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Towards Experience-Based Smart Product Design for Industry 4.0

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Abstract: This paper presents the concept of Smart Virtual Product Development (SVPD) system capable of supporting industrial product development process. It enhances the decision making process during different stages and activities involved in product development i.e. product design, manufacturing, and its inspection planning. The enhancement is achieved by using the explicit knowledge of formal past decision events, which are captured, stored and recalled in the form of set of experiences. The basic description and principle of the approach are introduced first, and then the porotype version of the system is developed and tested. Working of the design knowledge management module of the system is demonstrated with the case study, which verifies the feasibility of the proposed approach. The presented system successfully supports smart product design and it can play a vital role in Industry 4.0 development.

Keywords: Product Development, Product Life Cycle Management, Knowledge Management, Set of Experience Knowledge Structure, Decisional DNA.

1 Introduction

The global manufacturing industry is currently undergoing a transformation towards smart manufacturing (Feeney et al. 2015). The latest changes addressed by the incoming fourth industrial revolution have resulted in the development of more complex and smarter products with new capabilities. This trend has an impact on the overall product lifecycle with deep changes in classical product development processes (Nunes et al. 2017). Classical product development approaches, like Simultaneous engineering (SE), Concurrent engineering (CE), Integrated product development (IPD), or Lean product and process development, require reporting and reviewing which delays decision making information and knowledge capture, so decisions cannot be made in real time (Ottosson

2004, Wasim et al. 2013). This creates an urgent need for the development of new smart knowledge-based product development frameworks working in real time as required by the by the fourth industrial revolution (Forbes and Schaefer 2017, Santos et al. 2017).

Product development process consists of different sub processes i.e. product design, production system design, product introduction process, and the start of its production process (Johansen 2005, Rodgers and Clarkson 1998). Product development teams use computer-based supporting tools to make product design more effective by reducing errors at very early stages of engineering design (Hayes et al. 2011). These tools to be operational and proficient require representation and codification of design knowledge, which is very challenging and difficult issue (Hansen et al. 1999). We meet this challenge by using a smart knowledge management technique called set of experience knowledge structure (SOEKS) and decisional DNA (DDNA) (Sanin and Szczerbicki 2004, 2009). It captures, stores, and shares experience generated from smart products in the form of set of experiences (SOEs) and is used to provide decisional support to product design and development activities. The body of the paper includes the background in Section 2, smart virtual product development (SVPD) system presentation in Section 3, and case study with experimental results in Section 4 and Section 5. Last Section of the paper presents conclusions and future work.

2 Background

2.1 Product Development

Generally, a product is defined as a good, service, place, organization or an idea (Cagan and Vogel 2002). In this research, products are objects, which are manufactured for the end users. Product development is an integration of different processes and sub-processes. Initial market survey and technical assessment are part of early stages of product development, whereas actual design and development are performed at the later stages (Kušar et al. 2004). This research contributes towards the later stages.

The main aim of product development is to provide products at low production costs, good quality, high customers' satisfaction, and with quick access to the market (Cagan and Vogel 2002). Lean product and process development tries to achieve the above aim by integrating engineering knowledge into product development process. Knowledge-based engineering, mistake proofing, and continuous improvement are the core lean enablers for the lean product development process (Khan et al. 2013). Knowledge is probably the most important factor in the lean technology, so identifying it, formalizing, coding, and reusing is of utmost importance (Brown and Duguid 2000). The platform proposed in this paper represents an advanced lean technology which supports product development process by using knowledge-based engineering environment with embedded SOEKS and DDNA.

2.2 Set of Experience Knowledge Structure and Decisional DNA

Set of experience knowledge structure (SOEKS) has the ability to store formal decision events in an explicit manner (Sanin and Szczerbicki 2009, Sanin et al 2017, Shafiq et al 2014, 2016). It is basically a smart knowledge-based decision support tool which stores and maintains the experiential knowledge. This experiential knowledge is used for future decision making enhancement whenever a new query is generated or presented. A set of experience (SOE, a shortened form of SOEKS) has four basic components: variables (V), functions (F), constraints (C) and rules (R) (Sanin and Szczerbicki 2004, Sanin et al 2012). Variables define SOE's functions. Functions create relationships between variables and are used to develop multi-objective goals. Constraints are special functions which are applied by SOE to get feasible solutions and to control system's performance with respect to defined goals and limits. Rules, on the other hand, are the conditional relationships among the variables and are defined in terms of IF-THEN-ELSE logical statements. Therefore, a formal decision event is represented by a unique set of variables, functions, constraints, and rules within each SOE. Groups of SOEs create chromosomes. These chromosomes represent the specific area/domain within the given decision-making area, and they store decisional strategies for a given domain. Accurately structured and grouped sets of decisional chromosomes are collectively known as its DDNA (Sanin and Szczerbicki 2004, 2006, 2009).

2.3 Smart Products in Industry 4.0

Industry 4.0, is a combination of intelligent machines, systems, production, and processes to form a well-defined network (Kagermann et al. 2013). It highlights the idea of consistent digitization and linking of all productive units in a manufacturing set up, and creates a real world virtualization embedded in a dedicated information system. It is an integration and assimilation of component concepts such as “cyber-physical systems (CPS)”, “Internet of things (IoT)”, “Internet of services (IoS)”, and “Smart Products”, where CPS environment is represented by large number of models, systems, and technologies from an extremely wide range of domains (Lee and Seshia 2016). It can be perceived as a natural transformation of the traditional industrial production systems into cyber-physical virtuality triggered by the digitalization trend leading to the fourth industrial revolution - Industry 4.0. The main industrial issues and topics do not really change; just the technology and approaches for tackling the connected issues are entirely new (Rojko 2017). The Industry 4.0, concept is not limited to the direct manufacturing process in the company, but it also includes a complete value chain and life cycle of a product from providers to customers. It creates a new type of products, which are smart products. These products are integrated with the new intelligent manufacturing processes, and continue to provide the data about their state and experience during their life cycle. They support their manufacturing processes by storing information about the previous and further process steps regarding production and maintenance. Once they are finished products, they are fully aware of the parameters in which they should be manufactured and used (Kagermann et al. 2013).

Smart product holds three types of knowledge i.e.; (i) about itself, (ii) about its environment and (iii) about its users. Knowledge about itself, refers to the awareness of its characteristics and functionalities, as well as the product history. The second type is knowledge about the ability of smart products to interact with their environment. Finally, the third class of knowledge is related to the product capability of interacting with its users during the whole lifecycle and providing relevant information about its status and maintenance (Mühlhäuser et al. 2008). Therefore, developing smart products requires deep changes in the processes and activities by which a company adds value to their products, such as product development processes, marketing activities, manufacturing, logistics, and aftersales services (Kagermann et al. 2013).

3 Smart Virtual Product Development System

Smart virtual product development (SVPD) system is a decision support tool for product development process which stores, uses, and shares the experiential knowledge of past decisional events in the form of set of experiences (SOEs). It is developed to overcome the need for capturing knowledge in the digital form in engineering design, production planning, and inspection planning in smart manufacturing (Feng et al. 2017). This will help in enhancing the product quality and development time as required by Industry 4.0 concepts.

3.1 Architecture of SVPD System

Smart Virtual product development system consists of three main modules i.e. design knowledge management (DKM), manufacturing capability analysis and process planning (MCAPP), and product inspection planning (PIP). These modules interact with the decisional DNA knowledge repository of SVPD which holds in the form of SOE relevant knowledge of similar products developed in the past (Figure 1). DKM deals with material selection process and product geometric features generation; MCAPP provides solutions regarding manufacturing process planning, machines' selection, and machines' capability to perform particular manufacturing operation; and PIP involves selection of gauging or other measuring equipment for product inspection during manufacturing process stages.

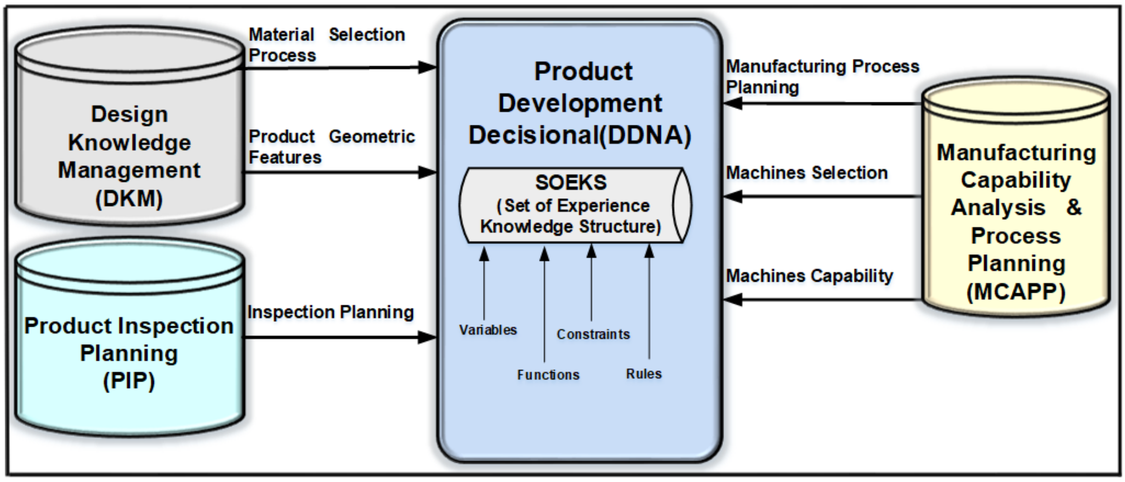

Figure 1. Architecture of Smart Virtual Product Development (SVPD).

Integrated SVPD modules provide validation that a given product is sustainable in nature, and can be manufactured in an existing facility. The case study presented in the following Section illustrates the working of DKM module of SVPD and explains how one of its sub- module i.e. material selection process functions.

4 The Case Study

Design and development of a threading tap (Figure 2), which is a multipoint cutting tool to create screw threads, continuous to provide the background for our case study (Ahmed et al. 2018). The objective of this case study is to show how the design knowledge management module selects the best available material for a threading tap similar to the one shown in Figure 2.

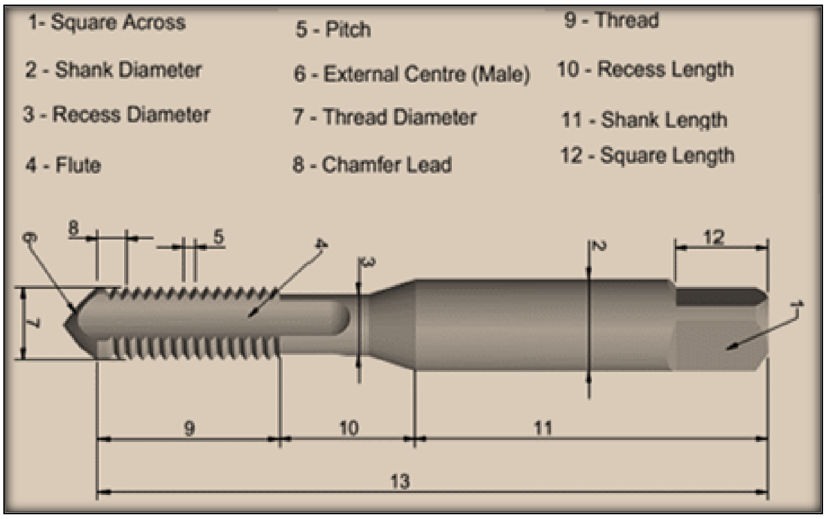

Figure 2. Important dimensions in a threading tap.

4.1 Working Algorithm of Material Selection Process

Material selection process is part of DKM module of SVPD. It deals with proper selection of suitable material in order to obtain desired mechanical properties of the product and to ensure its possible manufacturing in existing facility. The existing facility for the case study (threading tap) is a small manufacturing unit which comprises of a design office, a well-equipped machine shop (including conventional and non-conventional machines), and a heat treatment section. First, the necessary material-associated information in the form of variables for threading tap is identified, coded, and stored. These variables embody different properties of tool steels such as material hardness, machinability, sustainability and effects of alloying elements on tool steel properties (Oberg et al. 2004), and they are stored in the form of virtual engineering object (VEO) in a comma-separated values (CSV) file. VEO is the knowledge representation of an engineering object that embodies its associated knowledge and experience (Shafiq et al 2015) . It permits the real-world and computerized representation of an engineering artefact. VEO is a specialization of CPS in terms of its extension into knowledge gathering and reuse (Shafiq et al. 2015). For an illustrative purpose CSV file for material selection process with few important variables is shown in Appendix 1. DDNA is constructed in Java and applied in various other fields of applications. Thus, the parser for material selection process is also written in Java programming language. The pseudocode for parser reading CSV file for material selection process is shown below:

- *Reads variables, functions, constraints, and rules.*
- *Develops set of variables, set of functions, set of constraints, and set of rules.*
- *Combines sets of variables, functions, constraints and rules to form into one SOE.*
- *Forms a chromosome of material selection process by collecting SOEs of the same category.*
- *Provides top 5 proposed solutions.*
- *User selects the final solution and it is saved as SOE in decisional DNA of SVPD.*

5 Results and Discussion

Case study for material selection process was carried out on a Dell laptop with Windows 10 Enterprise 64-bit operating system having Intel ® Core ™ I5-7300u CPU @ 2.60 and 8 GB of RAM. Parser for material selection process reads data from a CSV file having information about 5 molybdenum high speed steel materials and 5 tungsten high speed materials. This CSV file stores material properties in the form of 21 variables, 2 functions, and 7 constraints. The graphical user interphase (GUI) for the material selection process is shown in Figure 3. It can be used to form a simple query and find its solution.

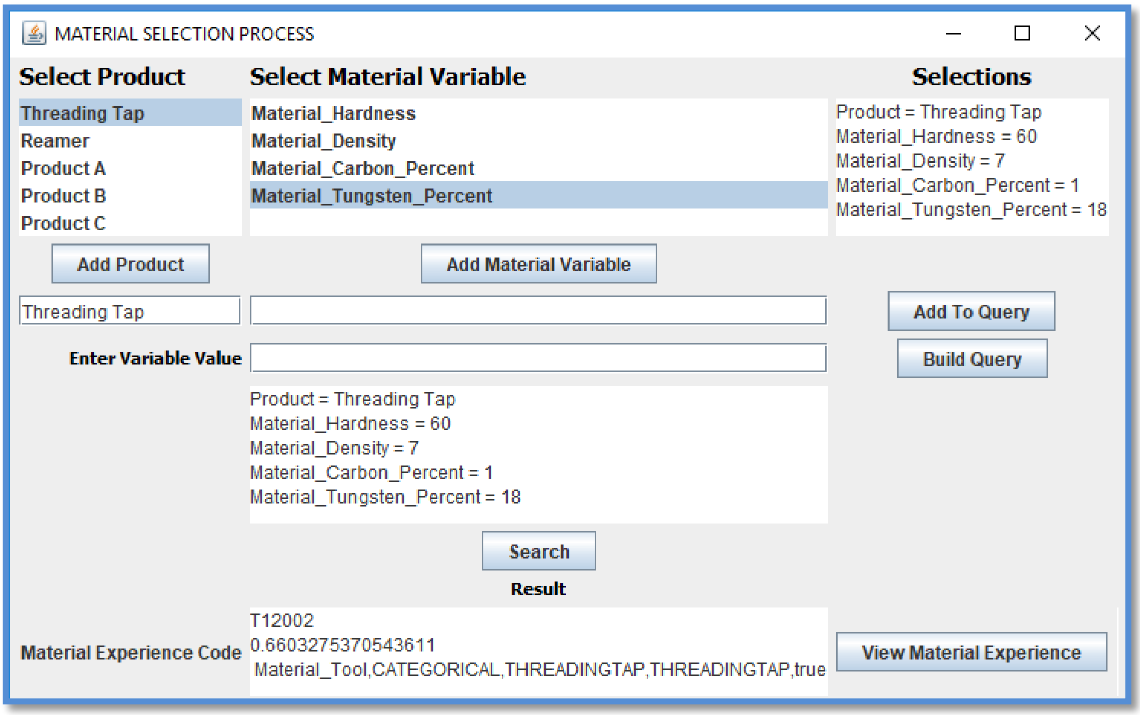

Figure 3. GUI for building query and viewing results for material selection process.

First of all, the user selects the product to be manufactured (Threading Tap) from “Select Product” section, and clicks the “Add Product” button (Figure 3). In next step, important variables involved in material selection process for threading tap are selected from “Select Material Variables” list box. User selects a variable, enters the value of that variable in the text box and clicks “Add to Query” button. Multiple variables can be selected and added. All selections are combined to build a query by clicking the “Build Query” button. This query appears in the form of a SOE in the “Build Query” text box of Figure 3, and a possible random query structure is shown below:

Product = Threading Tap

Material_Hardness = 60

Material_Hardness = 7

Material_Carbon_Percent =1

Material_Tungsten_Percent =18

Finally, the user clicks the “Search” button and the closest SOE that matches the query is returned to the user, as shown in the “Material Experience Code” text box. Complete details of all variables of the most similar material can be seen by clicking the “View Material Experience”.

The parsing process for sample query for material selection process was executed during the case study , producing an average parsing time of 0.018 seconds (Figure 4). This is considered a very good processing time, taking into account the complexities of SOEs having substantial number of variables, functions, and constraints.

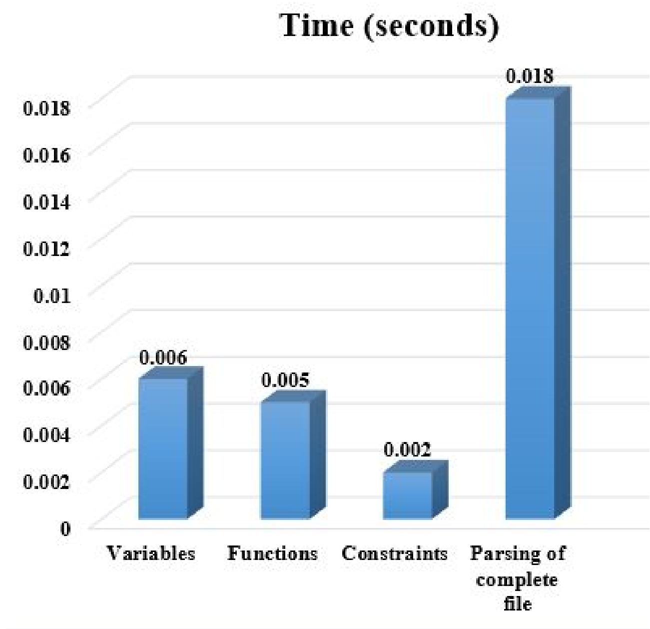

Figure 4. Parsing time vs SOE elements.

Additionally, parsing time for different SOE elements was as follows; time to read variables 0.006 seconds, time to read functions 0.005 seconds , and time to read constraints w 0.002 seconds. The similarity values of 10 stored as SOE tool steels from a random query are shown in Figure.5.

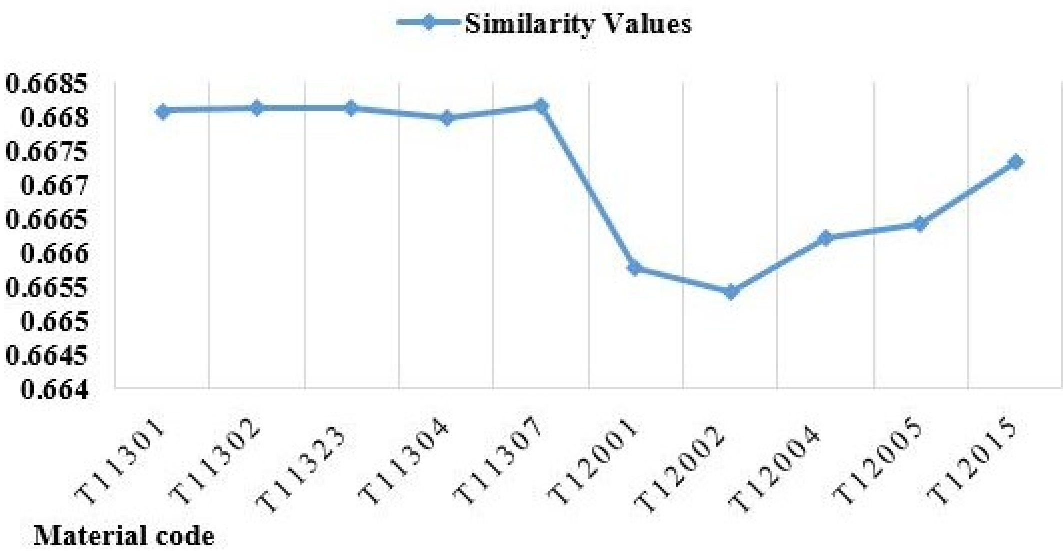

Figure 5. Similarity values for each SOEKS in material selection process.

6 Conclusion and Future Work

This paper presents the concept of SVPD system that enhances the industrial product development process. It is composed of three modules, namely design knowledge management module, manufacturing capability analysis and process planning, and product inspection planning. Working of DKM module has been explained by developing in Java and running as the case study one of its sub-modules i.e. material selection. It is evident from the results of the case study that developed system is capable of enhancing the process of material selection by using the material selection related experiential knowledge of similar products. Decisional DNA of the system is able to find the suitable solution for the query according to the set of required priorities and constraints. After query execution, the user selects the final solution, and this process is stored in in the decisional DNA of the system as new experiential knowledge that can be used for solving a similar cases in the future. Further research is planned to extend the Java representation for other SVPD modules.

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Appendix 1 CSV file component for material selection process.

Variables

Material_Tool	material_UNS_Code	Material_Hardness	Material_Density	Material_Elastic_Modulus	Material_Carbon_Percent	material_Tungsten_Percent	Material_Availability	Material_Sustainability
Threading Tap	T11301	65	7.89	210	0.88	2.10	Yes	Yes
Threading Tap	T11302	62	8.16	210	1.05	6.75	Yes	Yes
Threading Tap	T11323	66	8.16	210	1.25	6.75	Yes	Yes
Threading Tap	T11304	65	7.97	210	1.40	6.50	Yes	Yes
Threading Tap	T11307	65	7.95	190	1.05	2.10	Yes	Yes
Threading Tap	T12001	65	8.67	207	0.80	18.75	Yes	Yes
Threading Tap	T12002	62	7.86	210	0.90	19.00	Yes	Yes
Threading Tap	T12004	66	8.68	210	0.80	19.00	Yes	Yes
Threading Tap	T12005	66	8.75	210	0.85	19.00	Yes	Yes
Threading Tap	T1205	46	8.19	210	1.60	13.00	Yes	Yes