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Virtual Engineering Factory: Creating experience base for Industry

4.0

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In recent times traditional manufacturing is upgrading and adopting Industry 4.0, which supports computerization of manufacturing by round the clock connection and communication of engineering objects. Consequently, Decisional DNA based knowledge representation of manufacturing objects, processes and system is achieved by virtual engineering object (VEO), virtual engineering process (VEP) and virtual engineering factory (VEF) respectively. In this paper assimilation of VEO-VEP-VEF concept in the Cyber-physical system based Industry 4.0 is proposed. The planned concept is implemented on a case-study. Also, Decisional DNA features like similarity-identification and phenotyping are explored for validation. It is concluded that this approach can support Industry 4.0 and can facilitate in real-time critical, creative and effective decision making.

Keywords: Cyber-physical system (CPS), Industry 4.0, Decisional DNA, Virtual engineering object (VEO), Virtual engineering process (VEP), Virtual engineering factory (VEF).

Introduction

Unprecedented advancement in the field of information and communication technologies (ICT) has lured manufacturers to utilize its features like managing real-time big data, communication, visualization etc. for enhanced worry free productivity (Posada et al. 2015, Masood et al. 2014).

This idea leads to the emergence of the new concept of Industry 4.0. It is a powerful concept which promotes the computerization of traditional manufacturing plants and their eco-systems towards a connected and 24/7 available resources handling scheme. The goal is an intelligent factory characterized by adaptability, resource efficiency and ergonomics as well as the integration of customers and business partners in business and value processes. Industry 4.0 promotes vision of

smart factories and is based on the technological concepts of Cyber-Physical Systems (CPS) and Internet of Things (IoT)(Hermann, Pentek, and Otto 2015, Böhler 2012). CPSs refer to the next generation of engineering systems that require tight integration of computing, communication and control technologies to achieve stability, performance, reliability, robustness and efficiency in dealing with physical systems of many application domains (Lee 2008, Kyoung-Dae and Kumar 2012).

Knowledge engineering plays an important role in the Cyber-physical systems as there is a need for a unified framework to represent the myriad types of data and application contexts in different physical domains and interpret them under the appropriate context (Lui Sha , Lee and Seshia 2014). The concept of Virtual engineering object (VEO), Virtual engineering process (VEP) and Virtual engineering factory (VEF) is experienced based knowledge representation of engineering objects, processes and factory respectively (Shafiq et al. 2013, Shafiq, Sanin, and Szczerbicki 2014, Shafiq et al. 2014a, b, c, Szczerbicki, Sanin, and Shafiq 2015, Shafiq, Sanin, et al. 2015b, a, Shafiq, Sanin, Toro, et al. 2015). This concept is successfully developed and implemented already (Shafiq et al. (in press), Shafiq, Sanin, et al. 2015a). Also, it is established that VEO/VEP/VEF can be treated as a specialized form of the CPS and consequently can be utilized in designing Industry 4.0 (Shafiq, Sanin, et al. 2015a, Shafiq, Sanin, Toro, et al. 2015).

In this work, the concept of virtual manufacturing having three broad levels of VEO, VEP and VEF is deliberated (Shafiq et al. 2013, Shafiq, Sanin, and Szczerbicki 2014, Shafiq et al. 2014a, b, c, Szczerbicki, Sanin, and Shafiq 2015, Shafiq, Sanin, et al. 2015b, a, Shafiq, Sanin, Toro, et al. 2015). This article also focuses on the relevance of VEO-VEP-VEF concept in the CPS based Industry 4.0 by proposing a

framework for an intelligent factory. Finally, semantic capabilities such as similarity-identification and phenotype are demonstrated in a test case scenario.

The structure of this paper is as follows: section 2 gives an overview and the central idea of the proposed work. Furthermore, it deals with the basic concept, architecture and objectives of VEO, VEP and VEF. Section 3 discusses the role of the proposed concept in the Industry 4.0 scenario. In section 4, a case study is presented to demonstrate implementation of the planned concept and methodology to extract experience and to reuse it for decision making. Finally, section 5 outlines the potential benefits of this work and conclusions are presented.

VEO/VEP/VEF: Creating manufacturing footprints.

The central idea of this work is to replicate the knowledge and experience of the manufacturing factory and to represent it virtually. Figure 1 illustrates that the physical manufacturing scenario can be classified into three levels which are resources, process and factory; a factory performs various processes; a process in turn uses different resources for its manufacturing. Thus for the complete knowledge representation of a manufacturing system it is categorised into three levels; first is the virtual engineering object (VEO), second is the virtual engineering process (VEP) level and third is the virtual engineering factory (VEF) level. Knowledge representation of these levels is developed both at the individual level and in conjunction with each other. In other words, VEO-VEP-VEF is a mechanism to store and reuse experience related with objects, processes and factory working.

Virtual/knowledge representation of engineering objects, processes and system will be beneficial in asset, machine and entire system management respectively. In addition effective decisions can be made based on these intelligent virtual manufacturing levels.

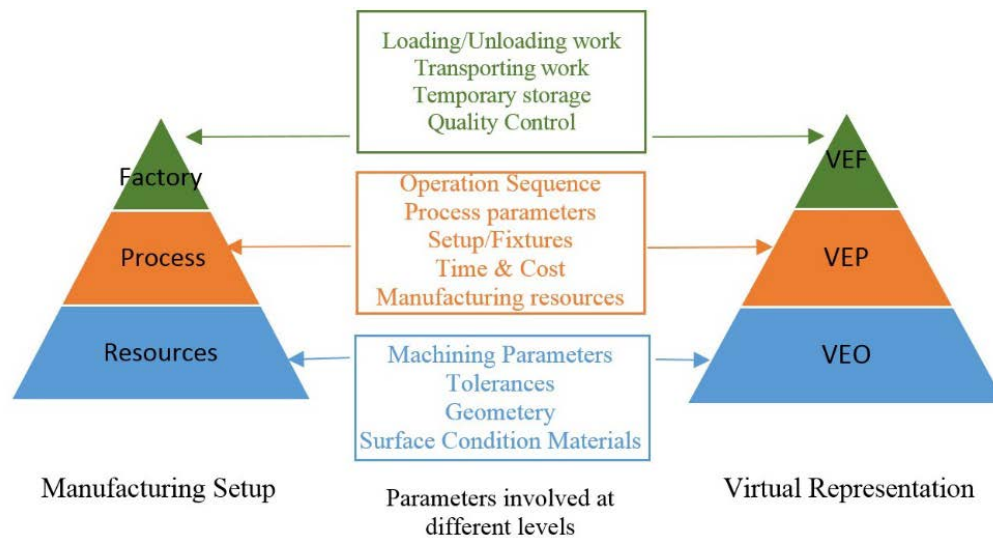


FIGURE 1 Correlation of physical and the virtual world

The three levels of virtual manufacturing are depicted in figure 1. The bottom level is VEO, which is the representation at the individual object/resource/artefact level and is capable of representing all the information at machine level like machining parameters, tolerances, surface conditions etc. The middle level VEP deals with the information at the process or shop floor level like operation sequences, process parameters, time, cost etc. Finally the top level is VEF, it stores the experience/formal decisions related with the various different aspects involved at the system level like material handling, storage quality control, transportation etc.

The powerful knowledge representation technique of Set of experience knowledge structure (SOEKS) and Decisional DNA (DDNA) is used as the technological base for VEO-VEP-VEF. SOEKS-DDNA (Sanin et al. 2012, Sanín et al. 2009, Sanín et al. 2012) is a unique and single structure for capturing, storing, improving and reusing decisional experience. Its name is a metaphor related to human DNA, and the way it transmits genetic information among individuals through time. The Decisional DNA consists of stored experienced decision events (i.e. experiential knowledge) that can be grouped according to areas of decision or categories. In other



words, each SOE (short form for SOEKS) built after a formal decision event can be categorized and acts similarly to a gene in DNA. A gene guides hereditary responses in living organisms, as a SOE directs responses of certain areas of the organization. Furthermore, assembled genes create chromosomes and human DNA, as groups of categorized SOE create decisional chromosomes and Decisional DNA. Thus, the aim of this research is to utilize Decisional DNA to develop manufacturing fingerprint or manufacturing DNA of a factory.

As mentioned above, VEO, VEP and VEF concepts are already developed, implemented and tested. Moreover, it is established that VEO-VEP-VEF has capabilities to enhance performance of not only the traditional manufacturing but also can be significantly important to Industry 4.0 scenario. Before discussing role of VEO-VEP-VEF in Industry 4.0, a brief discussion on these concepts is presented.

A VEO is a knowledge representation of an engineering artefact comprising experience models, domain and functionality along with a physical attachment to the virtual object in its conceptualization. A VEO can encapsulate knowledge and experience of every important feature related with an engineering object. This can be achieved by gathering information from six different aspects of an object viz. (i) Characteristics (ii) Functionality (iii) Requirements (iv) Connections (v) Present State (vi) Experience (Shafiq et al. 2013, Shafiq, Sanin, and Szczerbicki 2014, Shafiq et al. 2014a, b, c, Szczerbicki, Sanin, and Shafiq 2015).

Virtual engineering process (VEP) is a knowledge representation of manufacturing process/process-planning of artefact having all shop floor level information regarding required operations; their sequence and resources needed to manufacture it. To encapsulate knowledge of the above mentioned areas, the VEP is designed having the following three main elements or modules (i) Operations, (ii)



Resources, and (iii) Experience (Shafiq, Sanin, et al. 2015b, a, Shafiq, Sanin, Toro, et al. 2015).

A VEF is a knowledge representation of a manufacturing factory by collection of experience of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts. Different modules from which VEF gathers factory experience are (i) Loading/Unloading (ii) Transportation (iii) Storage (iv) Quality-Control (v) Experience (Shafiq et al. (in press)).

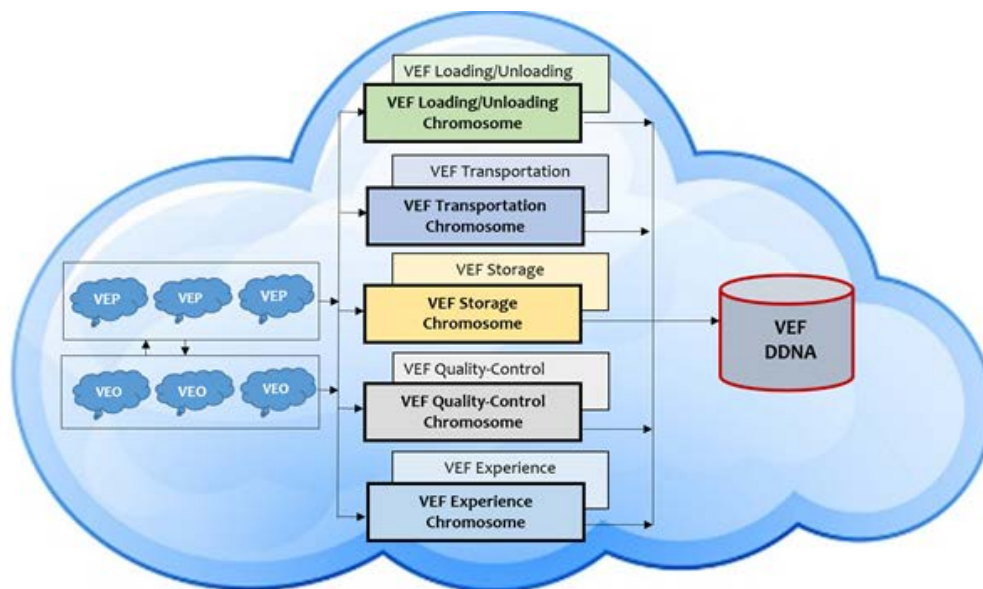


FIGURE 2 VEF Structure intergerating VEP and VEO(Shafiq et al. (in press))

Each factory level experience (i.e. VEF-SOEKS) is associated with a process experience of component (VEP-SOEKS) to be manufactured and that experience of component in turn is linked with objects experience (VEO-SEOKS) for its manufacturing. Based on this idea the architecture of VEF along with mechanism to encompass VEO and VEP within VEF is demonstrated in figure 2. Thus *VEF-DDNA* is created by collecting, connecting and linking VEF, VEP and VEO.

VEO/VEP/VEF relevance in Cyber Physical System based Industry 4.0

Industry 4.0 is combining of intelligent machines, systems, production and processes to form a sophisticated network. It emphasizes the idea of consistent digitization and linking of all productive units in a manufacturing set-up and creating real world virtualization into a huge information system. Industry 4.0 has to be an integration and assimilation of smaller concepts such as the “Cyber-physical systems (CPS)”, “Internet of things (IoT)”, “Internet of services (IoS)”, “smart products” etc (Henning Kagermann 2013). In a broad CPS environment, a large number of models, systems and concepts from an extremely wide range of domains play an important part in shaping that structure (Henning Kagermann 2013, Evans and Annunziata 2012, Lee and Seshia 2014). We propose to add VEO-VEP-VEF to this vision that will facilitate and open new manufacturing solutions and services (see figure 3).

Analysis of Industry 4.0, CPS and VEO-VEP-VEF reveals that there are fundamental similarities amongst these concepts both at philosophical as well as practical level (Shafiq, Sanin, et al. 2015a). These connections are displayed in figure 3. The figure shows that in industrial manufacturing domain CPPS is another specification of CPS at the level of process. CPPS is a collection of CPSs in a similar fashion as VEP is of VEOs.



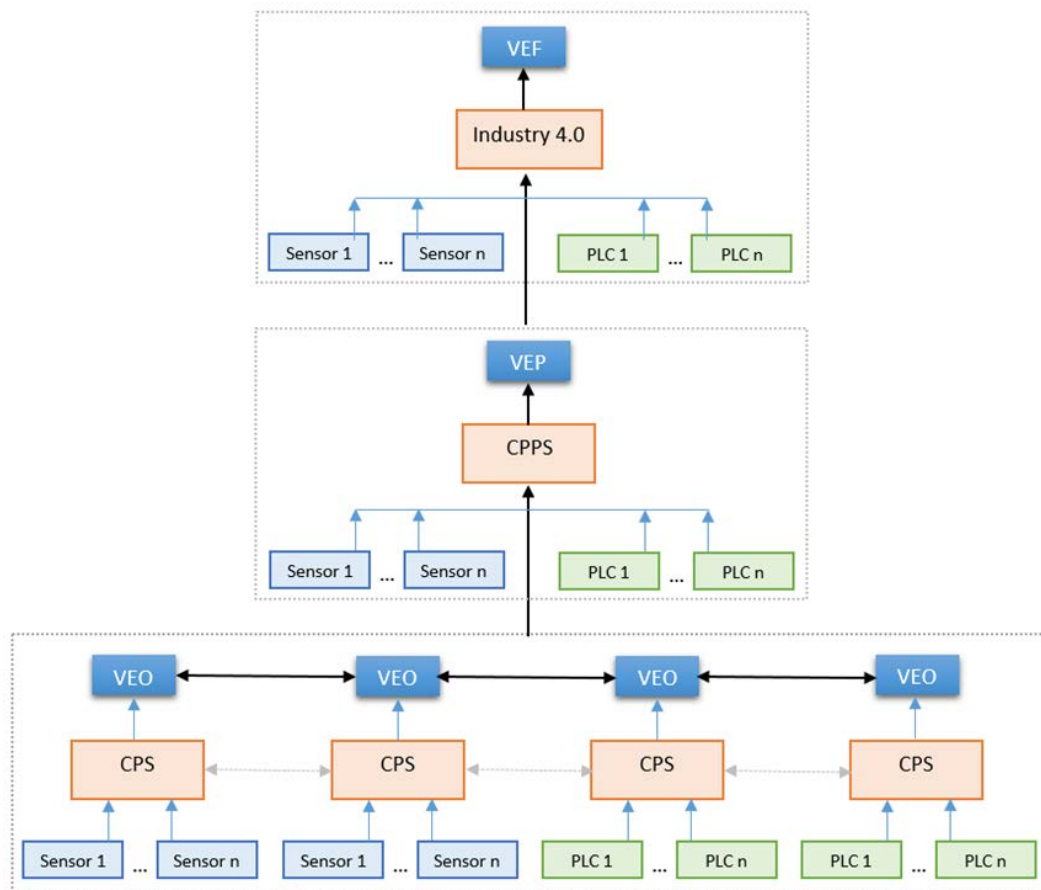


FIGURE 3 VEO-VEP-VEF support to Industry 4.0

The bottom level of figure 3 illustrates that VEO provides a knowledge structure for parts involved in the manufacturing process to possess information on themselves and suitable means of communication and therefore themselves form Cyber-physical systems. The VEO-VEP is to be embedded in the process as a whole and in extreme cases can control not only their own logistical path through production, but rather the entire production workflow that concerns them (see VEP in figure 3). VEO-VEP-VEF supplies compressed information suitably derived from the complex interrelationships and communicates in a personalized manner as the basis for their intervention in the process. In this way, a new form of cooperation between processes, machines and parts of machines arises. This will support both short term flexibility



and medium-term transformability and thus improve the resilience of production to CPS based Industry 4.0.

Benefits of VEO-VEP-VEF enabled Industry 4.0 are manifold, some important features at different manufacturing levels are listed in table 1. One of the most significant attribute of VEO-VEP-VEF is the self-awareness capability it provides at each component, process and system level. The consequence of self-awareness is that it results in better monitoring, prediction and efficient productivity.

TABLE 1 Salient features and benefits of VEO-VEP-VEF

| | VEO-VEP-VEF | |
|----------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| | <i>Attributes</i> | <i>Benefits</i> |
| Object | Self-aware Self-predict Precision Fault detection | Degradation monitoring & remaining useful life prediction |
| Process | Self-aware Self-predict Self-compare Condition-based monitoring & diagnostics | Up time with predictive health monitoring Productivity & performance |
| Factory | Self-configure Self-maintain Self-organize Productivity & OEE | Worry-free productivity Lean operations: work and waste reduction |

Case Study: Develop VEO-VEP-VEF and explore its semantic capabilities

The objectives of this study is to capture real-time data, convert it into SOEKS, develop VEO, VEP and VEF then finally to perform semantic analysis. The challenge is to utilize manufacturers own experience for better decision making and provide real-time intelligent monitoring scheme. A manufacturing unit having two machines (Smart Machine 1 and Smart Machine 2) and producing a variety of components is considered for this case-study. Input variables and output functions for VEF, VEP, and VEO in this case study are presented in the Appendix in tables 4, 5, and 6. Figure 4 exhibits that variables (see VEO Input variables in table 6 in the Appendix) of smart machine 1 and smart machine 2 are captured by the sensors, CPS, PLC etc.

then send to Information processing and semantic analysis (IPSA) centre of the manufacturing unit. At IPSA the information is normalized in the SOEKS formats and then converted into VEO for machines.

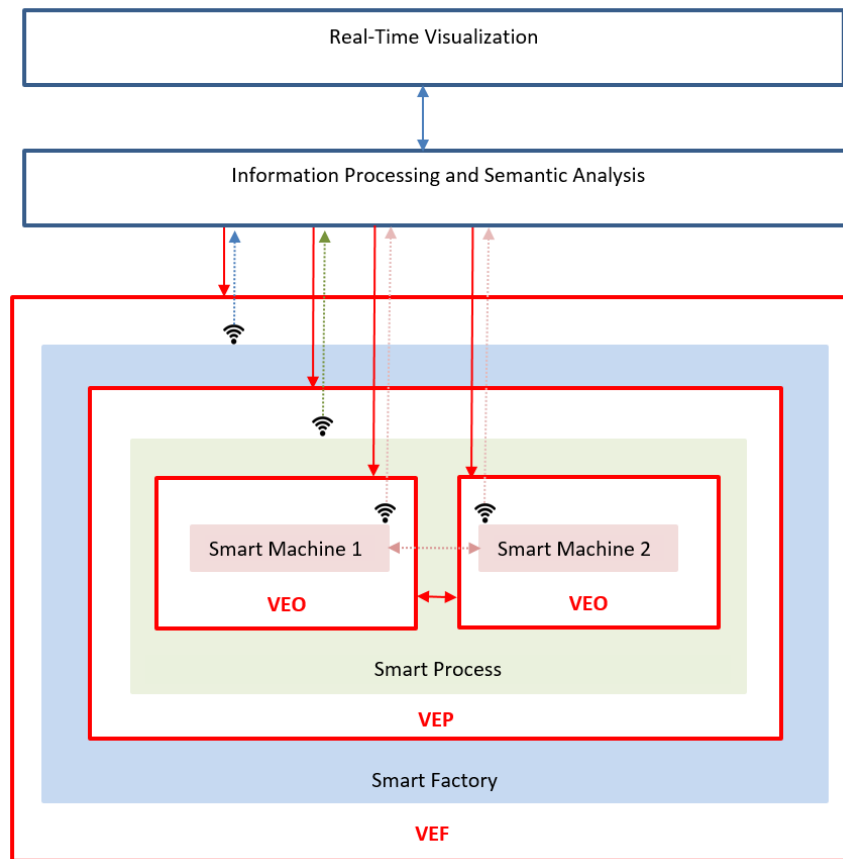


FIGURE 4 Framework for case study

The next level (see Smart Process in figure 4) of this set-up involves the process level information (see VEP Input Variable in table 5 in the Appendix) along with the already developed VEOs at previous level. As shown in figure 4 that a smart process will be capturing process information and transmitting it to IPSA, there it will be transformed into VEP.

The VEF of an intelligent manufacturing unit is the integration of Smart Factory level information (VEF Input Variables in table 4 in the Appendix) along with VEPs and VEOs.

As discussed the captured input variables of VEO, VEP and VEF goes to IPSA where they are converted into SOEKS-variables and also corresponding SOEKS-functions are calculated. For this case-study SOEKS-variables at VEO level are *Depth of Cut, Feed, Speed* etc. and SOEKS-functions is *Tool Life* (see table 6 in the Appendix). Similarly, table 5 and table 6 (in the Appendix) shows SOEKS-variables and SOEKS-functions for VEP and VEO defined and evaluated in IPSA. Thus each row in these tables represents an experience at individual level i.e. VEO_Exp, VEP_Exp and VEF_Exp-.

The other features of the proposed framework are the capabilities to perform semantic analysis like similarity-identification, phenotype calculation etc. and real-time visualization ability at each manufacturing level. In the next subsections semantic capabilities of VEO-VEP VEF are presented.

Similarity Identification calculation

Given a pair of Sets of Experience $vefDNA_i$ (entire VEF repository) and $querySOE_j$ (SOE made up of query) $\in S$, it is possible to generate a similarity metric of the variables called $S_V \in [0,1]$ by calculating the distance measure between each of the pairwise attributes $k \in vefDNA_i$ and $querySOE_j$. The Euclidean distance measure has been selected based upon its simplicity and extended use. Besides, a normalization form was included following the notion of range of comparison, that is, the maximum function. The similarity metric takes the following equation:

$$S_V(vefDNA_i, querySOE_j) = \sum_{k=1}^n w_k \left[\frac{|vefDNA_{ik}^2 - querySOE_{jk}^2|}{\max(|vefDNA_{ik}|, |querySOE_{jk}|)^2} \right]^{0.5} \quad \forall k \in vefDNA_i \wedge querySOE_j \quad (1)$$

$vefDNA_{ik}$, $querySOE_{jk}$ are the k^{th} attribute of the sets $vefDNA_i$ and $querySOE_j$, w_k is the weight given to the k^{th} attribute, in this case, variable; and n is the number of variables on $vefDNA_i$.

Phenotype calculation

The SOEKS structure are several elements connected (variables and functions) among them imitating part of a long strand of DNA, that is, a gene (Sanín 2007). A SOE can be assimilated to a gene, and, in the same way as a gene produces a *phenotype*, a SOE produces a value of a decision in terms of its objective functions. Such a value of a decision is of the kind of multi-objective optimization processes (MOO). This value of decision is what is called the *efficiency* of the SOE. The *efficiency* or *phenotype value* is a combination of the objective functions and the effect values of the variables. The SOEKS, in its functions, holds weight values (w) for each of them. Efficiency estimation is mathematically calculated as:

$$\text{Phenotype of the SOE } E_i = \sum_{j=1}^n w_{Fi} \cdot F_{ij}(V_i) \quad (2)$$

w_{Fi} is the weight associated to function F_{ij} . Variables and phenotypes of the Sets of Experience can be categorized and organized to mine them, as if variables were features and phenotypes were classes. Consequently, interesting results and relationships from the variables and the phenotypes can be extracted, establishing a process of knowledge discovery.

The proposed framework offers users the capability to query VEO-VEP-VEF repository and can find the most similar experience at every level. A query can be formed through a simple graphical user interface (GUI) as shown in figure 5. In the GIU, first the user selects the product to be manufactured (*Product-A*) then clicks

‘ADD Product’ button, then the factory level parameters required for manufacturing *Product-A* populates in the ‘Select Variable’ list-box. Then the user selects a variable and enters the value of that variable in the text-box. Multiple variables can be selected. Then all the selections are combined to build a query by clicking ‘add Query’ button. The query showed in build query text box of figure 5 is:

querySOE = (Product =A, Operating Time = 400, Total Pieces = 15,000, Good Pieces = 1450)

Finally, user clicks ‘run Query’ button and the best SOE which matches the query is returned to the user as shown in solution text-box of figure 5. In the ‘VEF Experience Code’ text-box, the code of the most similar VEF-SOE along with its similarity with the query-SOE is displayed. In the ‘VEP Experience Code’ text-box, the VEP code for the above displayed VEF-SOE is shown and in ‘VEO Experience Code’ text-box code for all the associated VEOs to the above displayed VEP-VEF are shown.

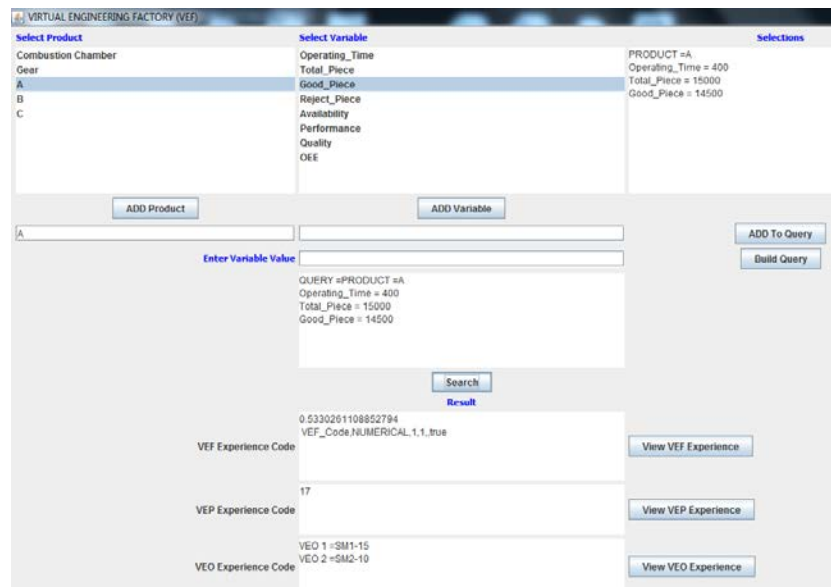


FIGURE 5 GUI for building query and viewing results

Results

In the VEO-VEP-VEF framework linkage of the different levels is from top to bottom i.e. VEF will have linkages of VEP and VEO (see figure 1 and figure 2). Similarly, VEP will have linkage of VEOs whereas VEOs will not have any connections with VEP and VEF. There are two methods of calculating the similarity-identification. First is the actual combined experience that occurred at each level in that manufacturing unit. And the second method is to find most suitable experience individually at each level and then by combining the similarity-identification through Phenotyping create a new virtual experience for the entire factory.

For this case-study the possible query structures, the levels through which it can be executed as well as the structure of solutions are shown in table 2.

Please insert Table 2 here.

Although *Query-1* has variables only of VEF but since VEF is linked with VEP and VEO thus *Result-1* show experience at factory level i.e. VEF_Exp and linked process experience i.e. VEP_Exp and object experience i.e. VEO_Exp. Similarly, structure of *Query-2* and *Query-3* and corresponding structure of *Result-2* and *Result-3* are shown in table 2.

Table 3 illustrates the mechanism to achieve a result with respect to a query.

Please insert Table 3 here.

For the sample test query shown in table 2 there can have three possible cases:

- If VEF is having highest priority, then VEF variables will be queried through *Query-1*. Although only VEF variables are queried result will be VEF_Exp along with corresponding VEP_Exp and VEO_Exp as they are linked from top to bottom. Similarity calculation between *Query-1* and VEF shown in figure 6 suggests that most similar factory experience is VEF_Exp =1 and the linked

process experience is $VEP_Exp = 17$ and object experience is $VEO_Exp = 15$ (see table 3). In this case there is no phenotyping as there is only one experience at each level thus the final result as shown in table 3 is $VEF_Exp = 1$, $VEP_Exp = 17$ and $VEO_Exp = 15$.

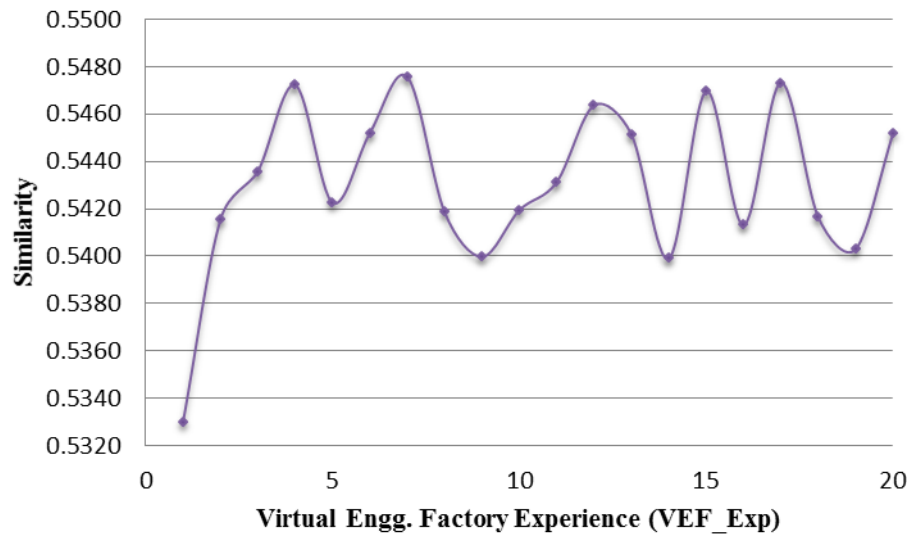


FIGURE 6 Similarity Calculation for Query-1

- If VEP is having highest priority in that case VEF_Exp will be obtained by executing *Query-1*. As mentioned in previous case *Query-1* will not only give VEF_Exp but also corresponding linked VEP_Exp and VEO_Exp (i.e. $VEF_Exp = 1$, $VEP_Exp = 17$, $VEO_Exp = 15$). Since the priority is for VEP, VEP level can also be queried by *Query-2*. Similarity calculation between *Query-2* and VEP shown in figure 7 indicates the most similar process experience is $VEP_Exp' = 11$ and the linked object experience is $VEO_Exp' = 8$. So the possible solutions can be the combination of the results of *Query-1* and *Query-2* (see table 3). Here the Phenotyping feature of Decisional DNA is utilized to achieve the best SOE at each level among the different results obtained from *Query-1* and *Query-2*. So, phenotype calculation can be

obtained between $VEP_Exp=17$, $VEP_Exp' =11$ for VEP and $VEO_Exp =15$, $VEO_Exp' = 8$ for VEO. Thus the final result in this case is $VEF_Exp = 1$, $VEP_Exp = 11$ and $VEO_Exp = 8$.

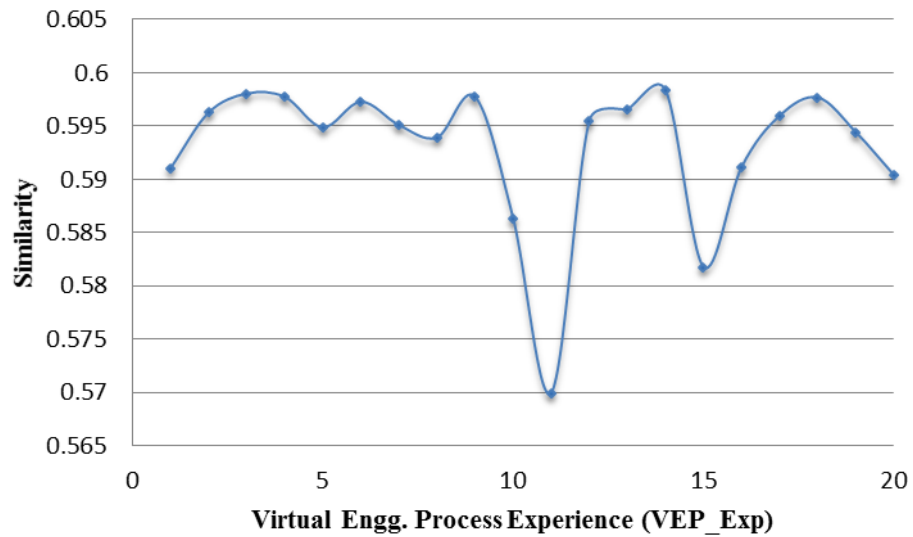


FIGURE 7 Similarity Calculation for Query-2

- If the VEO is having the priority in that case VEF_Exp and VEP_Exp can be achieved as discussed in above. For VEO there can three different SOEs, first two (VEO_Exp and VEO_Exp') can be obtained by executing *Query-1* and *Query-2*. The third SOE (VEO_Exp'') is obtained by executing *Query-3*, in this case phenotyping will be among $VEO_Exp =15$, $VEO_Exp' = 8$ and $VEO_Exp'' = 3$. In this case the VEO has the highest priority thus the final result after phenotype calculation as shown in table 3 is $VEF_Exp = 1$, $VEP_Exp = 17$, $VEO = 3$.



FIGURE 8 Similarity Calculation for Query-3

The benefit of using this approach is that two type of results can be attained. First, the most similar combined experience that occurred at each level of VEF, VEP and VEO can be identified. Secondly, each level of the framework can be treated as independent phase and according to requirement best experience be selected. These independent SOEs are combined together to create a new virtual experience. Thus, providing more options to the practitioners for effective decision making.

Conclusions

This paper throws lights upon basic principle and the role of VEO-VEP-VEF in designing and developing Industry 4.0. It also focuses how the similarity-identification and phenotyping features of DDNA associated with VEO-VEP-VEF can be exploited for creating new virtual experience from its own experience. These semantic analysis features along with visualization capabilities of VEO-VEP-VEF helps in attaining the inherent Industry 4.0 features like self-awareness, real-time monitoring and effective decision making.

TABLE 2 Query and result structure

| Sample Query Structure | Query level | Result Structure | Sample Test Query |
|-------------------------------------------------------|-------------|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Query-1 = (Operating Time, Total Pieces, Good Pieces) | VEO-VEP-VEF | Result-1 = VEF_Exp, VEP_Exp, VEO_Exp | [(Operating Time = 400, Total Pieces = 15,000, Good Pieces = 1450), (Machining Time = 30, Idle Time = 60), (Depth of Cut = 50, Speed = 450, Feed = 1.5)] |
| Query-2 = (Machining Time, Idle Time) | VEP-VEO | Result-2 = VEP_Exp', VEO_Exp' | |
| Query-3 = (Depth of Cut, Speed, Feed) | VEO | Result-3 = VEO_Exp'' | |

TABLE 3 Query execution mechanism

| Priority | Query Type | Possible Results | Phenotyping (~) | Final Result |
|----------|------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|----------------------------------------|
| VEF | Query-1 | VEF_Exp=1, VEP_Exp=17, VEO_Exp=15 | No | VEF_Exp =1, VEP_Exp = 17, VEO_Exp = 15 |
| VEP | Query-1 | VEF_Exp=1, VEP_Exp=17, VEO_Exp=15 | (VEP_Exp=17) ~ (VEP_Exp'=11) | VEF_Exp =1, VEP_Exp =11, VEO_Exp = 8 |
| | Query-2 | VEF_Exp=1, VEP_Exp'=11, VEO_Exp=15 VEF_Exp=1, VEP_Exp=17, VEO_Exp'=8 VEF_Exp=1, VEP_Exp'=11, VEO_Exp'=8 | (VEO_Exp=15) ~ (VEO_Exp'=8) | |
| VEO | Query-1 | VEF_Exp=1, VEP_Exp=17, VEO_Exp=15 | (VEP_Exp=17) ~ (VEP_Exp'=11) | VEF_Exp = 1, VEP_Exp = 17, VEO_Exp = 3 |
| | Query-2 | VEF_Exp=1, VEP_Exp'=11, VEO_Exp=15 | (VEO_Exp=15) ~ (VEO_Exp'=8)~(VEO_Exp''=3) | |
| | Query-3 | VEF_Exp=1, VEP_Exp=17, VEO_Exp'=8 VEF_Exp=1, VEP_Exp'=11, VEO_Exp'=8 VEF_Exp=1, VEP_Exp'=11, VEO_Exp''=3 VEF_Exp=1, VEP_Exp=17, VEO_Exp''=3 | | |



Appendix

TABLE 4 VEF input variables and output functions

| VEF_Exp | VEF Input Variables | | | Output Variables | | | | |
|---------|---------------------|--------------|-------------|------------------|--------------|-------------|---------|--------|
| | Operating Time(min) | Total Pieces | Good Pieces | Reject Pieces | Availability | Performance | Quality | OEE |
| 1 | 296 | 14,751 | 14,492 | 259 | 0.7048 | 0.8306 | 0.9824 | 0.5751 |
| 2 | 449 | 12,785 | 12,517 | 268 | 1.0690 | 0.4746 | 0.9790 | 0.4967 |
| 3 | 352 | 19,071 | 18,703 | 368 | 0.8381 | 0.9030 | 0.9807 | 0.7422 |
| 4 | 240 | 10,865 | 10,389 | 476 | 0.5714 | 0.7545 | 0.9562 | 0.4123 |
| 5 | 434 | 18,555 | 18,109 | 446 | 1.0333 | 0.7126 | 0.9760 | 0.7186 |
| 6 | 467 | 10,623 | 10,267 | 356 | 1.1119 | 0.3791 | 0.9665 | 0.4074 |
| 7 | 159 | 19,820 | 19,624 | 196 | 0.3786 | 2.0776 | 0.9901 | 0.7787 |
| 8 | 472 | 17,186 | 16,711 | 475 | 1.1238 | 0.6069 | 0.9724 | 0.6631 |
| 9 | 418 | 17,478 | 17,089 | 389 | 0.9952 | 0.6969 | 0.9777 | 0.6781 |
| 10 | 385 | 19,583 | 19,457 | 126 | 0.9167 | 0.8477 | 0.9936 | 0.7721 |
| 11 | 430 | 11,149 | 10,940 | 209 | 1.0238 | 0.4321 | 0.9813 | 0.4341 |
| 12 | 256 | 19,565 | 19,362 | 203 | 0.6095 | 1.2738 | 0.9896 | 0.7683 |
| 13 | 270 | 12,152 | 11,698 | 454 | 0.6429 | 0.7501 | 0.9626 | 0.4642 |
| 14 | 375 | 17,013 | 16,633 | 380 | 0.8929 | 0.7561 | 0.9777 | 0.6600 |
| 15 | 226 | 11,272 | 10,773 | 499 | 0.5381 | 0.8313 | 0.9557 | 0.4275 |
| 16 | 261 | 16,016 | 15,767 | 249 | 0.6214 | 1.0227 | 0.9845 | 0.6257 |
| 17 | 278 | 10,135 | 9,744 | 391 | 0.6619 | 0.6076 | 0.9614 | 0.3867 |
| 18 | 482 | 16,781 | 16,625 | 156 | 1.1476 | 0.5803 | 0.9907 | 0.6597 |
| 19 | 473 | 16,272 | 16,055 | 217 | 1.1262 | 0.5734 | 0.9867 | 0.6371 |
| 20 | 312 | 19,421 | 19,148 | 273 | 0.7429 | 1.0374 | 0.9859 | 0.7598 |

TABLE 5 VEP input variables and output functions

| VEP_Exp | VEP Input Variables | | Output Variables | |
|---------|---------------------|----------------|------------------|----------------|
| | Machining Time(min) | Idle Time(min) | Setup Time(min) | Surface Finish |
| 1 | 27 | 29 | 83 | Smooth |
| 2 | 16.3333 | 32.66667 | 49 | Fine |
| 3 | 12.1666 | 24.33333 | 36.5 | Smooth |
| 4 | 13 | 26 | 39 | Rough |
| 5 | 18.6666 | 37.33333 | 56 | Fine |
| 6 | 14.1666 | 28.33333 | 42.5 | Smooth |
| 7 | 18.3333 | 36.66667 | 55 | Rough |
| 8 | 20 | 40 | 60 | Fine |
| 9 | 13 | 26 | 39 | Smooth |
| 10 | 26.3333 | 52.66667 | 79 | Rough |
| 11 | 30.1666 | 60.33333 | 90.5 | Fine |
| 12 | 17.6666 | 35.33333 | 53 | Smooth |

| | | | | |
|----|----------|----------|------|--------|
| 13 | 15.6666 | 31.33333 | 47 | Rough |
| 14 | 11.1666 | 22.33333 | 33.5 | Fine |
| 15 | 32 | 64 | 96 | Smooth |
| 16 | 23 | 46 | 69 | Rough |
| 17 | 16.8333 | 33.66667 | 50.5 | Fine |
| 18 | 13.1666 | 26.33333 | 39.5 | Smooth |
| 19 | 19.3333 | 38.66667 | 58 | Rough |
| 20 | 23.66667 | 47.33333 | 71 | Fine |

TABLE 6 VEO input variables and output functions

| VEO_Exp | Machine | VEO Input Variables | | | Output Variables |
|---------|---------|---------------------|------------|----------|------------------|
| | | Depth of Cut(mm) | Speed(rpm) | Feed(mm) | Tool Life(min) |
| 1 | M1 | 47 | 459 | 1.5 | 6739.695 |
| 2 | M2 | 48 | 190 | 0.7 | 7354.066 |
| 3 | M1 | 51 | 478 | 1.8 | 7612.62 |
| 4 | M2 | 38 | 121 | 1.2 | 3522.131 |
| 5 | M1 | 46 | 471 | 1.9 | 5551.029 |
| 6 | M2 | 52 | 484 | 1.3 | 9031.615 |
| 7 | M1 | 55 | 262 | 1.1 | 9657.697 |
| 8 | M2 | 35 | 134 | 1.8 | 1629.253 |
| 9 | M1 | 52 | 442 | 1.4 | 8694.768 |
| 10 | M2 | 53 | 475 | 0.8 | 10102.63 |
| 11 | M1 | 54 | 413 | 1.7 | 8751.62 |
| 12 | M2 | 55 | 304 | 0.9 | 10099.86 |
| 13 | M1 | 37 | 335 | 1.2 | 3835.568 |
| 14 | M2 | 37 | 313 | 0.7 | 4436.902 |
| 15 | M1 | 41 | 265 | 1.4 | 4404.831 |
| 16 | M2 | 47 | 307 | 0.7 | 7420.59 |
| 17 | M1 | 42 | 103 | 1.8 | 3370.716 |
| 18 | M2 | 53 | 373 | 1.4 | 8816.126 |
| 19 | M1 | 38 | 392 | 0.7 | 4919.562 |
| 20 | M2 | 43 | 478 | 0.5 | 6842.263 |



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