FCA modelling for CPS interoperability optimization in Industry 4.0

Dmitry Morozov, Mario Lezoche, Hervé Panetto

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Dmitry Morozov*, Mario Lezoche*, Hervé Panetto*
* Research Center for Automatic Control of Nancy (CRAN),
Université de Lorraine, UMR 7039, Boulevard des Aiguillettes
B.P.70239, 54506 Vandoeuvre-lès-Nancy, France.
e-mail: {dmitrii.morozov, mario.lezoche,
herve.panetto}@univ-lorraine.fr

***Abstract* — Cyber-Physical Systems (CPS) lead to the 4-th Industrial Revolution (Industry 4.0) that will have benefits of high flexibility of production, easy and so more accessible participation of all involved parties of business processes. The Industry 4.0 production paradigm is characterized by autonomous behaviour and intercommunicating properties of its production elements across all levels of manufacturing processes so one of the key concept in this domain will be the semantic interoperability of systems. This goal can benefit of formal methods well known various scientific domains like artificial intelligence, machine learning and algebra. So the current investigation is on the promising approach named Formal Concept Analysis (FCA) to structure the knowledge and to optimize the CPS interoperability.**

Keywords: Formal Concept Analysis, Model, Cyber Physical System, Semantic Interoperability, Interoperability optimization, Industry 4.0

I. INTRODUCTION

The CPS (Cyber-Physical System) is the term that describes a broad range of network connected, multi-disciplinary, physically-aware engineered systems that integrates embedded computing (cyber-) technologies into the physical world (adapted from [1]). Inside this kind of network, each smart component (a sub-system of the CPS) is with sensing, data collection, transmission and actuation capabilities, and vast endpoints in the cloud, offering large amounts of heterogeneous data.

The CPSs are also thought will lead to the 4-th Industrial Revolution (Industry 4.0) that will have benefits of high flexibility of production, easy and so more accessible participation of all involved parties of business processes. Their immersion is based on the developments of computer science and the information and communication technologies. Actually, the Industry 4.0 production paradigm is characterized by autonomous behaviour and intercommunicating properties of its production elements across all levels of manufacturing processes.

In this regard the following research directions, related to the CPS and the Industry 4.0 paradigm, take their important place: optimization of sensor networks organization, handling big datasets, challenges about the information representation and processing. These research domains can benefit from scientific methods well known in artificial intelligence domain, machine learning methods and algebra. Basing our efforts on this motivation we are currently investigating application of a promising approach named Formal Concept Analysis (FCA).

The Proposal addressed in this paper is related to the study of FCA-based patterns for optimizing CPS interoperability in the Industry 4.0. The cooperative manufactory systems involve large number of Information Systems distributed over large, complex networked architecture in relation to physical machines. Such cooperative enterprise information systems (CEIS) have access to a large amount of information and have to interoperate between them and with the machines to achieve their purpose. CEIS architects and developers have to face a hard problem: interoperability. There is a growing demand for integrating such systems tightly with organizational and manufacturing work so that these information systems can be fully, directly and immediately exploited by the intra and inter-enterprise processes [2].

The main prerequisite for achieving the interoperability of information systems (and thus a set of collaborative CPSs, noted by the authors) is to maximize the amount of semantics that can be used and to enact it by making it increasingly explicit [3]. There are different approaches in conceptual modelling and these differences are reflected in the conceptual languages used for the modelling action. Entity-Relationship approaches (E-R) have been widely used and extended. They led to the development of different languages for data modelling [4,5,6]

Object-Oriented Modelling (OOM)) [7] approach addresses the complexity of a problem domain by considering the problem as a set of related, interacting Objects. However, the abstract semantics inherent to these approaches imposes the modeller to make subjective choices between entities, attributes and relationships artefacts for modelling a universe-of-discourse [8]. In order to cope with such heterogeneous modelling patterns, we focus our interest on approaches that enable their normalization to a fine-grained semantic model by fragmenting the represented knowledge into atoms called formal concepts.

II. FORMAL CONCEPT ANALYSIS

A. Basic Definitions

FCA is at its core a mathematical formalism which with time has developed and been extended with many theoretical and applied studies. Starting with a set of objects and a set of attributes FCA finds generalizations of the descriptions for arbitrary subset of objects.

Let G and M be sets, called the set of objects and attributes, respectively, and let I be a relation: $I \subseteq G \times M$.

For g ∈ G, m ∈ M, gIm holds iff the object g has the attribute m. The triple K=(G,M,I) is called a *formal context*. If A ⊆ G, B ⊆ M are arbitrary subsets, then the *Galois connection* is given by the following *derivation operators*:

$$A' = \{m \in M \mid g\,\mathrm{Im}\,\forall g \in A\},$$

$$B' = \{g \in G \mid g\,\mathrm{Im}\,\forall m \in B\}.$$

The pair (A,B), where A ⊆ G, B ⊆ M, A'=B, and B'=A is called *a formal concept of the context* K. A is called the *extent* and B the *intent* of the formal concept (A,B). From the properties of the derivation operators it follows that the conditions A'=B, B'=A can be represented in more simple way A''=A, or equivalently B''=B. This reformulated form signifies that a formal concept is such a pair of sets that either of them is *closed* under derivation operator (·)'.

The concepts, ordered by $(A_1, B_1) \geq (A_2, B_2) \Leftrightarrow A_1 \supseteq A_2$ form a complete lattice, called the *concept lattice* L(G,M,I).

B. Conceptual Scaling

Conceptual Scaling [9] is a technique which enables application of FCA by transformation of non-binary into binary data tables. Informally, this transformation is achieved by introduction of a set of substitute binary attributes. Each value of an initial non-binary attribute is mapped to a unique combination of values of substitute binary attributes, which allows full transition to a binary formal context. However, the number of substitute attributes and their interpretation differs depending on the particular scaling method.

Formally, *scale* for an attribute *m* of an multi-valued context (G,M,W,I) is a context $S_m=(G_m,M_m,I_m)$ where $m(G) \subseteq G_m$. Objects of a scale are called its values, and attributes of a scale – its attributes.

Let (G,M,W,I) be a multivalued context and S_m,m ∈M be the contexts of the scale, then the scaled context is a context (G,N,J) for which:

$$N = \bigcup_{m \in M} M_m$$

$$gJ(m,n) \overset{def}{=} m(g) = w, wI_m n$$

Let us demonstrate two useful scaling methods that we will apply in the remainder of the paper.

1) Nominal scale

Nominal scale of an attribute is a diagonal matrix, which means that each value of an attribute translates into an individual binary attribute of a scaled context. For example, let us consider attribute 'device type' which can take one of the four values: Light Sensor, Localization Sensor, Micro-controller, Light Bulb. The nominal scale of this attribute is depicted in the Table I.

TABLE I.
NOMINAL SCALE CONTEXT FOR THE 'DEVICE TYPE' ATTRIBUTE WHICH TAKES FOUR VALUES. IT TRANSLATES INTO FOUR SEPARATE BINARY ATTRIBUTES IN THE SCALED CONTEXT.

	Light Sensor	Localiz. Sensor	Micro-controller	Light Bulb
Light Sensor	X			
Localiz. Sensor		X		
Micro-controller			X	
Light Bulb				X

2) Interordinal scale

An interordinal scale is defined only for numerical attributes. For each value w_a of an attribute *a* it introduces two corresponding binary attributes $\leq w_a$ and $\geq w_a$ .This allows to encode every interval $[w_1,w_2]$ where $w_1,w_2 \in W(a)$ into a unique combination of values of corresponding binary attributes of the scaled context. As an example let us say that there is an attribute 'Position' which takes one of the values: 2.5, 3, 3.5. Its interordinal scale is given in the Table II.

TABLE II.
INTERORDINAL SCALE CONTEXT FOR THE 'POSITION' ATTRIBUTE WHICH TAKES THREE VALUES. IT TRANSLATES INTO A COMBINATION OF SIX BINARY ATTRIBUTES IN THE SCALED CONTEXT.

	≤ 2.5	≤ 3	≤ 3.5	≥ 2.5	≥ 3	≥ 3.5
2.5	X	X	X	X		
3		X	X	X	X	
3.5			X	X	X	X

III. ASSISTING MODELLING PROCESS OF CYBER-PHYSICAL SYSTEMS

Guided by the perspective proposed in the literature [10] we define our generalized model of CPS as a system of components that can be unambiguously divided onto two groups: a control decision and sensor () part, that will represent cyber layer of the system, and to a physical counter-part, i.e. all actuators that communicate all the actions into real world.

This explicit division between two abstract cyber and physical parts of a system in some sense imposes a limitation on the modelling approach. Nevertheless, as a guiding tool in design process its application does not lead to any restrictions on how the system will be later specified or implemented.

In our modelling approach we understand the division onto physical and cyber layers as a separation between the functional roles of the system components. We consider physical nodes as terminal execution nodes which materialize the behaviour of the system. In contrast sensor and computation nodes from the cyber layer provide data and decisions. The special cases where a cyber-node itself realizes tail end functions can be deduced to the above case by dividing its modelling element into two elements: a physical one which takes over these tail end duties and the cyber one which serves for computations.

Our research sets the goal to investigate combinatorial and statistical properties of concept lattices, in particular those properties which express and reflect the interoperability of systems. Although current paper does not go beyond basic FCA analysis, it proposes an illustrative case study of its application to CPS.

Understanding of a system is a gradual and iterative process, involving many levels of abstractions of the system, varying from a general outlook to focalization on details of specific subsystems. In FCA toolset, which is built around a complete lattice, this issue is naturally

addressed by arising structure of classes which covers all levels of generalization. Readily available lattice diagram helps in visual navigation, implication base outlines the axiomatic of the domain.

Another important subject in the context of CPSs concerns dealing with big scale systems, and situations when a lot of data being produced. Literature on FCA suggests number of techniques addressing this issue: iceberg concept lattices [11], projections of pattern structures [12], and conventionally used feature selection methods.

IV. Case Study: Automatic Smart Light Switch

As a case study for our approach we will take a CPS suggested in the article [13], which implements automatic activation of illumination in a room. This system constitutes a part of a bigger system aimed at improving quality of life for people with disabilities.

A scheme of our application CPS is depicted on Figure 1. Accordingly, the system consists of a controller and two sensors: a localization sensor, detecting the distance from the sensor to the target person, and light sensor measuring the strength of light in the room. A microcontroller connected to the sensors analyses the data transmitted by the sensors and if the pre-programmed constraints are satisfied it takes the decision to turn on the light. These constraints and activation scenarios can differ to adapt to the needs of the user.

Table III lists the elements of the system and their properties. Generally, properties of interest may differ depending on the purpose of analysis. It could be shallow outlook on a design of an envisioned system or a complete database that enables functioning of the running system and contains all its specifications. In the current application our analysis is driven rather by an illustrative motivation therefore the system could seem artificial to a certain degree.

Our example system consists of three cyber components and one physical component. They are all described in terms of the following properties:

- *Component type* – name of the class of devices to which the component belongs
- *Location* specifies the area where the component is situated. We assume that the system is installed in a living room of a house.
- *Position* gives precise coordinates of the location; in our example we limit ourselves with 2-dimensional coordinate system. Let us suppose that the dimensions of the living room are 4×6 m^2 and all the sensors are located just near the centre of the room under the ceiling. Whereas the lighting device is attached in the middle of a lengthwise wall.

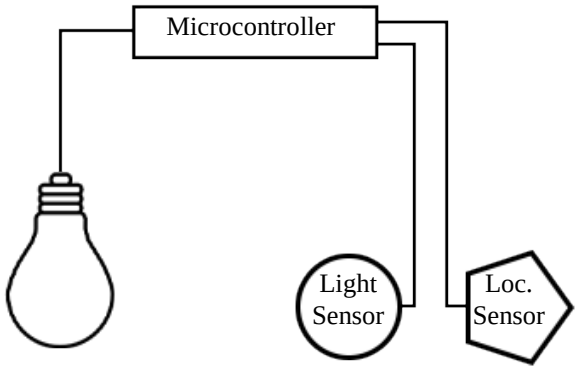

Figure 1. An Automatic Smart Light Switch consisting of four components: A Light Sensor, a Localization Sensor, a Micro-controller and a Light Bulb

- *Maintenance* – is the planned date for the next equipment inspection
- *Cyber* and *Physical* indicates to which abstract class the component belongs.

A. Construction of the formal context

Following the FCA approach we formulate the model in objects-attributes setting. Let G = {g_1, g_2, g_3, g_4} be the set of components of the system, and A – set of attributes. The binary relation I ⊆ G×A specifies for each component the attributes that it possesses.

First, following the procedure described in section II, we transform multivalued Table III into a binary context by applying nominal scaling to all non-numerical attributes, and inter-ordinal scaling to all numerical attributes. Table IV depicts the part of the scaled context that corresponds to *Position* attribute. Rows stand for objects, and columns give the values of new replacing attributes.

Table V shows the part of the scaled context corresponding to the rest of the attributes. Attributes *Light Sen*, *Loc Sen*, *mC*, *bulb* represent scaled *Component Type* attribute. *Room* is nominally scaled *Location* attribute. *Cyber* and *Physical* of the original table migrate without scaling into the new context creating *cyber* and *phys* attributes correspondingly.

For the sake of space, we have omitted the attribute *Maintenance* from the table and also it was excluded from the further analysis. *Position* attribute could have alternatively been translated into a binary attribute via simpler nominal scaling, but that would lead to information loss. Generally, construction of the formal context must be preceded by careful evaluation of the trade-off between expected complexity and desired precision of the model.

TABLE III.
Case Study: Automatic Smart Light Switch Application, Components of the System and Their Properties

	Component Type	Location	Position	Maintenance	Cyber	Physical
g_1	Light Sensor	Living Room	(2, 2.5)	18 Jan 2018	X	
g_2	Localization Sensor	Living Room	(2, 3)	22 Feb 2018	X	
g_3	Microcontroller	Living Room	(2, 3.5)	01 Apr 2019	X	
g_4	Light Bulb	Living Room	(0, 3)	01 Jun 2017		X

TABLE IV.
APPLICATION OF INTERORDINAL SCALING TO 'POSITION' ATTRIBUTE OF THE MULTI-VALUED CONTEXT TABLE III

	x ≤ 0	x ≤ 2	x ≥ 0	x ≥ 2	y ≤ 2.5	y ≤ 3	y ≤ 3.5	y ≥ 2.5	y ≥ 3	y ≥ 3.5
g_1		X	X	X	X	X	X	X		
g_2		X	X	X		X	X	X	X	
g_3		X	X	X			X	X	X	X
g_4	X	X	X			X	X	X		

TABLE V.
SCALED FORMAL CONTEXT OF THE AUTOMATIC LIGHT SWITCH SYSTEM. THE ELLIPSIS STANDS FOR THE PART OF THE TABLE CORRESPONDING TO POSITION ATTRIBUTE, WHICH IS EXPANDED IN THE TABLE IV

	Light Sen	Loc Sen	mC	bulb	room	…	cyber	phys
g_1	X				X	⋮	X	
g_2		X			X	⋮	X	
g_3			X		X	⋮	X	
g_4				X	X	⋮		X

B. *Analysis of formal concepts*

For our analysis we used implementation of FCA methods assembled in the ConExp tool [a]

Figure 2 depicts the diagram of the resulting concept lattice containing 10 formal concepts. Reduced labelling of concepts was used to facilitate reading: only the least general concepts containing objects show their labels in their extent, and only the most general concepts possessing properties show their labels in their extent. To determine the full contents of the extent and intent of a concept it is sufficient to look to the concepts reachable from it and aggregate the labels.

The top concept of the diagram Fig. 2 reports that all components of our CPS are located in *Living Room* (the *room* attribute) and they all dispersed in the rectangular area (0, 2.5) – (2, 3.5). An immediate successor specifies the subclass of cyber layer components, and that all of the cyber components are subjected to an additional constraint related to their position: x ≥ 2. Traversing the lattice further down will reveal the specifics of smaller classes and at the end particular components of the system. The lowest level allows to see what components constitute our system, and what unique properties they have. Accordingly, all of the elements of the system have at least one unique coordinate, except the Localization sensor, which shares *x* and *y* coordinate with some other devices.

From the point of view of system of systems, there could be a perspective to project the formal concepts of a lattice onto the lattice of another similar system. The pairs identified in this way represent twin-classes of components with similar properties. We can use these pairs of similar classes to better understand their differences and to try to standardize system design.

[a] S. Yevtushenko, ConExp, https://sourceforge.net/projects/conexp/

In relation to the branch of FCA that performs reasoning, we constructed an implication base (Duquenne-Guigues base) of the concept lattice. Accordingly, attribute implications of our Automatic Light Switch system satisfy the following base:

{ } → room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5;
Light Sen room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 → x ≥ 2 y ≤ 2.5 y ≤ 3 cyber;
room x ≤ 2 x ≥ 0 y ≤ 2.5 y ≤ 3.5 y ≥ 2.5 → Light Sen x ≥ 2 y ≤ 3 cyber;
room x ≤ 2 x ≥ 0 x ≥ 2 y ≤ 3.5 y ≥ 2.5 → cyber;
mC room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 → x ≥ 2 y ≥ 3 y ≥ 3.5 cyber;
Loc Sen room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 → x ≥ 2 y ≤ 3 y ≥ 3 cyber;
room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 y ≥ 3 → x ≥ 2 cyber;
room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 y ≥ 3.5 → mC x ≥ 2 y ≥ 3 cyber;
room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 cyber → x ≥ 2;
room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 phys → bulb x ≤ 0 y ≤ 3;
room x ≤ 0 x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 → bulb y ≤ 3 phys;
bulb room x ≤ 2 x ≥ 0 y ≤ 3.5 y ≥ 2.5 → x ≤ 0 y ≤ 3 phys;
room x ≤ 2 x ≥ 0 x ≥ 2 y ≤ 3 y ≤ 3.5 y ≥ 2.5 y ≥ 3 cyber → Loc Sen;

V. RELATED STUDIES

In the paper [13] the authors developed a method to model and specify a system's behaviour with the help of event paradigm. The events build their definitions on top of definitions of previously introduced events using constraints in the form of first-order predicates. In this way arises a hierarchy of classes of events. Although the paper keeps very close to the methodology of FCA they also modify existing definitions, adding for example

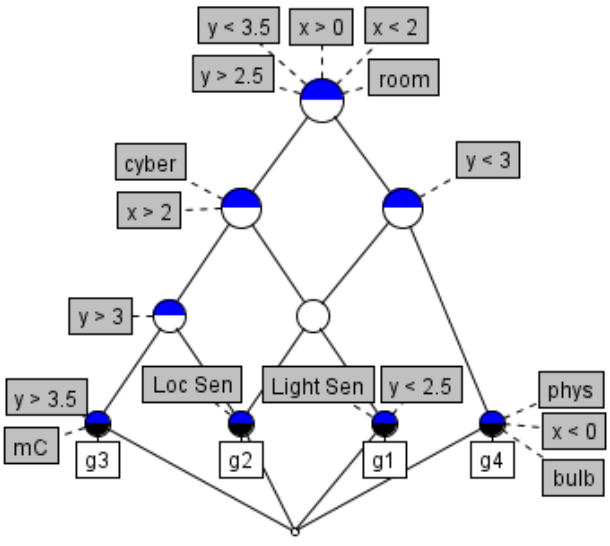

Figure 2. Concept lattice of the scaled context Table V

composition guards to the definition of formal concept, which in its turn prevents from definition of proper derivation operators. Such an approach claimed to provide advantages in system implementation and also in its analysis.

The authors of [14] describe an approach to investigate the architecture of software. The main purpose is to facilitate the process of identification of the components that implement features of software. In the proposed semi-automatic approach, it is required to design scenarios of execution of the program that reveal features to be investigated. Then a profiler tool is used on these scenarios during execution of the source code to identify the components of the program involved into supporting the features of the scenarios. Set of program components called during execution of a scenario is named an execution profile. A context is constituted by these profiles, that is each component has a set of scenarios in which it was called as its description (object intent). In this way resulting concept lattice represents a hierarchy of groups of components, where the upper part of lattice describes specialized components specific to certain features whereas the bottom part of the lattice corresponds to general purpose components utilized in many scenarios. As certain scenarios model number of features, analysis of lattice is done with respect to this correspondence.

There also have been conducted studies investigating use of FCA for RDF annotated datasets [15] [16] provides a case study where RDF descriptions of sensor capabilities are organized and stored into a lattice structure.

VI. Conclusion

Formal Concept Analysis have been applied in many domains as a knowledge representation and discovery tool. Current paper takes a step into adaptation of the approach and its evaluation for the needs of Cyber-physical systems modelling and analysis. We have demonstrated employment of the basics of FCA on a simple example, and outlined the major interest in its application in the interoperability context.

It is worthwhile to note the distinction of modelling control-flow of a system with FCA. Taking into account that FCA is a bottom-up approach in the sense that it starts with particularities of the domain and builds upon them a structure to allow to capture general dependencies. Traditional graphs-based formalisms (such as Petri-nets for Process modelling or Feature model in Software development) on the other hand are conceived specifically for modelling and appear to be more expressive. The research studying relation between FCA and graph modelling methods [17][18] indicates necessity of utilization of additional filtering after lattice is constructed. This basically signifies doubling of the cost of construction of the model.

Further research will aim at answering questions: How relationships between concepts of a lattice can be interpreted in terms of interoperability of the corresponding parts of the system. How can one benefit from establishing links between concepts of the lattices of two or more collaborating cyber-physical systems in terms of improving their interoperability?

References

[1] V. Gunes, S. Peter, T. Givargis, and F. Vahid, "A Survey on Concepts, Applications, and Challenges in Cyber-Physical Systems," *KSII Trans. Internet Inf. Syst.*, vol. 8, no. 12, pp. 4242–4268, 2014.

[2] Izza, S., "Integration of industrial information systems: from syntactic to semantic integration approaches". *Enterprise Information Systems*. 3(1), pp. 1-57, Taylor & Francis, 2009

[3] Obrst, L., "Ontologies for semantically interoperable systems". In *Proceedings of the 12th International Conference on Information and Knowledge Management*. New Orleans, USA, 2003

[4] Barker, R., *CASE* Method: Entity Relationship Modelling*, Addison-Wesley, Wokingham, England, 1990

[5] Czejdo, B., Elmasri, R., Rusinkiewicz, M. & Embley, D.W. 1990, "A graphical data manipulation language for an extended entity-relationship model", *IEEE Computer*, March 1990, pp. 26-37.

[6] Hohenstein, U. and Engels, G., "Formal semantics of an entity-relationship-based query language, Entity-Relationship Approach: the core of conceptual modelling", *Proc. 9th ER conf*., ed. H. Kangassalo, Elsevier Science Pub., Amsterdam, 1991

[7] Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., Lorensen W., *Object Oriented Modeling and Design*. Prentice Hall, Book Distribution Center, New York, USA, 1991

[8] Lezoche M, Panetto H., Aubry A., "Conceptualisation approach for cooperative information systems interoperability", ICEIS 2011. Beijing, China, 2011

[9] Ganter, B. and Wille, R., *Formal Concept Analysis*, Mathematical Foundations. Springer, 1999

[10] Khaitan, S. K., & McCalley, J. D., "Design techniques and applications of cyberphysical systems: A survey", *IEEE Systems Journal*, 9(2), 350-365, 2015

[11] Stumme, G., Taouil, R., Bastide, Y., Pasquier, N., & Lakhal, L., "Computing iceberg concept lattices with TITANIC". *Data & knowledge engineering*, 42(2), 189-222, 2002

[12] Ganter, B., & Kuznetsov, S. O., "Pattern structures and their projections". In International Conference on Conceptual Structures, pp. 129-142, Springer Berlin Heidelberg, 2001

[13] Tan, Y., Vuran, M. C., Goddard, S., Yu, Y., Song, M., & Ren, S, "A concept lattice-based event model for Cyber-Physical Systems". In Proceedings of the 1st ACM/IEEE International Conference on Cyber-physical Systems, pp. 50-60, ACM, 2010

[14] Eisenbarth, T., Koschke, R., & Simon, D., "Locating features in source code", *IEEE Transactions on software engineering*, 29(3), 210-224, 2003

[15] Alam, M., Buzmakov, A., Codocedo, V., & Napoli, A., "Mining definitions from RDF annotations using formal concept analysis". In International Joint Conference in Artificial Intelligence, 2015

[16] Derguech, W., Bhiri, S., Hasan, S., & Curry, E., "Using formal concept analysis for organizing and discovering sensor capabilities". *The Computer Journal*, 58(3), 356-367, 2015

[17] Carbonnel, J., Bertet, K., Huchard, M., & Nebut, C., "FCA for Software Product Lines Representation: Mixing Configuration and Feature Relationships in a Unique Canonical Representation", In *CLA: Concept Lattices and their Applications*, pp. 109-122, CEUR Workshop Proceedings, 2016

[18] Morozov, D., Kuznetsov, S. O., Lezoche, M., & Panetto, H., "Formal methods for process knowledge extraction". In 10ème Colloque sur la Modélisation des Systèmes Réactifs, MSR 2015, 2015