23rd International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

Smart Virtual Product Development (SVPD) to Enhance Product Manufacturing in Industry 4.0

Muhammad Bilal Ahmed[a*] , Cesar Sanin[b], Edward Szczerbicki[c]

[a] The University of Newcastle, muhammadbilal.ahmed@uon.edu.au, Newcastle 2230, Australia
[b] The University of Newcastle, cesar.sanin@newcastle.edu.au, Newcastle 2230, Australia
[c] Gdansk University of Technology, edward.szczerbicki@newcastle.edu.au, Gdansk, Poland

Abstract

This paper presents a system capable of enhancing product development process for industrial manufactured products. The system is known as Smart Virtual Product Development (SVPD), and it helps in decision making by using explicit knowledge of formal decision events. It stores and reuses the past decisional events or set of experiences related to different activities involved in industrial product development process i.e. product design, manufacturing, and product inspection. This system can be potentially used in large enterprises manufacturing a range of similar products in mass production, or a group of small and medium enterprises (SMEs). This research explains that how product manufacturing can be enhanced by using SVPD in Industry 4.0, where cyber-physical systems have to play the key role. The analysis of basic concepts and implementation method proves that this is an expert system facilitating product manufacturing which can play a vital role towards Industry 4.0.

Keywords: Smart Virtual Product Development, Product Development, SOEKS, Manufacturing Capability Analysis and Process planning, Manufacturing Process Planning

1. Introduction

Manufacturing organizations which produce similar products are facing shear competition due to: continuous market changes, need for short product lifecycles, and accomplishing customer's expectations for producing quality products at lower cost. This forces them to adopt new product development strategies regularly and systematically[1]. Product design and manufacturing are vital steps involved in product development process, as they require robust information and knowledge regarding customers' demands[2]. Successful product development organizations acquire at least two types of design knowledge; first one is regarding the product itself, and the second one is concerned about its manufacturing in an effective way to meet cost, quality, and short product development time[3]. Manufacturing

* Corresponding author.*E-mail address:* muhammadbilal.ahmed@uon.edu.au

knowledge is an expression with enormous meanings, it may include: knowledge of the effect of material properties in decision making, machine and process selections, and understanding the unintended consequences of design decisions on manufacturing[4]. Designers have to do manufacturing planning to evaluate manufacturability in terms of criteria and metrics, such as cost and time. Therefore, the use of inappropriate manufacturing knowledge can lead to mistakes during product development and can harm the environment. These mistakes are likely to be caused by designers relying on poor or inadequate manufacturing knowledge during the product design process[5].

Electronics and IT have played a key role in the 3rd industrial revolution by increasing automation of production. Now, the global manufacturing industry is moving towards Industry 4.0, which is the 4th industrial revolution. Conventional manufacturing processes will be replaced by smart manufacturing, which consists of new concepts, i.e. Internet of Things (IoT), Internet of Services (IoS), Cyber-Physical Systems (CPS), Mass collaboration, High-speed internet, and affordable 3-D printing[6]. Fourth industrial revolution has addressed several changes to the conventional manufacturing systems and this has resulted in the development of more complex and smarter products with new capabilities. Therefore, it has an impact on the whole product lifecycle and is causing the emergence of advanced digital tools for product development and prototyping, which comprise of advanced computing platforms. Producing these smart products means profound changes in classical product development processes, who have experienced several achievements in the last few decades in terms of theory, methods, and approaches[7]. Therefore, relationship between the product development process and fourth industrial revolution is un-explored, but the huge amount of data retrieved from smart manufacturing makes it interesting. It arises different types of questions in terms of product development process, such as: how can it help in satisfying the customers' requirements, minimizing the development cycle time, and controlling the product development cost. This all has created a great potential for the development of new smart knowledge-based product development frameworks for the design and development of smart products[8].

The concept of smart manufacturing is also closely related to knowledge-driven decision making to meet customers' demands for new products. In order to make decisions at various stages of product development, it is very important to have complete knowledge of each manufacturing process and its possible outcomes. Furthermore, engineering knowledge is embedded in various stages in the product lifecycle in the form of rules, logical expressions, ontologies, predictive models, statistics, and information extracted from previous experiences and sensors in real-world situations, such as production, inspection, product use, supplier networks, and maintenance. Currently, knowledge is not completely captured and stored in a digital form during all phases of product life cycle. Therefore, organizations are aiming at achieving streamlined knowledge capture and curation through knowledge management[9].

We try to cope this problem by proposing a system that uses a collective, team-like knowledge created from relevant past experiences; we named this system as Smart Virtual Product Development (SVPD). This approach uses a smart knowledge management technique called Set of Experience Knowledge Structure (SOEKS or SOE in short) and Decisional DNA[10]. It captures, stores, and shares the experiential knowledge in the form of set of experiences during important phases of industrial product development i.e. product design, manufacturing, and product inspection (quality aspects). Whenever a similar query is presented during the problem solving process, this stored knowledge is recalled to overcome the problem. It provides a list of proposed optimal solutions according to the priorities set by the user. By the passage of time, system achieves more expertise in specific domains as it stores relevant knowledge and experience related to formal decision events.

This paper is organized as: in Section 2, basic concepts are introduced i.e. Product development, Set of experience knowledge structure (SOEKS), Smart manufacturing, and Cyber-physical systems. Section 3 introduces the proposed Smart Virtual Product Development (SVPD) system and explains its architecture. Design of test case study for one of the important modules of proposed system i.e. manufacturing capability and process planning (MCAPP) is presented in Section 4. Section 5, presents results and discussion. Finally, conclusions and future work are given in Section 6.

2. Background

2.1 Product Development

Product development is a series of interconnected processes and sub-processes, which covers product design, production design, product introduction process, and the start of its production[11]. The main aim of product development process is to integrate engineering and industrial design requirements through a structural process that

allows the achievement of lower production cost, higher quality, and shorter development time with quick access to market, so that it can contribute to customers' satisfaction and companies' financial benefits[12]. In past, various classical methods such as Stage-Gate model process, Product development process by Ulrich and Eppinger, Development funnel product model process, Simultaneous engineering (SE), Concurrent engineering (CE), Integrated product development (IPD), and Lean product and process development (LPPD) have played key roles in the product development process[13].

As mentioned earlier the arrival of fourth industrial revolution, which encompasses a set of advancements in both products and manufacturing processes. Therefore, the adaptation of this new industrial pattern and the production of smart and connected products means intense changes in the whole organizations value chain, especially in product development process. Henceforth, organizations that produce smart products need to adopt the most suitable product development approaches. Resource optimization and waste elimination are one of the important factors to consider during development of the smart products in order to increase company's competitiveness. This can be achieved by introducing and developing new technological tools which can eliminate mistakes during early stages of product development[7]. Lean product and process development have achieved a great success in recent past by integrating engineering knowledge into product development process. Few of the core lean enablers for product development process are: Knowledge based engineering, Mistake proofing (Poka-Yoke), and Continuous improvement culture (Kaizen)[14]. This research also uses a smart knowledge management technique called Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA) to enhance the product manufacturing process, which is one of the important step in industrial product development.

2.2 Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA)

Set of experience knowledge structure (SOEKS) has the ability to store and share the formal decision events in an explicit manner[15]. 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).

Variables define SOE's functions, while 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 the SOE. Groups of SOEs create chromosomes, which 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[15].

Set of experience and DDNA have been successfully applied in various fields such as industrial maintenance, semantic enhancement of virtual engineering applications, state-of-the-art digital control system of the geothermal and renewable energy, storing information and making periodic decisions in banking activities and supervision, e-decisional community, virtual organization, interactive TV, and product innovation[16].

2.3 Smart Manufacturing and Cyber-Physical Systems

Smart manufacturing refers to the combination of advanced manufacturing capabilities and digital technologies to improve the productivity, agility, and sustainability of manufacturing systems. It uses the Cyber-physical system concept through the collaboration of computational elements to control various physical entities in the manufacturing environment[17]. It is an emerging form of production which integrates manufacturing assets of today and tomorrow with sensors, computing platforms, communication technology, control, simulation, data intensive modelling and predictive engineering.

Cyber-physical systems (CPSs) are the key part of smart manufacturing along with internet of things, cloud computing, artificial intelligence and data science. They can be described as the transformative technologies for managing interconnected systems between its physical assets and computational capabilities with the possibility of human machine interaction[18]. CPSs are increasingly important in manufacturing due to the digitization of the industry driven by advances in technology and connectivity. They have advanced machines and sensors capable of producing

high volumes of data. Therefore, data analysis tools can be used with these machines to create intelligent, autonomous, and robust systems[19]. In modern manufacturing organizations, especially high-tech industries, CPS can be further designed for managing knowledge and experience in the form of Big Data and leveraging the interconnectivity of machines to reach the goal of intelligent factories[20].

3. Smart Virtual Product Development System (SVPD)

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 SOEs. It is developed to overcome the need for capturing knowledge in the digital form in product design, production planning, and inspection planning in smart manufacturing[9]. This will help in enhancing the product quality and development time as required by Industry 4.0 concepts.

3.1 Architecture of Smart Virtual Product Development

Our proposed Smart Virtual Product Development (SVPD) 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 of the system which holds all the relevant knowledge of similar products. This knowledge repository is filled with past formal decisional events involved in manufacturing of these similar products in existing facility. The proposed system stores decisional DNA knowledge in the form of SOEs. The architecture of the SVPD system is shown in Fig. 1.
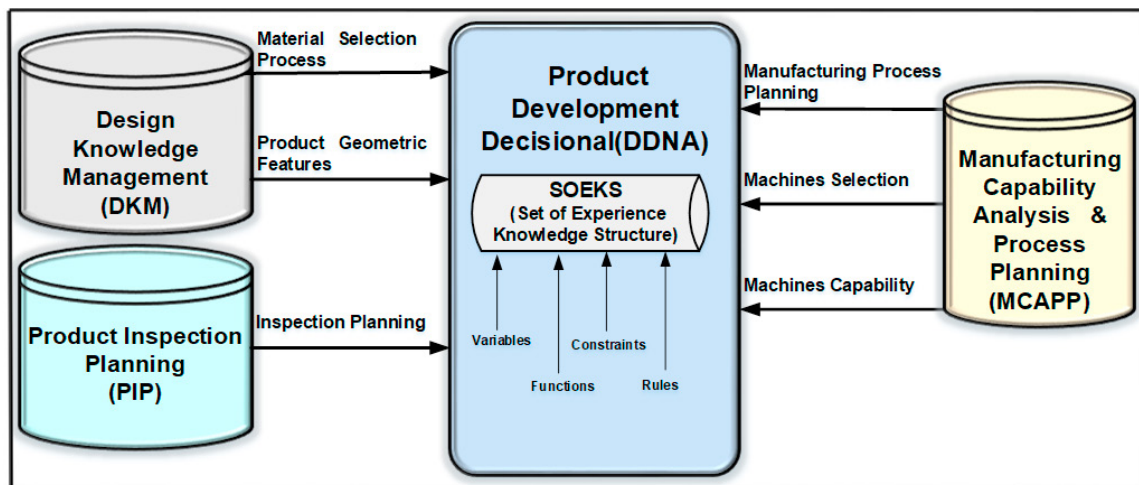

Fig. 1. Architecture of Smart Virtual Product Development (SVPD).

These modules have further different steps to perform particular decisional activity. Design knowledge management deals with material selection process and product geometric features generation; manufacturing capability analysis and process planning provides solution regarding manufacturing process planning, machines' selection, and machines' capability to perform particular manufacturing operations; and inspection planning involves selection of different measuring equipment and gauges for product inspection during manufacturing and at final stage.

Once all of these modules are successful, it provides validation that a product can be easily manufactured in an existing facility. Detailed working of design knowledge management module has been explained in our previous work[21]. The aim of this research is to explain the working mechanism of MCAPP module, which will illustrates that how manufacturing knowledge can be provided to design experts during early stages of product development.

4. Design of a Test Case Study for the MCAPP-Module

Design and development of a threading tap (a tool to create screw threads which is called threading) is our case study, as it was also used for DKM module in our previous work[21]. We are considering a machine-use threading tap, as shown in Fig. 2 with few important dimensions. As mentioned above, this research copes with important variables involved in the MCAPP module, so we will explain the working of manufacturing process planning, which is one of the important steps in this module.
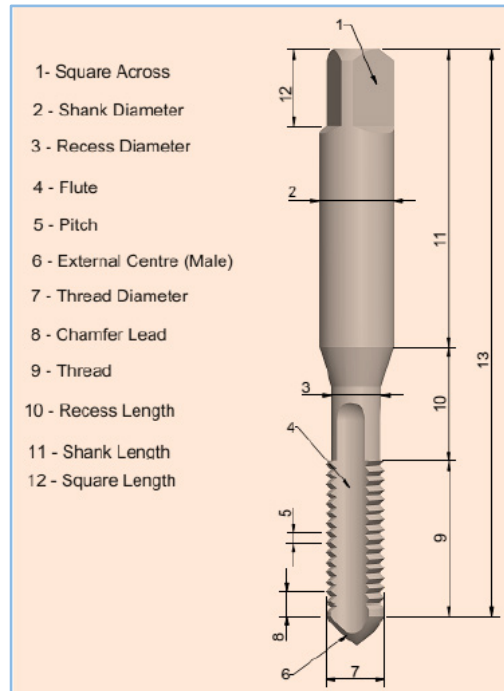

1- Square Across
2 - Shank Diameter
3 - Recess Diameter
4 - Flute
5 - Pitch
6 - External Centre (Male)
7 - Thread Diameter
8 - Chamfer Lead
9 - Thread
10 - Recess Length
11 - Shank Length
12 - Square Length

Fig. 2. Important dimensions in threading tap.

4.1 Working Algorithm of Manufacturing Process Planning

Manufacturing process planning is part of manufacturing capability analysis and process planning module of SVPD. It deals with the processes required to manufacture the product in the existing facility[13]. The existing facility for the case study (Threading Tap) is a small tool manufacturing factory which comprises of a design office, a well-equipped machine shop (including conventional and non-conventional machines), metrology (inspection unit), and heat treatment section. In this step, we have to decide which machining operations are required to manufacture the product under consideration. Every process will start by inputting the query into the decisional DNA of the system based on initial objectives. For the present case study of threading tap, let us consider that selected material is high speed steel and the initial objective is to define manufacturing processes for this product. These manufacturing operations can be simply recalled from an existing virtual engineering process (VEP) of a family of similar products. Whereas, a VEP is a knowledge representation of manufacturing process-planning involving the required operations, their sequence, and resources[22]. This data is stored in the form of VEP in a comma-separated values (CSV) file.

For illustrative purpose CSV file for manufacturing process planning is shown in Table 1. As the DDNA is constructed in Java, the parser for manufacturing process planning is also written in Java programming by using Windows 10 operating system. The pseudocode for parser reading CSV file for manufacturing process planning is shown below:
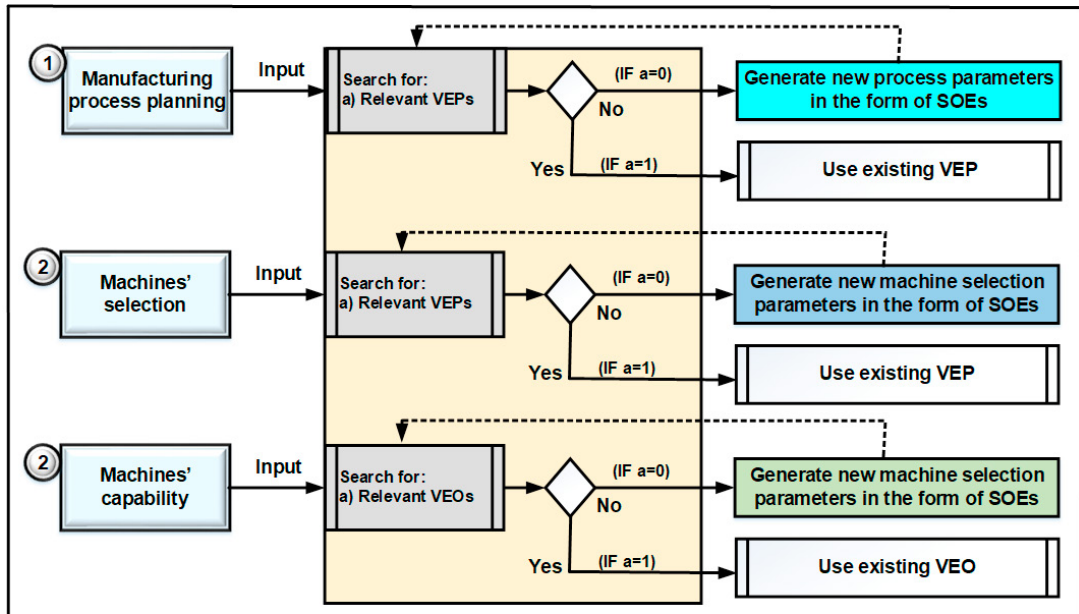
- *Reads variables, functions, constraints, and rules.*
- *Develops set of variables, set of functions, set of constraints, and set of rules.*
- *Creates a Set of Experience (SOE) = Set of variables + Set of functions +Set of rules.*
- *Form a chromosome of manufacturing process planning by collecting SOEs of the same category.*
- *Provide top 5 proposed solutions.*
- *User selects the final solution and it is saved as SOE in DDNA of SVPD for future reference.*

Table 1: CSV File format for manufacturing process planning

Variables

P_tool	P_material	P_operation1	P_operation2	P_operation3	P_operation4	P_operation5	P_operation6
Threading Tap	T11301	Material Cutting	Turning	Milling	Heat Treatment	Cylindrical Grinding	Thread Grinding
Threading Tap	T11302	Material Cutting	Turning	Milling	Heat Treatment	Cylindrical Grinding	Thread Grinding
Threading Tap	T12001	Material Cutting	CNC Turning	CNC Milling	Heat Treatment	Cylindrical Grinding	Thread Grinding
Threading Tap	T12002	Material Cutting	CNC Turning	CNC Milling	Heat Treatment	Cylindrical Grinding	Thread Grinding

Similarly, the data for machines' selection process is saved in the form of a VEP in a CSV file and is recalled by putting an input query. However, the data about machines' capability is stored in the form of a virtual engineering object (VEO) in a CSV file and is recalled by placing an input query. Whereas, a VEO is the knowledge representation of an engineering object that embodies its associated knowledge and experience. It is specialization of CPS in terms of its extension into knowledge gathering and reuse[23].Working mechanism of all steps/sub-modules of MCAPP modules is depicted in Fig.3.

(1= Successful, 0 = Unsuccessful)

Fig. 3. Working of MCAPP module.

5. Results and Discussion

Case study for manufacturing process planning 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 manufacturing process planning reads the data from a CSV file having information about 10 different types of threading types according to material classification and type of use. This CSV file stores manufacturing processes in the form of 22 variables, 2 functions, and 3 constraints. The parsing process for manufacturing process planning was executed, producing an average parsing time of 0.098 seconds, as depicted in Fig.4. This is considered a very good time, taking into account that those SOE are quite complex due to the substantial number of variables, functions, and constraints. Similarly parsing time for different SOE elements was; time to read variables 0.035 seconds, time to read functions 0.046 seconds , and time to read constraints was 0.012 seconds.
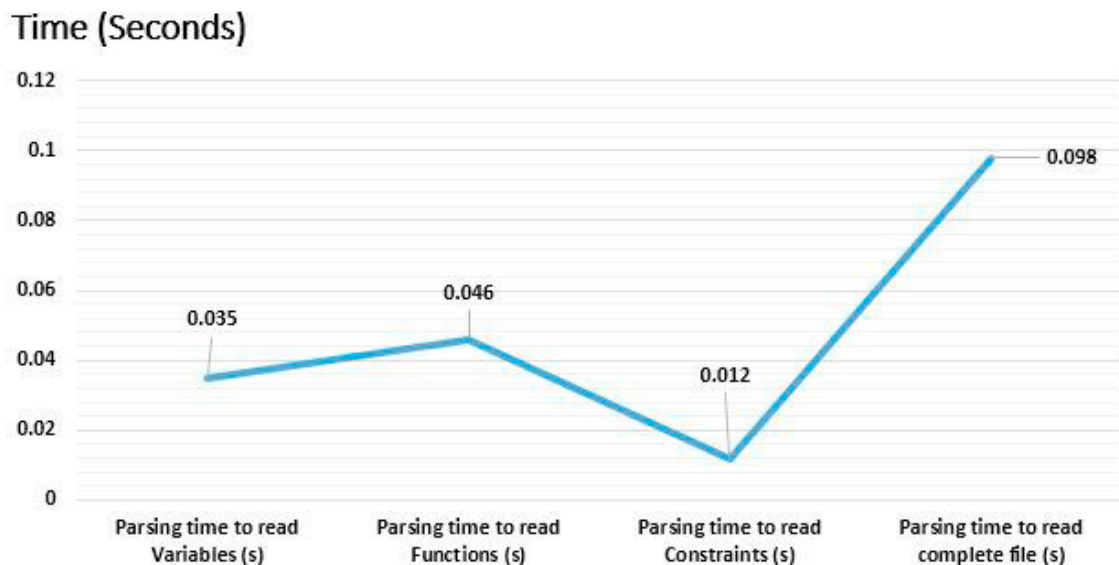

Fig. 4. Parsing time vs SOE elements for manufacturing process planning.

6. Conclusion and Future Work

This research revealed a system to support product development process by using experiential knowledge. The system is composed of three modules, namely design knowledge management module (DKM), manufacturing capability analysis and process planning (MCAPP), and product inspection planning (PIP). Working of MCAPP module has been explained by developing one of its sub-modules i.e. manufacturing process planning in JAVA. It is evident from the results of the case study that this system is capable of enhancing the technique of manufacturing process planning by using the manufacturing related experiential knowledge of the similar products.

Decisional DNA of the whole system is capable of finding the suitable solution for the query according to the set priorities and constraints. The user then selects the final solution, and this process is stored in in the Decisional DNA of the product development system as experiential knowledge that can be used in future for solving a similar query. The SVPD System behaves as a group of experts as it captures, stores, maintains, and reuses the experiential knowledge of all similar products. Future work includes the extension of the SVPD system to explain the important variables involved in working of product inspection planning (PIP) module.

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