	0	0	0	0	NS
	PQ	1	0	0	0	0	0	0	0	NS
	Reg	0	0	0	0	0	0	1	0	S
	C	0	0	1	0	0	0	0	0	NS
	R	0	1	0	0	0	0	0	0	NS
	IRS	2	1	1	0	0	0	1	0	S
	L	2	1	1	0	0	0	1	1	S
	UT	0	0	0	1	1	1	1	0	S
		T	T	T	NT	NT	NT	T	NT	T

The framework can be applied in concrete areas such as identification of crosscutting concerns in any phase of software life cycle [4] or the definition of crosscutting metrics, e. g. to quantify the intensity of crosscutting. Another interesting application is the cascading of crosscutting patterns, which can be used to model crosscutting relations across several levels, for example from concern modelling, to requirements, architectural design to detailed design and implementation. As such, it provides an approach for traceability analysis [5].

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