Experience-based Decisional DNA (DDNA) to Support Product Development

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Abstract: Knowledge and experience are important requirements for product development. The aim of this paper is to propose a systematic approach for industrial product development. This approach uses smart knowledge management system comprising of Set of Experience Knowledge Structure and Decisional DNA (DDNA) along with Virtual Engineering Tools (Virtual engineering object, Virtual engineering process, and Virtual engineering factory). This system provides a new direction to researchers working on product development, especially designers and manufacturers. It will reduce their communication gap by allowing them to work on the same platform. The proposed system adopts an early consideration of manufacturing issues. Therefore, it can shorten product development cycle time, minimize overall development cost, and ensure a smooth transition into production. The proposed system is dynamic in nature because it updates itself after every time a new decision related to product development activity is made. Product development process can be performed systematically and efficiently by using this system as it stores knowledge of experiences of different activities.
Keywords: Product Development, Product Design and Manufacturing, Set of Experience Knowledge Structure, Decisional DNA.

1 Introduction and Background

Organizations involved in manufacturing have to persist in a competitive global market. They have to fight vigorously to provide good products having greater value, and low cost. In order to achieve this, they try to employ best product development strategies. In past few years, there is a huge rise in market growth and technological changes, and this tempestuous environment requires new methods and techniques to bring successful new products to the marketplace (Gonzalez and Palacios 2002).

The world markets demand short product development times. This can be achieved by reducing all non-useable repetitive processes and mistake proofing at early stages of product development. It is very important for companies with short product life cycles to quickly develop new products and new product platforms that fulfill reasonable demands on quality, performance, and cost.

The capability to develop successful products depends highly on the quality of knowledge that supports decision making in the development (Liker and Morgan 2011). Information Technology (IT) has played a key role in improving product development process in various ways (Vilaseca-Requena et al. 2007). For example, increasingly more organizations are forced to move from traditional face-to-face teams to virtual teams or to adopt a combination of these two types of teams. As the result, they have to invest heavily in IT to enhance their market performance and competitiveness. Several companies report that they successfully use IT in their product development activities enhancing development speed, productivity, collaboration and communication, versatility, knowledge management, decision quality, and product quality (Ozer 2000).

Electronics and IT has played a key role in the 3rd industrial revolution by increasing automatization of production. Now, the world is moving towards Industry 4.0, which is the 4th revolution of the industry. Conventional processes will have been replaced by 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. This all have created a great potential for the development of new smart knowledge-based product development frameworks (Forbes and Schaefer 2017).

Knowledge management and knowledge-based systems have always focused on utilization of available knowledge to increase the organizational performance. They can enhance different activities i.e. marketing, costing, design, and manufacturing. In a new product and process development, an organized transformation of knowledge from previous projects can enhance quality, efficiency, cost and time to market. Unfortunately, existing knowledge management systems do not seem to provide information on well-known manufacturing constraints and product attributes identified during product development in the past. Secondly, the problem with existing systems is that they do not provide easy ways to capture, formalize and utilize the tacit knowledge which has a high impact on overall product development process. Therefore, knowledge and experience obtained from ongoing projects is poorly documented and is not available for reuse in future projects (Oduoza and Harris 2011).

Decision makers look back on the lessons learned from the previous similar situations, as the base for making current decisions. Insufficient knowledge administration and failure to capitalize the experiences within the organization creates hurdle in this process (Waris et al. 2016). Our proposed solution to this problem is based on applying collective intelligence tools to enhance the product development process. These tools are: Decisional DNA (DDNA), Virtual Engineering Object (VEO) and Virtual Engineering Process (VEP) (Sanin et al. 2017).They can be used for collecting, structuring, storing, and reusing past product development experiences. The aim is to develop an intelligent system capable of optimal resource management and minimization of waste management. Such system will grow and mature with time by gaining more expertise in its domain.

2 Fundamental Concepts

2.1 Product Development

Product development is a process which covers product design, production system design, product introduction process, and the start of its production (Johansen 2005). Kusar et al. (2004) summarized different stages of new product development, in which at the earlier stages, the goal is to make an initial market, business, and technical assessment, whereas at the later stages they recommend to actually design and develop the product(s). Eppinger and Ulrich (2003) defined it as a process of bringing new products or services to the market. The main aim of product development process is to provide the product at lower production costs, good quality, and quick access to market so that it can contribute to customers' satisfaction (Cagan and Vogel 2002). In our approach we propose product development platform supported by Set of Experience Knowledge Structure (SOEKS) and DDNA.

2.2 Set of Experience Knowledge Structure and Decisional DNA

Set of experience knowledge structure (SOEKS) has got the ability to store formal decision events in an explicit manner (Sanin and Szczerbicki 2009, 2004). 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) as shown in Figure 1.

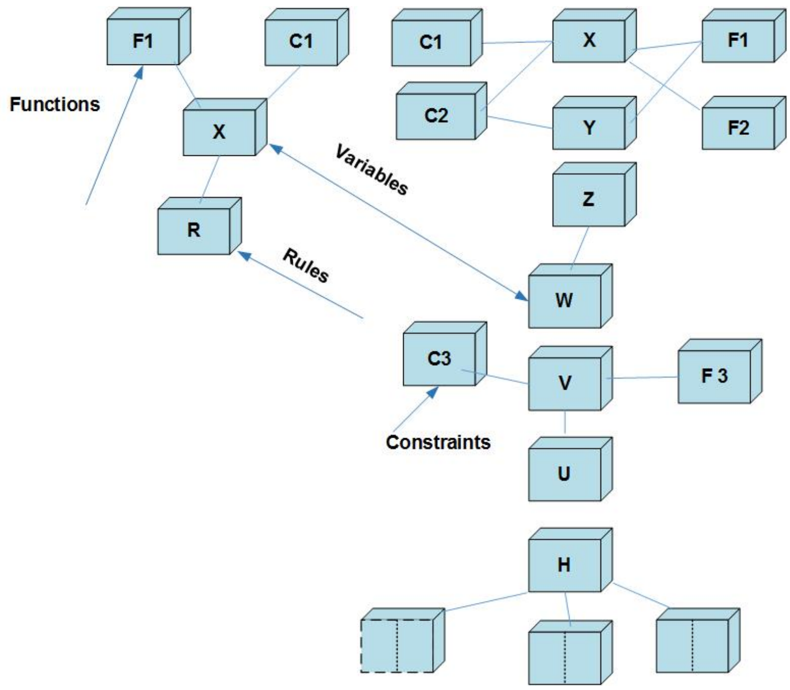

Figure 1. 3- Dimensional view of set of experience

Variables define SOE's functions. 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.

Groups of SOEs create chromosomes. These chromosomes represent the specific area/domain within the organization, and they store decisional strategies for a given domain. Accurately structured and grouped sets of chromosomes of the organization are collectively known as its Decisional DNA (Sanin and Szczerbicki 2009).

SOE 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 decision-support medical systems (Shafiq et al. 2014, Sanchez et al 2013).

2.3 Virtual Engineering Objects, Process, and Factory

Virtual engineering object (VEO) is a novel knowledge representation technique of an engineering object associated with its experience and formal decisions. It gathers and reuses its own experience-based knowledge. This is attained by collecting information from six different aspects of a given object i.e. (i) Characteristics, (ii) Functionality, (iii) Requirements, (iv) Connections, (v) Present State, and (vi) Experience (Shafiq et al. 2015). Virtual engineering process (VEP) is a knowledge representation of manufacturing process-planning regarding the required operations, their sequence, and resources. The VEP stores its knowledge in three main modules (i) Operations, (ii) Resources, and (iii) Experience (Shafiq et al. 2016a). Virtual engineering factory (VEF) is a knowledge representation of a complete manufacturing process and it is an extension of the VEO-VEP concept to a factory level. The VEF elements include: (i) VEF-Loading/Unloading, (ii) VEF-Transportation, (iii) VEF-Storage, (iv) VEF-Quality Control, (v) VEF-Experience (Shafiq et al. 2016b). The relationship between physical and virtual processes in terms of VEO, VEP and VEF is shown in Figure 2.

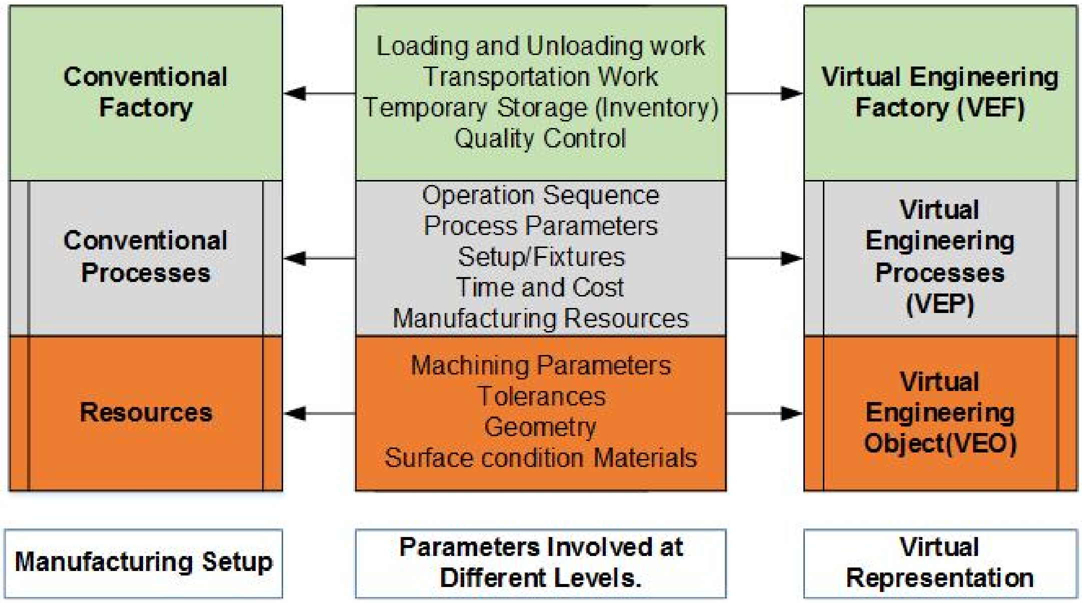

Figure 2. Relationship between physical and virtual world

VEO, VEP, and VEF are powered by SOEKS and decisional DNA. They are capable of presenting a group of knowledge structure able to gather and share collective intelligence, experience, and knowledge related to engineering processes run in a given organisation (Sanin et al. 2017).

2.4 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. 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 smaller concepts such as “cyber-physical systems (CPS)”, “Internet of things (IoT)”, “Internet of services (IoS)”, and “Smart Products”, where Cyber-Physical Systems environment is represented by large number of models, systems, and concepts from an extremely wide range of domains (Lee and Seshia 2016).

Industry 4.0 can be perceived as a natural transformation of the traditional industrial production systems into cyber-physical virtuality triggered by the digitalization trend.

This view is supported by comparison of ‘conventional’ topics in industrial production systems and Industry 4.0 topics. It is obvious that the main issues or topics do not really change, just the technology and approaches for tackling the connected issues are entirely new. The Industry 4.0 concept is not just limited to the direct manufacturing in the company, but it also includes a complete value chain from providers to customers. It is a specialization of the IoT applied to the manufacturing/industrial environment by assuming broad support of an entire life cycle of systems, products, and series. Industry 4.0 will be producing a new type of products, which will be smart products. These products are not smart only because of new intelligent manufacturing processes that create them. They also continue to provide the data about their state and experience during their lifecycle. This data can be used for different purposes, for example for preventive maintenance and to provide the manufacturer with some useful information about lifetime and reliability of their products (Rojko 2017).

These new smart products are implanted with sensors, identifiable components, and processors. They will be carrying information and knowledge to convey the functional guidance to the customers and transmitting the users’ feedback to the manufacturing system. In addition, a full production information log can be embedded in a product assisting its developer in optimizing the design, prediction, and maintenance (Abramovici and Stark 2013).

2.5 Concept of Product and Product Families

In the last few years, demand for individualized products has increased highly. This has also made product configuration and evolution more challenging. In response to these challenges diverse product versions have been developed. They can include series of products with different functions, series of components with different configurations, and series of features with different dimensions. This gives rise to product families that contain variants of products and their parts, components, and configurations. There are six distinguishable levels in the hierarchy of parts, products, and product families, which are shown in Figure 3 (ElMaraghy 2009).

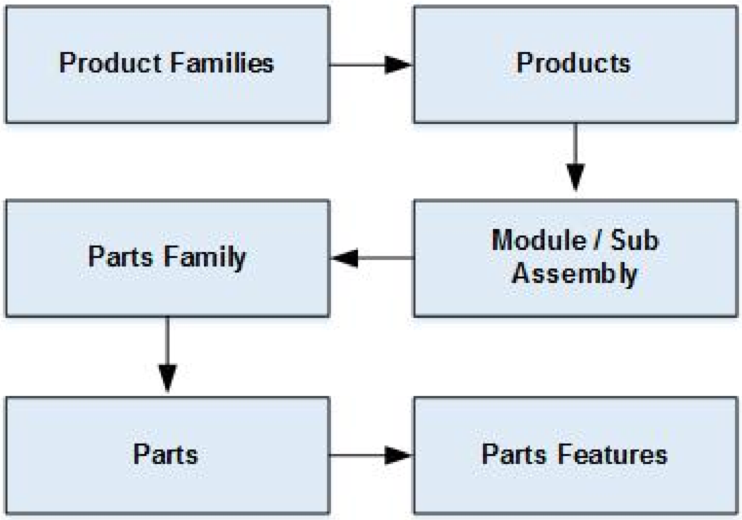

Figure 3. Products variation hierarchy

Our research takes into consideration the perspective of product development based on evolving range of products. We use an approach to develop a new product from existing product families and part hierarchies (Simpson et al. 2001). Francalanza et al. (2017), explained product hierarchy in terms of products families and product features, which can be formulated as follows:

$$[Product\ Family] \Leftarrow [Prod]_1 + [Prod]_2 + [Prod]_3 \ldots + [Prod]_x \tag{1}$$

Based on Tjalve 2015, a product can be further described as being made up of the structured assembly of part objects, which can be expressed as:

$$[Product] \Leftarrow [Part]_1 + [Part]_2 + [Part]_3 \ldots + [Part]_x \tag{2}$$

Equation (2) illustrates the idea that a product is made up of a structured assembly of parts, $[\mathrm{Part}]_1$, $[\mathrm{Part}]_2$, $[\mathrm{Part}]_3$, etc.

The next step is to define part objects. Part object [Part] is considered to consist of a set of part properties (Tjalve (2015). These properties include the five basic properties as shown in expression (3):

$$[Part] \Leftarrow \{M \wedge F \wedge D \wedge T \wedge SF \wedge Q\} \quad (3)$$

As illustrated by (3), each [Part] has a set of properties, these include Material (M), Form (F), Dimensions (D), Tolerances (T), Surface Finish (SF) and Quantity (Q). Manufacturing processes require to produce a range of products are defined by process requirements. Manufacturing processes are basically modelled as a number of steps within a process plan model:

$$[Process\ Plan\ Model] \Leftarrow [Process\ Step]_1 + [Process\ Step]_2 + [Process\ Step]_x \quad (4)$$

Whereas the process steps can be further defined in terms of their properties as follows:

$$[Process\ Step]_1 \Leftarrow \{(Tp) \wedge (Ts) \wedge (SN) \wedge (P)\} \quad (5)$$

where $[Process\ Step]_1$ has its unique type (Tp), time (Ts), step number (SN) and properties (P).

3 Product Development Process and its Decisional DNA

The proposed architecture of product development system is shown in Figure 4. It develops new products from existing products or families of products, using hierarchies and virtual tool introduced in previous sections. Product development activities are performed by recalling and modifying the existing VEOs and VEPs for products, product parts, and/or product families. The proposed system tries to capture experiences related to past product development activities from the dedicated set of experiences (SOEs).

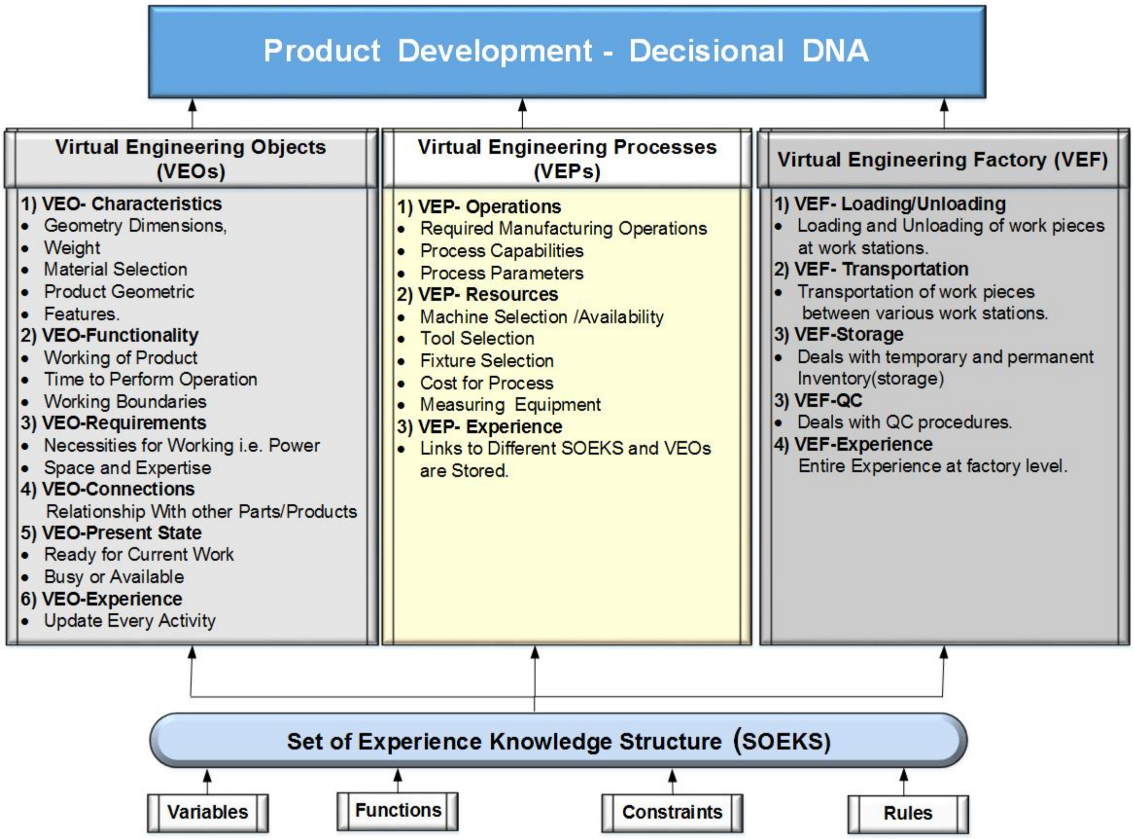

Figure 4. Architecture of a Product Development- Decisional DNA

A group of sets of experience of the same category is called decisional product development activity chromosome. The product development decisional DNA contains the collection of decisional chromosomes and holds complete knowledge of different queries i.e. material selection, product geometric features, process parameters, machines selection, required tooling and measuring equipment, etc. For example, if we take an example of design and development of a threading tap (a tool to create screw threads, which is called threading), a single product development activity decision deals with the material selection and it uses the corresponding set of experience or decisional gene of the threading tap's material range. Subsequently, the decisional chromosome will consist of a number of such decisions, and the sum of such types of decisional chromosomes will be stored in DDNA of the whole design and development of threading tap.

For evolving products, knowledge representation structures are never completed as they also keep evolving. They are updated with new decisions that are captured by SOE and added to DDNA of the system. In this way, the DDNA continues to gain new and updated experiential knowledge, which helps it to support and enhance future decisions related to product development process. This knowledge is stored in different VEOs, VEPs and finally a whole factory experience is maintained in VEF.

3.1 The working of Proposed Concept

The query based on product development activity is fed into the DDNA system. This query is converted to a Set of Experience (SOE), which contains a unique combination of variables, functions, constraints, and rules. Figure 5 illustrates the process in which the system extracts knowledge required by the query. Design and development of a threading tap continues to be the case study.

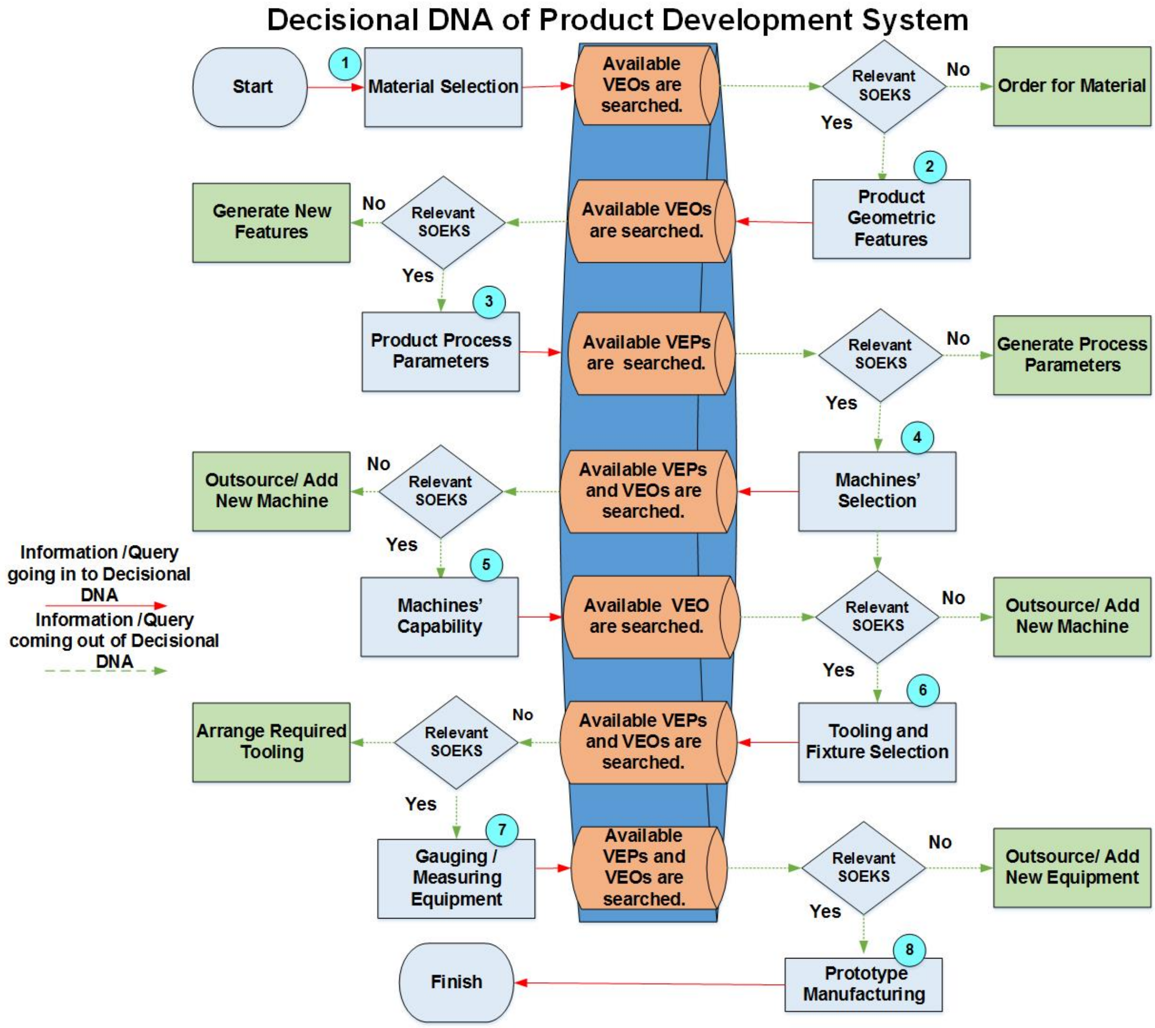

Figure 5. Working of the Proposed Concept

The working of the steps numbered in Figure 5 from 1 through 8 are explained as follows:

STEP 1 Material Selection: In this step, the user provides requirements regarding material selection, for example required hardness, tensile strength, and various metallic ingredients. Proper material selection and its availability are our primary goals and this information enters into DDNA of product development. The query tries to find an appropriate VEO, within the family of the same product. Two events could happen:

(a) relevant VEO can be found and its SOEKS can be used for the selection of existing material,

(b) there is no relevant VEO so a new one is formed and added to the knowledge base as the new experience generated by the material selection query.

***STEP 2 Product Geometric Features*:** When analysing the component to be designed, it needs to be assessed at the part level. This makes it easy to understand its overall functional requirements, its method of operation and the components with which the component of interest interfaces. The functional requirements of the individual features and their physical attributes need to be identified, including the form, the feature relationships, and associations (Urbanic and ElMaraghy 2009). Therefore, keeping this in mind, as the user provides inputs regarding some geometric features requirements, it enters as a query in DDNA of product development and tries to find any further geometric features within the family of the same product VEOs. Two things could happen:

(a) relevant VEO can be found and its SOEKS can be used for the selection of existing product generation features,

(c) there is no relevant VEO so a new one is formed and added to the knowledge base as a new experience generated by the product geometric features query.

The fundamental logic behind the remaining steps is the same as above. The difference is that starting with Step 3, the search process related to the current query involves VEPs, as briefly described below.

***STEP 3 Process Parameters Generation*:** Once the design parameters are generated, the next step is to define process parameters. In case of a threading tap, we have to decide which machining operations are required. These parameters can be simply recalled from existing VEP of a family of similar products. If no relevant VEP is found, a new SOEKS is generated and used to form a new VEP which is saved for future reference. The new process parameters generation query information is in the form of SOE (variables, functions, constraints, and rules) and is structured as follows:

IF selected product is Threading Tap of High-Speed Steel material, THEN

Manufacturing processes are:

• Material cutting • Turning • Milling • Heat treatment • Cylindrical Grinding • Thread Grinding • Cutter Grinding • Engraving

STEP 4 Machines' Selection/Availability**:** In this step, all machines required for manufacturing processes are checked for their availability. If some machine is not available in terms of physical availability or due to a busy schedule, it needs to be outsourced. An existing set of VEPs is searched based on the manufacturing resources query. If it is not found, the new machine selection information is generated in the form of SOE and is structured as follows:

IF selected product is Threading Tap of High-Speed Steel material, THEN

Required machines are:

• Metal Cutter • CNC Lath • CNC Milling • Heat treatment Furnace required for High-Speed Steel • Cylindrical Grinding Machine • Thread Grinding Machine • Cutter Grinding Machine • Engraving Machine

STEP 5 Machines' Capability**:** It is not only machine's availability which need to be considered by designers and manufacturers. They should also be well aware of each machine's capability. It is measured in terms of its maximum and minimum processing limits. Therefore, the capability of each machine will be checked in this step. A VEO can be recalled from the existing Product Development DDNA, which will provide the required upper and lower limits of the selected machine. If it is not found, the new machine capability information is generated in the form of SOE and is structured as follows:

IF the selected machine is CNC Milling, THEN

Available machines' capacity is:

- *Maximum Capacity is: x-axis = 500 mm, y-axis = 250 mm, z-axis = 100 mm*
- *Minimum Capacity is: x-axis = 10 mm, y-axis = 10 mm, z-axis = 10mm*

STEP 6 Tooling and Fixture Selection: Tool and fixture selection are of great importance in manufacturing operations. In this step, all required tools and fixtures for different machines performing various processes are selected. The search process based on a tooling selection query and its results are similar in nature as in former steps.

***STEP 7 Gauging / Measuring Equipment*:** The measuring instruments selection is an important part of the manufacturing process. Once again, the relevant VEP for selection of gauges and instruments are searched and the logic of the above steps repeats.

STEP 8 Protype Manufacturing: Once it is confirmed that required threading tap can be easily manufactured in existing facility, the final step is to create production drawings by using available CAD tool, and start with prototype manufacturing.

4 Conclusion and Future Work

This article introduces the concept of a new approach to the product development process. The presented concept employs DDNA and SOE to support and enhance smartness of this important process . It is based on knowledge representation structure that applies past experiences. The proposed system carries the promise to support the product development activities quickly and efficiently as required by the incoming fourth industrial revolution. It is dynamic in nature as it updates itself after every time a new decision is made. With time and gathered experience, it can behave as an expert entrepreneur capable of making quick and smart decisions. The concept is illustrated with the example of design and development of threading tap to understand the architecture and the working of the system that is introduced. In the next research step, we will refine the components of the proposed architecture and translate it into software representation on a Java platform.

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