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Enhancing Product Manufacturing Through Smart Virtual Product Development (SVPD) for Industry 4.0

Muhammad Bilal Ahmed[1], Farhat Majeed[2],Cesar Sanin[1], and Edward Szczerbicki[3]

[1] *Department of Mechanical Engineering, University of Newcastle, Callaghan, NSW, Australia*

(muhamadbilal.ahmed@uon.edu.au, cesar.sanin@newcastle.edu.au)

[2] *School of Engineering and Built Enviroment, Griffith University, Nathan, Qld, Australia*

(farhat.majeed@alumni.griffithuni.edu.au)

[3] *Faculty of Management and Economics, Gdansk University of Technology, Gdansk, Poland*

(edward.szczerbicki@zie.pg.gda.pl)

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Abstract:

This paper proposes the Smart Virtual Product Development (SVPD) system, which enhances industrial product manufacturing processes. The proposed system comprises of three main modules: design knowledge management (DKM), manufacturing capability and process planning (MCAPP), and product inspection planning (PIP). Smart virtual product development system collects, stores, and uses experiential knowledge from formal decisional events in the form of set of experience (SOE). This research explains the working mechanism of MCAPP module, and shows how manufacturing knowledge of similar products having some common features and functions is used to enrich the manufacturing process. First, the basic description and principles of the approach are introduced, then the prototype version of the system is developed and tested for manufacturing capability and process planning (MCAPP) module for the case study, which verifies the feasibility of the proposed approach. The presented system successfully supports smart manufacturing, and can play a vital role in Industry 4.0.

1 Introduction

Different activities involved in the product development process are becoming extremely complex, as they require greater understanding and range of knowledge. These activities must be formalized and structured in such a way that all the decisions should be made on proven knowledge and successful experiences. Therefore, superior product development capabilities of a firm are highly dependent on its ability to create, distribute, and utilize the knowledge throughout the product development process (Sorli et al. 2012).

Experts working on product development exploit an extensive range of knowledge resources, i.e. knowledge related to the product design, its manufacturing, and knowledge related to quality procedures. Design knowledge is regarding geometrical features and functionalities of the product, whereas manufacturing knowledge is concerned with how the product will be manufactured effectively to meet cost, quality, and quick reach to the market. Manufacturing knowledge is an expression with vast meanings, which may include knowledge regarding the effects of material properties, manufacturing processes, required machines and equipment and their capabilities. It is very important for designers to evaluate the manufacturability of proposed/designed products during early stages of product development. However, there are not many techniques and tools for conceptual manufacturing planning. Therefore, the use of inappropriate manufacturing knowledge can lead to mistakes during product development (Hedberg Jr et al. 2017). Similarly, the latest changes addressed by the incoming fourth industrial revolution (Industry 4.0) have resulted in the development of more complex and smarter products with new capabilities. This trend has an impact on the overall product lifecycle and demands for changes in classical product development processes (Nunes, Pereira, and Alves 2017).

Furthermore, engineering knowledge involved in various stages of product lifecycle is embedded in the form of rules, logical expressions, ontologies, predictive models, statistics, and information extracted from the sensors in real-world situations. Currently, knowledge is not completely captured and stored in a digital form during all phases of product life cycle, especially during product manufacturing. Therefore, organizations are aiming at achieving streamlined knowledge capture and curation through knowledge management. This requires powerful tools to analyse such data and knowledge which are extracted from real time sensors and enterprise resource planning (ERP) systems used for product manufacturing (production), product inspection, product use, supplier networks, and maintenance. This problem can be solved by using an applicable form of knowledge management technique (Feng et al. 2017).

We try to overcome this problem by proposing a system that uses a collective team-like knowledge created from relevant past experiences; we call 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 (Sanin and Szczerbicki 2007). It captures, stores, and shares the experiential knowledge in the form of set of experiences (SOEs). 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. Over time, this system achieves more expertise in specific domains as it stores relevant knowledge and experiences related to formal decisional events.

The structure of this paper comprises of the background in Section 2, which presents the basic concept of product development and smart manufacturing. Introduction to SVPD, which describes the architecture of proposed system is presented in Section 3. Section 4 explains the implementation of SVPD to enhance product manufacturing. Section 5 presents the results and discussion. Finally, the concluding remarks and future work are presented in Section 6.

2 Background

2.1 Product development

Product development process is a series of interconnected processes and sub-processes which covers product introduction, its design, and start of its production. Different factors such as technological advancement, competition, and market changes force companies to develop new products (Unger and Eppinger 2011). The main aim of product development process is to design and develop products at lower production cost, higher quality, and shorter development time to meet customers' requirements (Cagan and Vogel 2002).

In past, 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 development have played key roles in product development process (Wasim et al. 2013). Fourth industrial revolution (Industry 4.0) 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 deep 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 (Nunes, Pereira, and Alves 2017).

Lean product and process development have achieved a great success in recent past as they integrate engineering knowledge into product development process. Knowledge-based engineering, mistake proofing (Poka-Yoke), and continuous improvement are the core lean enablers for lean product development process (Khan et al. 2013). Knowledge is an important factor to get competitive advantage over competitors; therefore, organizations are focussing on their competencies of knowledge generating, saving and sharing in product development process. It is very important to identify the required knowledge and the ability to utilize it in an effective way (Brown and Duguid 2000).

2.2 Smart manufacturing

Smart manufacturing is an evolving form of production which integrates manufacturing assets of today and tomorrow with sensors, computing platforms, communication technology, simulations, data intensive modelling, and predictive engineering. It uses the Cyber-physical system concept through the collaboration of computational elements to control various physical entities in the manufacturing environment. It also improves the productivity, agility, and sustainability of conventional manufacturing systems (Wolf 2009).

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 (Kusiak 2018). 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 (Thiede, Juraschek, and Hermann 2016).

3 Introduction to Smart Virtual Product Development System

Smart Virtual Product Development (SVPD) system is a decision support tool to enhance the product development process for industrial manufactured products by using experiential knowledge. This experiential knowledge is stored, used, and shared in the form of set of experiences (SOEs).

It is based on a smart knowledge management technique called set of experience knowledge structure (SOEKS or SOE) and decisional DNA, which were first presented by Sanin and Szczerbicki (2007). The main components of SOE are variables, functions, constraints, and rules. Variables are the source of other SOE components and are the centre root or the starting point of the structure. Functions create relationships between variables and are used to develop multi-objective goals. Constraints are also functions and they are applied by SOE to get feasible solutions and to control system's performance with respect to defined goals. 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.

3.1 Architecture of Smart Virtual Product Development

Smart virtual product development (SVPD) system is developed to overcome the need for capturing the experiential knowledge in the digital form in product design, production planning, and inspection planning in smart manufacturing (Feng et al. 2017). Therefore, it comprises 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 in the form of SOEs which are involved in design and development of these similar products in existing facility. The architecture of the SVPD system is shown in Figure 1.

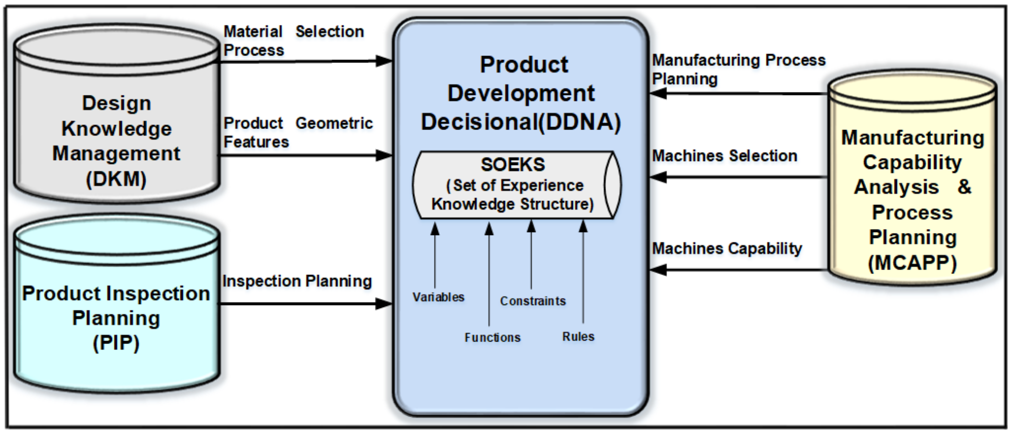

Figure 1. Architecture of Smart Virtual Product Development (SVPD).

Each of these modules have further different sub-modules to perform particular decisional activity. For example, 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 metrological instruments for product inspection during its design and manufacturing stages. Once all of these modules are successful, it provides validation that a product can be easily manufactured in an existing facility. Working mechanism of DKM module was presented in our previous work (Bilal Ahmed et al. 2019), this research deals with explanation of MCAPP module of the proposed system.

4 Manufacturing Capability and Process Planning Module

Manufacturing capability and process planning (MCAPP) module is the second main module of the proposed system, and it deals with different aspects involved in industrial product manufacturing. It can be successfully used during new product design and can help designers in selecting suitable manufacturing processing and machines in an existing facility. Similarly, it can be used for repetitive manufacturing of existing products. It consists of the following three sub-modules:

a) manufacturing process planning
b) machines' selection
c) machines' capability

4.1 Design of a test case study for 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 design knowledge management module in our previous work (Bilal Ahmed et al. 2019). We are considering a machine-use threading tap, as shown in Figure 2 with few critical dimensions. As mentioned above, this research deals 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.

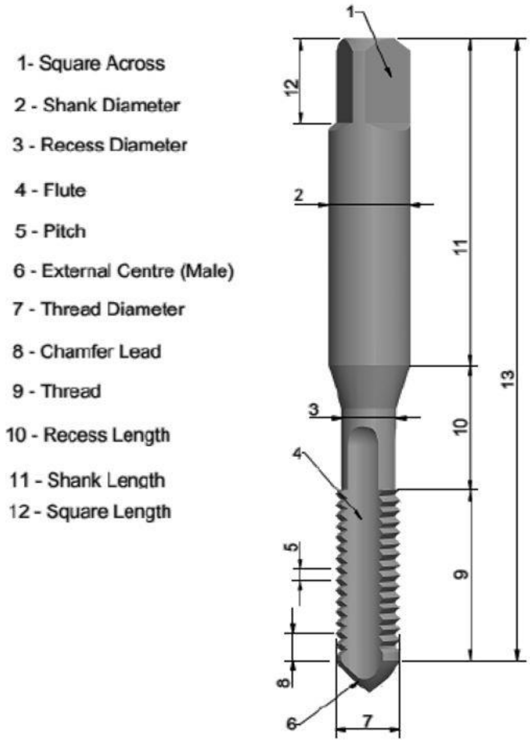

Figure 2. Critical dimensions in a threading tap.

4.2 Working algorithm of manufacturing process planning

Manufacturing process plans are designed to ensure consistency and use of best available machinery in the existing facility. The first step to design manufacturing process plan is to recognize a set of geometric features and their interrelationships from the part design. Set of machining functions are selected based on product geometric features, which can be treated as a general machining process without detail machining methods (Ndip-Agbor, Cao, and Ehmann 2018).

Manufacturing process planning is part of MCAPP module, and it generates manufacturing processes required to manufacture the product. The user has to input the query into the decisional DNA of the system based on initial objectives. This action is performed through a user-friendly Graphical user interface (GUI) of smart virtual product development system, which is shown in Figure 3. Once the user enters the manufacturing process planning submodule, there is an option to select the product to be manufactured (Threading Tap) from "Select product" section, and clicks the "Add product" button.

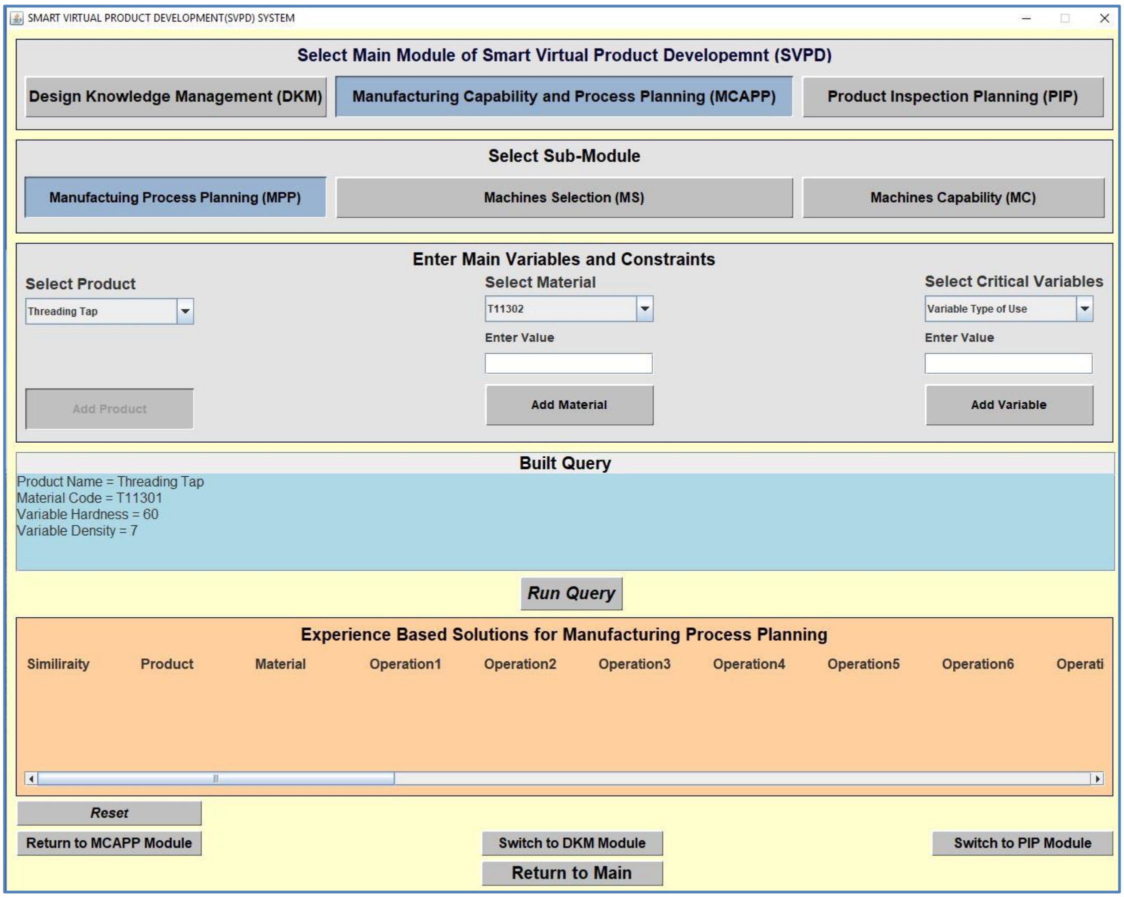

Figure 3. GUI for building query for manufacturing process planning (MPP) in SVPD system.

In next step, material for threading tap is selected from "Select material" list box. The user selects a material and enters the code of material in the text box, and clicks "Add material" button. Similarly, critical variables are selected from "Select critical variables" list box and again user selects a variable, enters its value in the next box and clicks "Add variable" button. Multiple variables can be selected and added. All selections are combined to build a query in "Build query" section. 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 Name = Threading Tap*

- *Material Code =T11303*
- *Variable Hardness=60*
- *Variable Density=7*

Finally, the user clicks the "Run Query" button and the closest SOE that matches the query is returned to the user in the next section under the heading of "Experienced based solutions for manufacturing process planning". This SOE contains the similarity of the query SOE with output SOE, product name, its material, and all the manufacturing operations performed to finalize the CAD model of the finished product. Similarity among SOEs is calculated on the basis of Euclidian distance with its value ranging from 0 to 1 (zero being the closets). These manufacturing operations can be simply recalled from an existing set of experiences (SOEs) of a family of similar products, which are stored in a comma-separated values (CSV) file. For illustrative purpose, a CSV file for manufacturing process planning is shown in Appendix 1.

As the DDNA is constructed in Java, the parser for manufacturing process planning is also written in Java programming. 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.
```

5 Results and Discussion

A case study for manufacturing process planning was executed 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 their mechanical properties. This CSV file stores manufacturing processes in the form of 22 variables, 2 functions, and 3 constraints for each experience. The parsing process for manufacturing process planning was executed, producing an average parsing time of 0.098 seconds, as depicted in Figure 4.

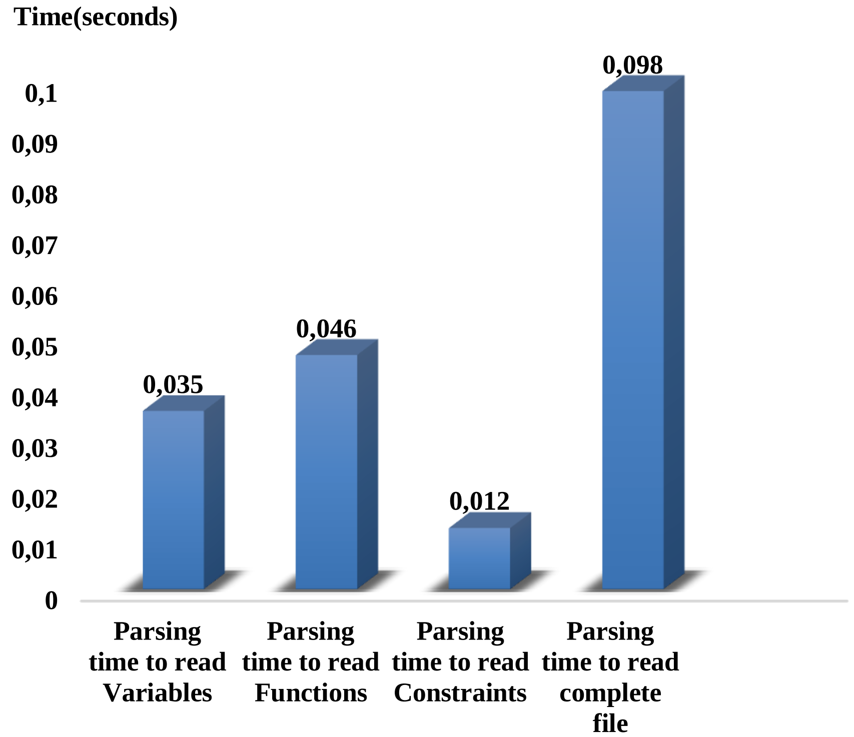

Figure 4. Parsing time vs SOE elements for manufacturing process planning.

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. This is considered an excellent time taking into consideration the large group of SOEKS. The similarity values of 10 tools stored as SOE according to their material code and recalled from a random query are shown in Figure 5.

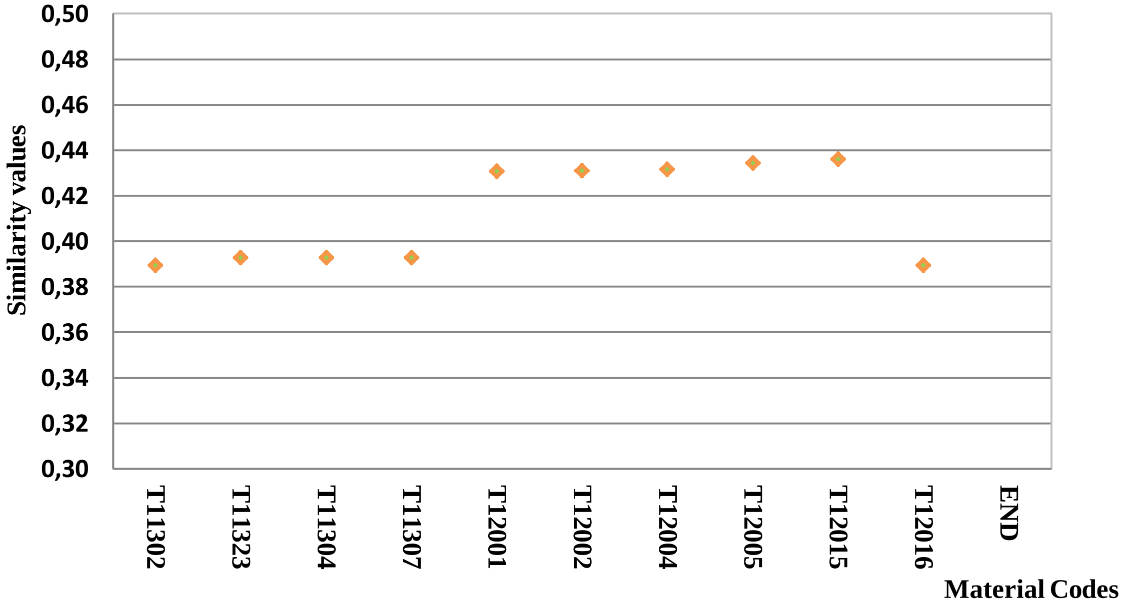

Figure 5. Similarity values for each SOEKS of stored products.

6 Conclusion and Future Work

This study explained the use of smart virtual product (SVPD) system to enhance the product manufacturing process. Proposed system is based on set of experience knowledge structure (SOEKs) and decisional DNA. Case study results for manufacturing process planning submodule show that system is capable of proposing the set of possible solutions. The user then selects the final solution, and the process is stored in decisional DNA of the system as experiential knowledge, which can be used in the future for solving a similar query.

The proposed system works as a group of experts working in different areas related to product development process, as it captures, stores, and maintains the experiential knowledge of all similar products. Manufacturing organizations can integrate proposed system with various ERP systems such as SAP and oracle discrete manufacturing, and can take proper and enhanced decisions related to product manufacturing processes.

Future work includes the extension of the system to extend the Java representation of product inspection planning (PIP) module.

References

- Bilal Ahmed, Muhammad, Syed Imran Shafiq, Cesar Sanin, and Edward Szczerbicki. 2019. "Towards Experience-Based Smart Product Design for Industry 4.0." Cybernetics and Systems 50 (2):165-75.
- Brown, John Seely, and Paul Duguid. 2000. "Balancing act: How to capture knowledge without killing it." Harvard business review 78 (3):73-80.
- Cagan, Jonathan, and Craig M Vogel. 2002. Creating breakthrough products: Innovation from product planning to program approval: Ft Press.
- Feng, Shaw C, William Z Bernstein, Thomas Hedberg, and Allison Barnard Feeney. 2017. "Toward Knowledge Management for Smart Manufacturing." Journal of Computing and Information Science in Engineering 17 (3):031016.
- Hedberg Jr, Thomas D, Nathan W Hartman, Phil Rosche, and Kevin Fischer. 2017. "Identified research directions for using manufacturing knowledge earlier in the product life cycle." International Journal of Production Research 55 (3):819-27.
- Khan, Muhammad S, Ahmed Al-Ashaab, Essam Shehab, Badr Haque, Paul Ewers, Mikel Sorli, and Amaia Sopelana. 2013. "Towards lean product and

process development." International Journal of Computer Integrated Manufacturing 26 (12):1105-16.

- Kusiak, Andrew. 2018. "Smart manufacturing." International Journal of Production Research 56 (1-2):508-17
- Ndip-Agbor, Ebot, Jian Cao, and Kornel Ehmann. 2018. "Towards smart manufacturing process selection in Cyber-Physical Systems." *Manufacturing Letters* 17:1-5.
- Nunes, M Lopes, AC Pereira, and AC Alves. 2017. "Smart products development approaches for Industry 4.0." Procedia Manufacturing 13:1215-22.
- Ottosson, Stig. 2004. "Dynamic product development - DPD." Technovation 24 (3):207-17.
- Sanin, Cesar, and Edward Szczerbicki. 2007. "Towards the construction of decisional DNA: A set of experience knowledge structure java class within an ontology system." Cybernetics and Systems: an international journal 38 (8):859-78.
- Sorli, Mikel, Maksim Maksimovic, Ahmed Al-Ashaab, Robert Sulowski, Essam Shehab, and Amaia Sopelana. 2012. Development of KBE system to support LeanPPD application Paper presented at the 2012 , 8th International ICE Conference on Engineering, Technology and Innovation.
- Thiede, Sebastian, Max Juraschek, and Christoph Herrmann. 2016. "Implementing cyber-physical production systems in learning factories." Procedia CIRP 54:7-12.
- Unger, Darian, and Steven Eppinger. 2011. Unger, Darian, and Steven Eppinger. 2011. "Improving product development process design: a method for managing information flows, risks, and iterations." Journal of Engineering Design 22 (10):689-99.

- Wasim, Ahmad, Essam Shehab, Hassan Abdalla, Ahmed Al-Ashaab, Robert Sulowski, and Rahman Alam. 2013. "An innovative cost modelling system to support lean product and process development." The International Journal of Advanced Manufacturing Technology 65 (1-4):165-81.
- Wolf, Wayne H. 2009. "Cyber-physical systems." IEEE Computer 42 (3):88-9.

Appendix 1 CSV file for manufacturing process planning.

Variables

Product_Name	material_UNS_Code	Material_Hardness	Material_Density	Operation_01	Operation_02	Operation_03	Operation_04	Operation_05	Operation_06
Threading Tap	T11302	62	8.16	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding
Threading Tap	T11323	66	8.16	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding
Threading Tap	T11304	65	7.97	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding
Threading Tap	T11307	65	7.95	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding
Reamer	T12001	65	8.67	Material Cutting	Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Cutter Grinding
Threading Tap	T12002	62	7.86	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding
Drill	T12004	66	8.68	Material Cutting	Turning	Milling	Surface Treatment	Cylindrical Grinding	Cutter Grinding
Threading Tap	T12005	66	8.75	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding
Milling Cutter	T12015	46	8.19	Material Cutting	Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread Grinding

Threading Tap Grinding	T12015	46	8.19	Material Cutting	CNC Turning	CNC Milling	Surface Treatment	Cylindrical Grinding	Thread