# Ontology-based Model-Driven Patterns for Notification-Oriented Data-Intensive Enterprise Information Systems

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***Abstract*—In the fourth industrial revolution, the current Enterprise Information Systems (EIS) are facing a set of new challenges raised by the applications of Cyber-Physical Systems (CPS) and Internet of Things (IoT). In this scenario, a data-intensive EIS involves networks of physical objects with sensing, data collection, transmission and actuation capabilities, and vast endpoints in the cloud, thereby offering large amounts of data. Such systems can be considered as a multidisciplinary complex system with strong inter-relations between the involved components. In order to cope with the big heterogeneousness of those physical objects and their intrinsic information, the authors propose a notification-based approach derived from the so-called Notification Oriented Paradigm (NOP), a new rule and event driven approach for software and hardware specification and execution. However, the heterogeneity of those information and their interpretation relatively to an evolving context impose the definition of model-driven patterns based on some formal knowledge modelled by a set of skill-based ontologies. Thus, the paper focuses on the open issue related to the formalisation of such ontology-based patterns for their verification, ensuring the coherence of the whole set of data in each contextual engineering domain involved in the EIS.**

## I. INTRODUCTION

Nowadays, governments, organizations, and industries worldwide have noticed the trend of "the fourth industrial revolution" and intended to catch up with this new wave of transformation. Lots of high-level plans and projects are incessantly carried out, such as, the "Industrie 4.0" in Germany [1], the "La Nouvelle France Industrielle" in France [2], the "Future of Manufacturing" in United Kingdom [3], the "Factories of the Future (FoF)" in European Union [4], the "Industrial Internet Consortium (IIC)" [5] and "Advanced Manufacturing Partnership (AMP)" [6] in United States, the "Innovation in Manufacturing 3.0" in South Korea [7], the "Super Smart Society" in Japan [8], the " Research, Innovation and Enterprise (RIE) 2020 Plan" in Singapore [9], and the "Made in China 2025" in China [10]. Because of these governmental driving forces, more and more research centres, companies, and universities have taken part and contributed to this new challenge through either laboratory experiments (such as the Smart Factory OWL [1]), or industrial applications (such as the Digital Enterprise Software Suite[2] by Siemens). Although there exist some different focuses among the above-mentioned plans and projects, this new industrial revolution is commonly recognized as the technical integration of CPS [11] into manufacturing and logistics and the use of IoT [12] in industrial processes [1].

The CPS 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 [13]). 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. Though, there already exists some cloud-based IoT platforms (such as IBM Bluemix[3], Google Cloud Platform[4], and Microsoft Azure [5]) to provide functions like connectivity, storage, analytics and visualization in a secure way and at scale, the critical issue about the transition of the legacy EIS to adopt this change is still remain open.

In particular, the strong inter-relations among the CPS along a product's life cycle increase dramatically the complexity of managing their local coherency and their global interoperability [14]. There is a need to develop some methods, or even paradigms, for formalizing those relationships and ensuring the coherence between CPS data exchange, based on the knowledge coming from the stakeholders employing the data produced jointly by sub-sets of those smart components. In this case, one of the possible solutions is to empower current EIS with a new interoperability infrastructure.

This paper proposes a notification-based approach derived from the so-called Notification Oriented Paradigm (NOP) [15], a new rule and event driven approach for

[1] Smart Factory OWL: http://www.smartfactory-owl.de/index.php/en/

[2] Digital Enterprise Software Suite: https://www.industry.siemens.com/topics/global/en/digital-enterprise-suite/pages/default.aspx

[3] IBM Bluemix: https://console.ng.bluemix.net/

[4] Google Cloud Platform: https://cloud.google.com/

[5] Microsoft Azure: https://azure.microsoft.com/

software and hardware specification and execution, to model every part and aspect of data transfers explicitly, at appropriate level(s) of abstraction, by using a modelling formalism(s). The remaining part of this paper is organized as follows: Section 2 presents the systematic literature review about the influences of IoT and CPS on the current EIS from the interoperability perspective. Based on the discoveries, Section 3 proposes the ontology-based model-driven patterns for the formalization of the data exchange scenario in the next generation EIS. Then, an example involving a network of CPS for ensuring the access security of a building is given to demonstrate the proposed solution is capable of resolving the heterogeneity of data and making explicit their interpretation relatively among EIS. At the end, the conclusion and future works are presented in Section 4.

## II. SYSTEMATIC LITERATURE REVIEW

The main research question that our work intends to address is: *How the legacy EIS are able to face the new requirements in the fourth industrial revolution era?* More specifically, for this particular paper, it is subdivided into the following two sub-research questions: (1) *Q1: What are the new requirements that raised by the CPS and IoT for the legacy EIS?* (2) *Q2: What are the existing research efforts, from the interoperability perspective, that have already been dedicated to the EIS transition?* In order to more neutrally collect and analyse data in an outcome unpredictable situation [16], this paper applied the systematic literature review method [17], [18].

### A. Literature Collection

To collect a comprehensive set of papers that contribute to the next generation EIS through CPS and IoT, two search strings were created. The first search string was constructed by combining the operator "or" between "Cyber Physical Systems", "CPS", "Internet of Things", and "IoT". The second search string was constructed by combining the operator "or" between "Enterprise Information Systems" and "EIS". Finally, these two search strings are joined together through the operator "and" for the systematic search in the largest abstract and citation database, *Scopus*.

Meanwhile, all the collected papers should also satisfy the following three conditions:

- They contain at least one term in each search string (both its singular form and plural form) in the paper titles, abstracts, or keywords;
- They were published in conference proceedings, book series, or journals;
- They were written in the English language.

### B. Inclusion and Exclusion

To ensure that all the collected papers could be more objectively assessed, six inclusion and exclusion criteria were proposed (see Table 1). After removing duplicates, the following two processes were performed.

First, based on the defined criteria, the initial review process was carried out to briefly review the paragraphs where the search terms (e.g. CPS, IoT, EIS) appeared. Besides those papers without full-text to be accessed (*WF* in Table 1), this process aims to exclude those that (1) are not academic (*NA* in Table 1), (2) had only their titles, abstracts, and keywords in English (*SER* in Table 1), and (3) are not related to the CPS, IoT and EIS research (*NR-1* and *NR-2* in Table 1).

After that, all the eligible papers were studied in detail and then organized into the corresponding inclusion categories (*PR* and *CR* in Table 1). The corresponding data of interests were collected during this process: (1) For *Q1*, they are the *new EIS requirements* that each included paper

TABLE I.
INCLUSION AND EXCLUSION CRITERIA

| I/E | Criteria | Criterion Explanations |
|---|---|---|
| Exclusion | Without Full-text (**WF**) | We do not have access to its full text. |
| | Search Engine Reason (**SER**) | It has only its title, abstract, and keywords in English but not its full-text. |
| | Non-Academic (**NA**) | It is not an academic paper, for example, conference review. |
| | Not Related (**NR**) | It is not focusing on the research related to CPS, IoT and EIS.<br>**NR-1**: The definition of CPS, IoT, or EIS is out of our research context. (e.g. EIS is used as the abbreviation of Electrochemical Impedance Spectra)<br>**NR-2**: CPS, IoT, or EIS is only appearing once or twice as a cited expression. |
| Inclusion | Closely Related (**CR**) | It is explicitly and specifically focusing on the review, survey, proposition or application related to interoperability issues within IoT, CPS and EIS context. |
| | Partially Related (**PR**) | Its main focus is not about interoperability issues within IoT, CPS and EIS context, only part of its contents is related. |

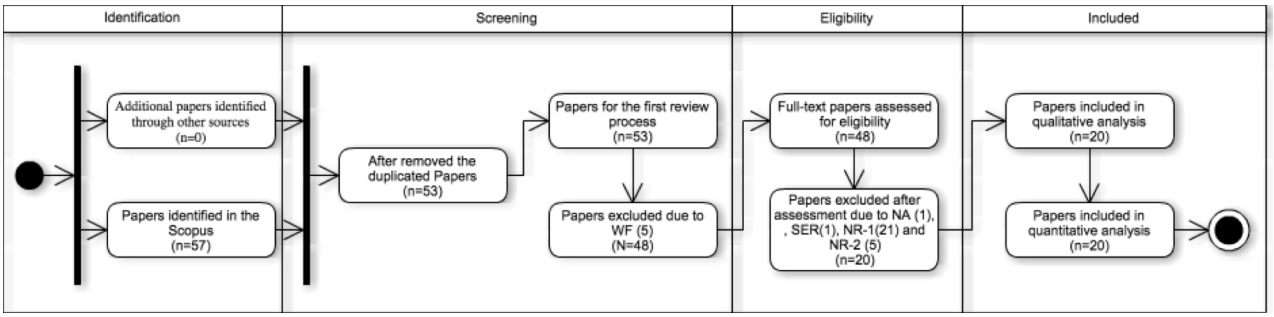


Figure 1. The UML activity diagram of the systematic literature review phases based on the PRISMA flow chart.

discovered or tried to address; (2) For *Q2*, they are the *research problems* related to interoperability and the *proposed solutions* in each *CR* paper.

### C. Qualitative and Quantitative Analysis

As can be seen from Fig.1, through the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) Statement flow chart [19], different phases of this systematic literature review are illustrated. In total, 20 papers out of 57 initial ones were included.

#### 1) New Requirements for Future EIS

During this phase, the qualitative and quantitative analysis of the collected *new EIS requirements* for *Q1* were performed.

Firstly, seven main categories of requirements for the future EIS were summarized from [20], [21]:

- *Omnipresence*: The implementation or existence of EIS on a wide range of computing and other platforms (e.g. tablets, smart phones, smart watches) through cloud technology.
- *Openness*: The technological and legal accessibility of software entities, artefacts and distributed collaborative process based on knowledge sharing between peers.
- *Cyber Security and Privacy*: The ability to ensure and protect the data that they exchange, store and use against the misuse and unauthorized accesses.
- *Self and Environmental Awareness*: The ability to gather and organize phenomenon or events within itself or from its environments in real-time (e.g. through sensors of other devices)
- *Semantic Awareness*: The ability to assign a meaning to the observation (e.g. sensor data) and align them with higher level semantic constructs (e.g. through ontologies).
- *Dynamic Re*-configurability: The ability to function in a different manner, to perform the same function, or accomplish a different set of functions, using the same or improved set of resources
- *Computational Flexibility*: The ability to perform fuzzy reasoning depending on incomplete data, information, and knowledge available for various contexts.

Then, based on these categories, the collected *new EIS requirements* that each included paper discovered or tried to address were qualitatively classified into their corresponding categories. At the end, as can be seen from Fig. 2, the numbers and percentage of papers that involved in each requirement categories are quantitatively listed.

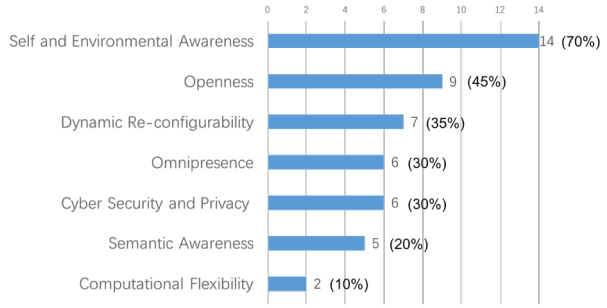


Figure 2. The number and percentage of papers involved in each new requirement category for the future EIS.

It can be found that, 70.0% of the included papers (14 papers) were mentioning or addressing the requirements within the *Self and Environmental Awareness* category. In this case, the future EIS should, first of all, be able to accept, process and perform various functions based on big amount of heterogeneous lower level sensory data from distributed or co-located devices [20]. The heterogeneity of those data and their interpretation relatively to an evolving context, namely the interoperability issues related to the networked smart CPS components and the future EIS, is becoming the primary subject to deal with.

#### 2) Current Research Efforts about Interoperability for Future EIS

Nowadays, the envisaged paradigms, such as CPS and IoT, are gradually becoming a reality. More and more identifiable resources with communication and computing capability, like sensors, mobile devices and RFID tags, are introduced and integrated into the manufacturing field. On one hand they will significantly contribute to different phases along a product's life cycle. On the other hand, they are also dramatically increasing the complexity for the traditional EIS to manage their local coherency and their global interoperability, which turns out to be incomplete and insufficient in attempting to address this issue. To empower those legacy EIS with a new interoperability infrastructure is one of the possible solutions.

Among all the included papers, 40.0% of them (8 papers) are explicitly and specifically focusing on addressing the interoperability issues within the IoT, CPS, and EIS context. More specifically, their main *research problems* and corresponding *proposed solutions* collected for *Q2* are illustrated in Table 2. It can be found that, certain research efforts have been made, such as reviewing some existing

TABLE II.
RESEARCH PROBLEMS AND PROPOSED SOLUTIONS ABOUT INTEROPERABILITY FOR FUTURE EIS

| Papers | Research Problems | Proposed Solutions |
|---|---|---|
| [23] | The application of RFID to the real-life manufacturing enterprises | An agent-based smart objects management system |
| [22] | The role of information architecture to address evolving supply chain needs | A review of the information architecture for supply chain quality management |
| [24] | The lack of standardized approach to support IoT solution in enterprise | A context-awareness and product lifecycle information management |
| [21] | Legacy consideration of the interoperability fail to meet the future IoT challenges | Interoperability as a Property (IaaP) of every ubiquitous system |
| [25] | Dynamic systems, evolved information models, and "liquid" semantic domains | A mediator system to enable self-sustainable interoperability |
| [26] | Few approaches combine efficiently modelling and simulation and real execution in the workflow | Use web services and work-flow for interoperability between simulation and real-world application |
| [20] | The necessitate to identify new requirements that address both theoretical and practical aspects of the EIS | New perspectives for the future interoperable enterprise systems |
| [14] | The extended view of EIS in the IoT introduces additional complexity to the interoperability problems. | The formal definition of the systems' interoperability capability |

concepts and technologies [22], addressing some domain specific issues [23]–[26], and proposing new properties, perspectives, and capabilities of interoperability [14], [20], [21]. However, there is still a lack of unifying theories, systematic design methods, techniques or tools to formally model the relationships and ensure the coherence of data exchanges among the heterogeneous CPS for such data-intensive EIS.

## III. PROPOSITION

In IoT era, on one hand, engineers and engineering organizations no longer have to be restricted to the availability of advanced processing capabilities but can adopt a 'pay as you go' approach which will enable them to access and use software resources for engineering activities from any remote location in the world. On the other hand, such network of systems is also producing and consuming a large amount of data coming from or going to all other systems and their environment. A data-intensive EIS, in such case, is to facilitate acquisition and processing of those data coming from the whole set of Cyber Physical Production Systems (CPPS). Therefore, to model those complex interrelationships and to ensure more coherence data exchange among CPPS, with this work, an modelling formalism(s) extracted from NOP specification [27] is proposed. In which, each data transfer is considered as a kind of notification.

### A. Ontology-based NOP Modelling Primitives

The essence of NOP is based upon the concept of small, smart, and decoupled pieces of entities that collaborate by means of notifications [15], [27], which potentially makes easier to compose distributed systems. As can be seen from Fig. 3, the NOP modelling primitives essentially include the following eight main elements:

- *Fact Base Element (FBE)*: It is a NOP factual element, which represents a system element identified in CPPS. Such as, *an ID card reader*, *a biometric (BIO) reader*, *a gate*, and *a recording system*. It has quite active entities called *Attributes* and quite reactive entities called *Methods*.
- *Attribute:* It is a part of an *FBE*, which keeps one of its variables and can notify (by means of an event) this state to other entities. For example, it can either be the *employee ID* collected from the *ID card reader*, or the *employee BIO data* identified by the *BIO reader*.
- *Method*: It is a part of an *FBE*, which deals with one of its service and can be instigated by other entities. Such as the *open gate service* inside the *gate* FBE and *entry record service* inside the *recording system* FBE.
- *Rule:* It is a NOP logical unit, which represents a set of explicit principles (control rules) within CPPS. It executes the pre-defined *Actions* (e.g. to open the gate and record the numbers of entries) when all its *Conditions* (e.g. both the employee ID and the employee BIO data are confirmed) are satisfied
- *Premise*: It is an associated entity of one or more *Conditions*. It contains either one or two *Attributes* for the evaluation of their states. For example, it can be either the employee ID is confirmed (*Premise 1*) or the employee BIO data is confirmed (*Premise 2*).
- *Condition*: It is the decisional part of one *Rule*, which can contain one or more *Premises*. For example, it can

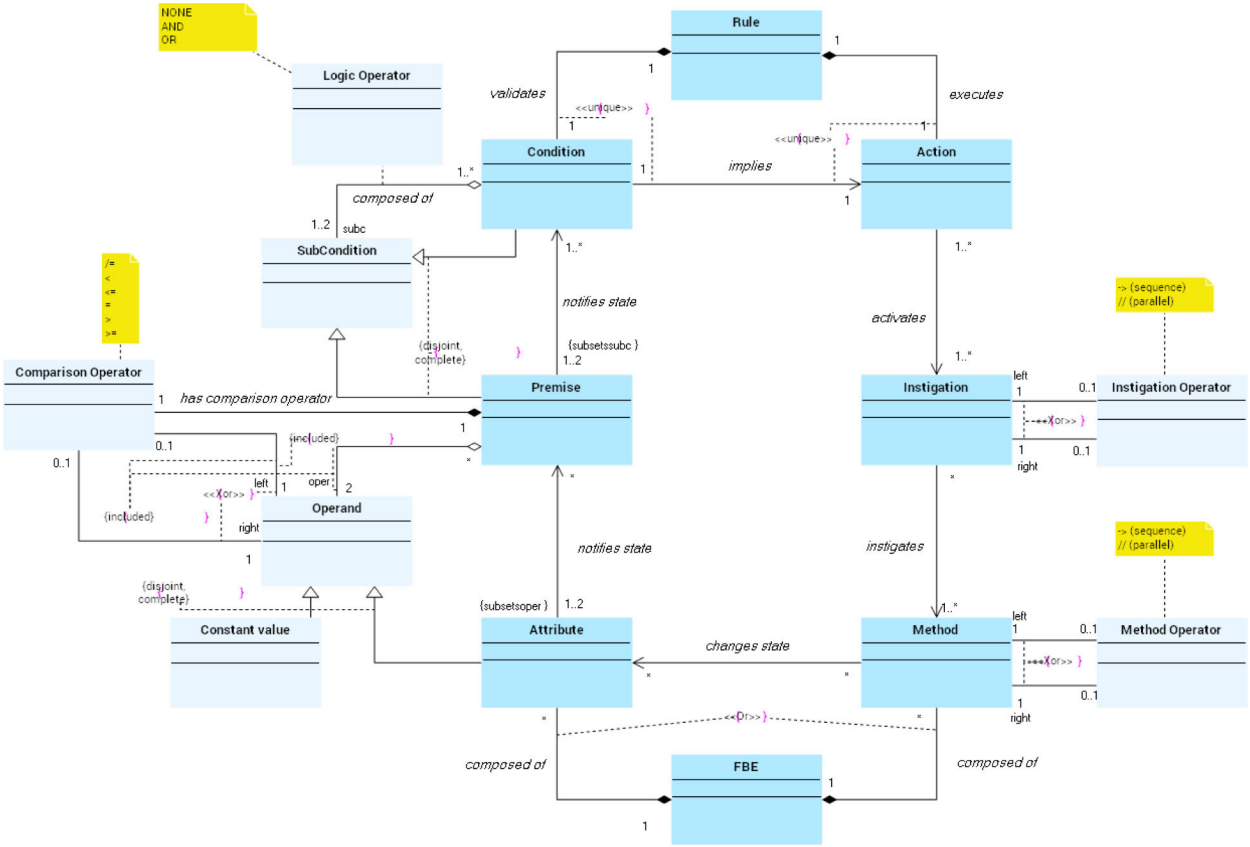


Figure 3. The Meta-Model of the Notification Oriented Paradigm (NOP).

be the combination of the *Premise 1* and the *Premise 2* through the operator AND.

- *Instigation:* It is an associate entity of one or more *Actions* and is also linked to one or more *Methods*. For example, it can be either to instigate the open gate service (*Instigation 1*) or to instigate the entry record service (*Instigation 2*).
- *Action*: It is the execution part of one *Rule*, which can contain one or more *Methods*. It describes the sequential or parallel relation between *Instigations*. For example, the *Instigation 1* and *Instigation 2* can be carried at the same time.

Moreover, in order to enable future EIS with not only the *Self and Environmental Awareness* capability but also the *Semantic Awareness* capability, the NOP modelling primitives were also represented into an ontology through Protégé OWL editor. As can be seen from Fig. 4, the class hierarchy is illustrated. Based on these ontology-based model-driven patterns, the relationships among different system elements and the entire data exchange scenario of CPPS can be formally described.

### B. Notification-Oriented Data-Intensive EIS

In NOP specification, a notification is an explicit advice from a NOP factual element to another one, indicating that a change of a value or a state in the system occurred. In this paper, a notification is considered as the representation of a data transfer from a system or even its element to another one identified in CPPS. Fig.5 shows a notification-oriented data-intensive EIS, in which, the data exchange (1) between cyber and physical world entities, (2) in the Cloud-based IoT Platform, and (3) between EIS and CPPS will be formally described based on the NOP modelling primitives that established in the previous section.

More specifically, for each data transfer in this data exchange scenario, a general view of the adopted modelling procedures is extended from [28] and introduced as follows:

- To analyse a data transfer aiming at:
  1) Identifying the source and target *System Elements* of the data transfer.
  2) Identifying the *Function* of the data transfer.
  3) Identifying the *Variables* of the source *System Elements* that are used during the data transfer.
  4) Identifying the *Procedures* in the target *System Elements* that are instigated during the data transfer.
  5) Identifying the *Pre-conditions* of the *Function* that related to those identified *Variables*.
  6) Identifying the *Post-conditions* of the *Function* that related to those identified *Procedures*.
- To create a *FBE* for every *System Element* (both source and target ones) identified in step 1. It is drawn as a dotted line rectangle. Four examples are given on the both sides of Fig. 6.
- To create a *Rule* for every *Function* identified in step 1. It is drawn as a solid line rectangle. An example is illustrated in the middle of Fig. 6.
- To create an *Attribute* for every *Variable* identified in step 1. It is drawn a cycle connected by an out-coming arrow of a *FBE*. An example is given on the left hand side of Fig. 6.

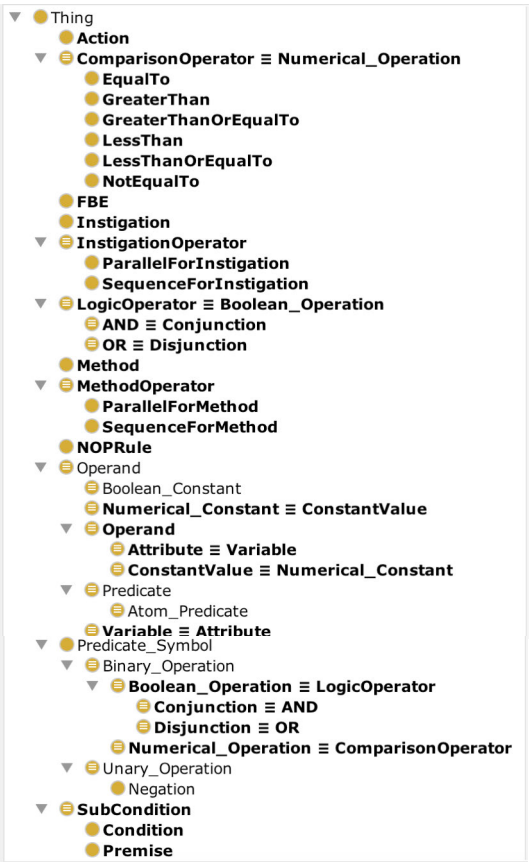


Figure 4. The class hierarchy of the NOP modeling primitives.

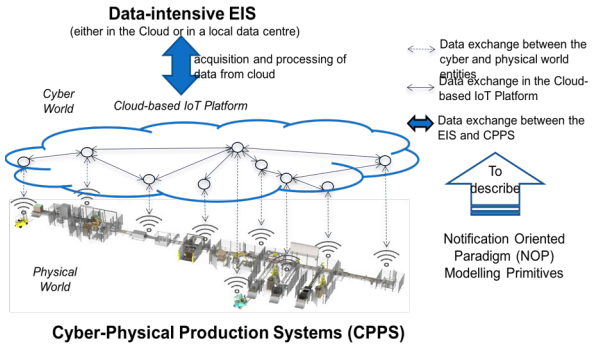


Figure 5. Notification-Oriented Data-Intensive EIS.

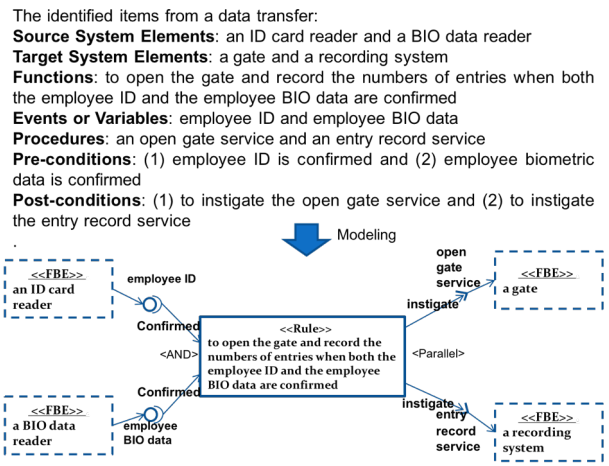


Figure 6. The NOP modeling example of a data transfer.

- To create a *Method* for every *Procedure* identified in step 1. It is drawn as a right angle connected by an in-coming arrow of a *FBE*. An example is given on the right hand side of Fig.6
- To create a *Condition* with corresponding *Premises* for every *Pre-condition* identified in step 1. It is drawn as hollow arcs next to some *Attributes* and connected by in-coming arrows of a *Rule*. An example is given on the left hand side of Fig. 6.
- To create an *Action* with corresponding *Instigations* for every *Post-condition* identified in step 1. It is drawn as arrow coming out from a *Rule* and pointing to a *Method* of a *FBE*. An example is illustrated on the right hand side of Fig. 6.
- Finally, to merge FBEs and Rules with analogous FBEs and Rules previously created.

## IV. CONCLUSION

The main objective of this work is to discover the potential challenges that the legacy EIS face in the fourth industrial revolution, and to propose some potential solutions. Via the systematic literature review, seven main categories of requirements for future EIS were summarized. Based on the qualitative and quantitative analysis, the interoperability issues related to the networked smart CPS components and future EIS turns out to be the primary subject to deal with. Therefore, this paper mainly focuses on empowering current EIS with a new interoperability infrastructure, which can formally model the relations and ensure the coherence of data exchanges among the heterogeneous CPS. To achieve this goal, one solution is to employ a modelling formalism(s) extracted from NOP specification, namely the ontology-based model-driven patterns for notification-oriented data-intensive EIS. The research work in the next stage will focus on collecting the experimental data from a real smart factory laboratory, and applying the proposed modelling patterns to address the big amount of data involved in a data-intensive EIS.

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